Science and Technology

LOSKA A. **Remarks about modelling of maintenance processes with the use of scenario techniques.** Eksploatacja i Niezawodnosc - Maintenance and Reliability 2012; 14 (2): 92-98.

This article aims at presenting the results of research use of modelling of exploitation processes in practical applications (industrial). Firstly, there has been made an identification and of solutions in this area, particular attention was paid equally to the problems associated with processes modelling in the context of wider organizational and technical approach. Basing on the performed studies, of both basic (theoretical) and industrial character, the research problem has been defined. It concentrates on the difficulties of using exploitation process models in relation to the maintenance organization in an industrial enterprise, because of their "flat" nature. Based on the developed research problem, there has been proposed a way of its solution by applying scenario techniques. Secondly, following a review of the state of knowledge (literature) in the context of exploitation scenario building, there has been prepared and presented a detailed research procedure, that will result in the development of methodology for creation of exploitation scenarios, including the way of their use in practice.

LOSKA A. **Uwagi o modelowaniu procesów eksploatacyjnych z wykorzystaniem technik scenariuszowych.** Eksploatacja i Niezawodnosc - Maintenance and Reliability 2012; 14 (2): 92-98.

Celem artykułu jest zaprezentowanie wyników przeprowadzonych badań w zakresie sposobów wykorzystania metod modelowania procesów eksploatacyjnych w zastosowaniach praktycznych (przemysłowych). W pierwszej kolejności dokonano identyfikacji i klasyfikacji stosowanych w tym zakresie rozwiązań, zwrócono przy tym uwagę na problemy związane z modelowaniem procesów w aspekcie szerszego ujęcia organizacyjno-technicznego. W oparciu o przeprowadzone badania, które miały charakter zarówno podstawowy (teoretyczny), jak i przemysłowy, sformułowano problem badawczy. Jego istota sprowadza się do trudności wykorzystania modeli procesów eksploatacji w odniesieniu do funkcjonujących organizacji utrzymania ruchu przedsiębiorstw przemysłowych ze względu na ich „płaski" charakter. W oparciu o sformułowany problem badawczy zaproponowano sposób jego rozwiązania poprzez zastosowanie do modelowania procesów eksploatacji technik scenariuszowych. Następnie po dokonaniu przeglądu stanu wiedzy (literatury) w aspekcie budowy scenariuszy eksploatacyjnych, opracowano i przedstawiono szczegółowo procedurę prowadzenia badań, których efektem będzie opracowanie metodologii tworzenia scenariuszy eksploatacyjnych, z uwzględnieniem sposobu praktycznego ich wykorzystania.

ZAHARIA S M, MARTINESCU I, MORARIU C O. **Life time prediction using accelerated test data of the specimens from mechanical element.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 99–106.

In accelerated life testing, products are exposed to stress levels higher than those at normal use in order to obtain information in a short time. In this paper ,we expand the limits of performing accelerated life tests to an aerospace product (supple platinum). Specimens from the IAR 330 Puma helicopter structure, made of supple platinum, were subjected to accelerated life testing, and a significant reduction of the testing time was obtained. A simulation of the accelerated life testing data from the same case study was performed using the Monte Carlo method, with the purpose of comparing the data resulting from the experimental study (accelerated life tests) with the simulated data.

ZAHARIA S M, MARTINESCU I, MORARIU C O. **Prognozowanie czasu pracy elementu mechanicznego z wykorzystaniem danych z badań przyspieszonych.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 99–106.

W przyspieszonych badaniach cyklu życia, produkty poddaje się naprężeniom o wartościach wyższych niż występujące w normalnych warunkach użytkowania, w celu szybszego uzyskania informacji. W przedstawionym artykule poszerzamy granice zastosowań badań przyspieszonych o produkt przemysłu lotniczego (giętka platyna, ang. supple platinum). Próbki z giętkiej platyny pochodzące z elementu konstrukcji śmigłowca IAR 330 Puma poddano badaniom przyspieszonym otrzymując znaczne skrócenie czasu badania. Dla otrzymanych danych z badań przyspieszonych przeprowadzono symulację metodą Monte Carlo, w celu porównania danych eksperymentalnych (z badań przyspieszonych) z danymi symulacyjnymi.

DĘBSKI H, KOSZAŁKA G, FERDYNUS M. **Application of FEM in the analysis of the structure of a trailer supporting frame with variable operation parameters.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 107–114.

This work presents a numerical analysis of the structure of a trailer frame of adjustable length and an increased load capacity designed for the transportation of oversize loads. The study was aimed at developing adequate numerical FEM models which would allow identification of the effort of the structure and the state of strain under operating loads. The analysis was carried out using ABAQUS/Standard, a numerical tool which enables calculations in the geometrically non-linear range with the use of the incremental–iterative Newton–Raphson method. As a result of the analysis, trouble areas in the frame were found in which dangerous stresses occurred. This enabled modification of the structure, leading to a reduction of the stresses to a safe level.

DĘBSKI H, KOSZAŁKA G, FERDYNUS M. **Wykorzystanie MES w analizie struktury nośnej ramy naczepy o zmiennych parametrach eksploatacyjnych.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 107–114.

W pracy zaprezentowano numeryczną analizę konstrukcji ramy naczepy o zmiennej długości i podwyższonej nośności przeznaczonej do transportu ładunków ponadnormatywnych. Prowadzone badania miały na celu opracowanie adekwatnych modeli numerycznych MES umożliwiających identyfikację wytężenia konstrukcji oraz stanu odkształcenia w warunkach obciążeń eksploatacyjnych. Zastosowanym do analizy narzędziem numerycznym był program Abaqus/Standard, umożliwiający prowadzenie obliczeń w zakresie geometrycznie nieliniowym z wykorzystaniem przyrostowo-iteracyjnej metody Newtona-Raphsona. W wyniku przeprowadzonych prac ustalono newralgiczne obszary ramy w których występowały niebezpieczne naprężenia. Umożliwiło to modyfikację konstrukcji pozwalającą na zmniejszenie naprężeń do bezpiecznego poziomu.

ZHANG XL, HUANG HZ, WANG ZL, XIAO NC, LI YF. **Uncertainty analysis method based on the combination of maximum entropy principle and point estimation method**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 115–120.

Uncertainty is inevitable in product design processes. Therefore, to make reliable decisions, uncertainty analysis incorporating all kinds of uncertainty is needed. In engineering practice, due to the incomplete knowledge, the distribution of some design variables can not be determined. Furthermore, the performance function is highly nonlinear, therefore, the high order moments of the performance function are needed to calculate the probability of failure accurately. In this paper, an uncertainty analysis method combining the maximum entropy principle and the bootstrapping method is proposed. Firstly, the bootstrapping method is used to calculate the confidence intervals of the first four moments for mixed random variables and sample variables. Secondly, the high order moments of limit state functions are estimated using the reduced dimension method. Thirdly, to calculate the probability density function (PDF) and cumulative distribution function (CDF) of the limit state functions, an optimization model based on the maximum entropy principle is formulated. In the proposed method, the assumptions that the distribution of the random variables are known

ZHANG XL, HUANG HZ, WANG ZL, XIAO NC, LI YF. **Metoda analizy niepewności oparta na połączeniu zasady maksymalnej entropii i metody oceny punktowej**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 115–120.

Niepewność jest nieodłącznym elementem procesów projektowania produktu. Dlatego też podejmowanie niezawodnych decyzji wymaga analizy niepewności, która uwzględniałaby wszystkie rodzaje niepewności. W praktyce inżynierskiej, z powodu niepełnej wiedzy, wyznaczenie rozkładu niektórych zmiennych projektowych nie jest możliwe. Co więcej, funkcja stanu granicznego jest wysoce nieliniowa, co sprawia, że do poprawnego obliczenia prawdopodobieństwa uszkodzenia potrzebna jest znajomość momentów wyższych rzędów tej funkcji. W niniejszej pracy zaproponowano metodę analizy niepewności łączącą zasadę maksymalnej entropii z metodą bootstrapową. W pierwszej części pracy wykorzystano metodę bootstrapową do obliczenia przedziałów ufności czterech pierwszych momentów dla zmiennych losowych typu mieszanego oraz zmiennych z próby. Następnie, wyznaczono momenty wyższych rzędów funkcji stanu granicznego przy użyciu metody redukcji wymiarów. Po trzecie, w celu obliczenia funkcji gęstości prawdopodobieństwa (PDF) oraz dystrybuanty (CDF) funkcji stanu granicznego, sformułowano model optymalizacji oparty na

and the calculation of the sensitivity for limit state function with respect to the Most Probable Point (MPP) are avoided. Finally, comparisons of results from the proposed methods and the MCS method are presented and discussed with numerical examples.

zasadzie maksymalnej entropii. Proponowana metoda nie wymaga założenia znajomości rozkładów zmiennych losowych ani obliczania wrażliwości dla funkcji stanu granicznego w odniesieniu do najbardziej prawdopodobnego punktu awarii. W końcowej części artykułu porównano na podstawie przykładów numerycznych wyniki otrzymane za pomocą proponowanej metody oraz symulacji Monte Carlo (MCS).

ZHANG Z, ZHOU Y, SUN Y, MA L. **Condition-based maintenance optimisation without a predetermined strategy structure for a two-component series system.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 121–130.

Most existing research on maintenance optimisation for multi-component systems only considers the lifetime distribution of the components. When the condition-based maintenance (CBM) strategy is adopted for multi-component systems, the strategy structure becomes complex due to the large number of component states and their combinations. Consequently, some predetermined maintenance strategy structures are often assumed before the maintenance optimisation of a multi-component system in a CBM context. Developing these predetermined strategy structure needs expert experience and the optimality of these strategies is often not proofed. This paper proposed a maintenance optimisation method that does not require any predetermined strategy structure for a two-component series system. The proposed method is developed based on the semi-Markov decision process (SMDP). A simulation study shows that the proposed method can identify the optimal maintenance strategy adaptively for different maintenance costs and parameters of degradation processes. The optimal maintenance strategy structure is also investigated in the simulation study, which provides reference for further research in maintenance optimisation of multi-component systems.

ZHANG Z, ZHOU Y, SUN Y, MA L. **Optymalizacja zależnego od stanu technicznego utrzymania urządzeń dla dwuskładnikowego systemu szeregowego nie wymagająca z góry ustalonej struktury strategii.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 121–130.

Większość badań nad optymalizacją utrzymania systemów wieloskładnikowych bierze pod uwagę jedynie rozkład czasu życia elementów składowych. Kiedy przyjmie się dla systemów wieloskładnikowych strategię utrzymania urządzeń zależną od ich bieżącego stanu technicznego (condition-based maintenance, CBM), struktura strategii staje się złożona w związku z dużą liczbą stanów składowych oraz ich kombinacji. W konsekwencji, często przyjmuje się pewne z góry ustalone struktury strategii utrzymania przed optymalizacją utrzymania systemu wieloskładnikowego w kontekście CBM. Opracowanie takich z góry ustalonych struktur strategii wymaga jednak specjalistycznego doświadczenia, a i tak brak dowodów na optymalność tych strategii. W artykule zaproponowano metodę optymalizacji utrzymania szeregowego systemu dwuskładnikowego, która nie wymaga wcześniej ustalonej struktury strategii. Proponowaną metodę opracowano na podstawie semimarkowskiego procesu decyzyjnego (SMDP). Badanie symulacyjne pokazało, że za pomocą proponowanej metody można ustalać optymalną strategię utrzymania w sposób adaptacyjny dla różnych kosztów utrzymania oraz parametrów procesów degradacyjnych. Za pomocą symulacji badano także optymalną strukturę strategii utrzymania, jako punkt odniesienia dla przyszłych studiów nad optymalizacją systemów wieloskładnikowych.

WU W, HUANG HZ, WANG ZL, LI YF, PANG Y. **Reliability analysis of mechanical vibration component using fuzzy sets theory.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 131–134.

The conventional reliability analysis of mechanical vibration component only considers the randomness of vibration but rarely for the fuzziness that may exist. It is therefore difficult to be consistent with the engineering practices. Based on the mechanical vibration theory, a novel fuzzy reliability approach by integrating the fuzzy comprehensive evaluation and fuzzy set theory is proposed in this paper. The fuzzy comprehensive evaluation is used to optimize the fuzzy factors of the reliability analysis of vibration component. With the aim of comparing the performance of the proposed approach with the conventional approach, two engineering examples are presented. The results demonstrate that the proposed approach is better than the conventional approach for its capability of covering fuzzy factors in the engineering problems.

WU W, HUANG HZ, WANG ZL, LI YF, PANG Y. **Analiza niezawodnościowa mechanicznego elementu wibracyjnego z wykorzystaniem teorii zbiorów rozmytych.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 131–134.

Tradycyjna analiza niezawodnościowa wibracyjnego elementu mechanicznego bierze pod uwagę jedynie losowość drgań, rzadko zaś wyjaśnia mogącą występować rozmytość. Taka analiza nie odpowiada zatem praktyce inżynierskiej. Opierając się na teorii drgań mechanicznych, w niniejszym artykule zaproponowano nowatorskie podejście w ramach teorii rozmytej niezawodności, które łączy rozmytą ocenę kompleksową oraz teorię zbiorów rozmytych. Rozmytej oceny kompleksowej użyto do optymalizacji rozmytych czynników analizy niezawodnościowej elementu wibracyjnego. W celu porównania efektywności proponowanego podejścia z efektywnością podejścia tradycyjnego przedstawiono dwa przykłady z dziedziny inżynierii. Wyniki pokazują, że proponowane podejście jest lepsze od tradycyjnego ze względu na możliwość objęcia w problemach inżynierskich czynników rozmytych .

GALAR D, GUSTAFSON A, TORMOS B, BERGES L. **Maintenance decision making based on different types of data fusion.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 135–144.

Over the last decade, system integration is applied more as it allows organizations to streamline business processes. A recent development in the asset engineering management is to leverage the investment already made in process control systems. This allows the operations, maintenance, and process control teams to monitor and determine new alarm level based on the physical condition data of the critical machines. Condition-based maintenance (CBM) is a maintenance philosophy based on this massive data collection, wherein equipment repair or replacement decisions depend on the current and projected future health of the equipment. Since, past research has been dominated by condition monitoring techniques for specific applications; the maintenance community lacks a generic CBM implementation method based on data mining of such vast amount of collected data. The methodology would be relevant across different domains. It is necessary to integrate Condition Monitoring (CM) data with management data from CMMS (Computer Maintenance Management Systems) which contains information, such as: component failures, failure information related data, servicing or repairs, and inventory control and so on. These systems are the core of traditional scheduled maintenance practices and rely on bulk observations from historical data to make modifications to regulated maintenance actions. The most obvious obstacle in the integration of CMMS, process and CM data is the disparate nature of the data types involved, and there have benn several attempts to remedy this problem. Although, there have been many recent efforts to collect and maintain large repositories of these types of data, there have been

GALAR D, GUSTAFSON A, TORMOS B, BERGES L. **Podejmowanie decyzji eksploatacyjnych w oparciu o fuzję różnego typu danych.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 135–144.

W ostatniej dekadzie coraz częściej stosuje się integrację systemów, która pozwala przedsiębiorstwom zwiększać wydajność procesów biznesowych. Nowością w zarządzaniu infrastrukturą techniczną jest zwiększanie efektywności już poczynionych inwestycji w systemy kontroli procesów. Pozwala to zespołom do spraw operacyjnych, utrzymania ruchu oraz kontroli procesów monitorować i ustalać nowe poziomy alarmowe na podstawie danych o stanie fizycznym maszyn krytycznych. Utrzymanie urządzeń zależne od ich bieżącego stanu technicznego (condition-based maintenance, CBM) to filozofia utrzymania ruchu opierająca się na tym masowym poborze danych, wedle której decyzje dotyczące naprawy lub wymiany sprzętu zależą od jego obecnego oraz przewidywanego przyszłego stanu technicznego. Ponieważ dotychczasowe badania były zdominowane przez problem technik monitorowania stanu dla konkretnych aplikacji, nie opracowano ogólnej metody wdrażania CBM opartej na eksploracji (data mining) owych olbrzymich ilości zebranych danych, która miałaby zastosowanie w różnych domenach. Konieczna jest integracja danych z monitorowania stanu (condition monitoring, CM) z danymi dotyczącymi zarządzania pochodzącymi ze skomputeryzowanych systemów zarządzania utrzymaniem ruchu (CMMS), które zawierają informacje na temat uszkodzeń elementów składowych, dane związane z uszkodzeniami, a także informacje dotyczące obsługi lub napraw czy sterowania zapasami. Systemy te stanowią

relatively few studies to identify the ways these to datasets could be related. This paper attempts to fulfill that need by proposing a combined data mining-based methodology for CBM considering CM data and Historical Maintenance Management data. It shows a system integration of physical and management data that also supports business intelligence and data mining where data sets can be combined in non-traditional ways.

podstawę tradycyjnych praktyk obsługi planowej, a zasadzają się na całościowych obserwacjach dokonywanych na podstawie danych eksploatacyjnych, które pozwalają modyfikować regulowane działania obsługowe. Najbardziej oczywistą przeszkodą w integracji danych CMMS, danych procesowych oraz danych z monitorowania stanu jest rozbieżność ich natury. Dotychczas podjęto jedynie kilka prób rozwiązania tego problemu. Chociaż ostatnio wiele wysiłku włożono w gromadzenie i utrzymanie dużych zasobów tego typu danych, istnieje stosunkowo niewiele badań na temat możliwych sposobów powiązania owych zestawów danych. W prezentowanej pracy poczyniono próbę wypełnienia tej luki proponując metodologię łączoną opartą na eksploracji danych dla celów CBM, która bierze pod uwagę dane z monitorowania stanu i eksploatacyjne dane z zarządzania ruchem. W pracy przedstawiono integrację systemową danych fizycznych i danych z zarządzania, która wspiera także analitykę biznesową (business intelligence) oraz eksplorację danych, gdzie zestawy danych można łączyć w sposób nietradycyjny.

JEDLIŃSKI Ł. **Multi-channel registered data denoising using wavelet transform.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 145–149.

In order to obtain information regarding given phenomenon or object, it is usually necessary to register selected measurement signals obtained using sensors. Unfortunately, obtained signals, apart form desired information, contain disturbances caused by, amongst many other, properties of the measurement channel and processes associated with object operation. In many cases it is necessary to measure the same value in different places and/or directions. Thus, there is a demand for a tool improving signal to noise ration of the multi-channel registered signals.Wavelet transform is a relatively new method of data processing used in different fields (e.g. technique and physics). In case of signals it can be used for denoising, compression, trend detection or discontinuity detection. In this work it was used to denoise vibration signals registered by two three-axis sensors. Object of investigation was the bevel toothed gear. Signals denoising was to improve efficiency of the diagnosis of transmission gears teeth damage.

JEDLIŃSKI Ł. **Odszumianie danych rejestrowanych wielokanałowo z użyciem transformaty falkowej.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 145–149.

W celu uzyskania informacji o interesującym nas zjawisku lub obiekcie najczęściej rejestrowane są wybrane sygnały pomiarowe otrzymane za pośrednictwem czujników. Niestety uzyskane sygnały oprócz pożądanej informacji zawierają również zakłócenia, które są spowodowane m.in. właściwościami toru pomiarowego i procesami towarzyszącymi działaniu obiektu. W wielu przypadkach zachodzi potrzeba pomiaru takiej samej wielkości w różnych miejscach obiektu i/lub kierunkach. Potrzebne są zatem narzędzia do poprawy stosunku sygnału do szumu sygnałów rejestrowanych wielokanałowo.Transformata falkowa jest stosunkowo nową metodą przetwarzania danych, która znalazła zastosowanie w różnych dziedzinach takich jak technika i fizyka. W odniesieniu do sygnałów może być używana do odszumiania, kompresji, wykrywaniu trendu czy nieciągłości sygnału. W pracy tej transformata falkowa została użyta od odszumiania sygnałów drgań zarejestrowanych z dwóch trójosiowych czujników. Obiektem badań była przekładnia zębata stożkowa. Odszumianie sygnałów miało na celu poprawę skuteczności diagnozy uszkodzenia kół zębatych przekładni.

TOMPOROWSKI A. **Stream of efficiency of rice grains multi-disc grinding.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 150–153.

A search for design solutions for grain grinding devices offering energy-saving production processes justify the research into the improvement of the theory and the design of grinders. The efficiency, functionality and performance of the rice grains grinding are significantly influenced by processes, difficult to describe, occurring within the working space of the grinder. Although there are some studies on the principles of the functionality and analysis of multi-disc grinders, an attempt has not been made so far at describing the influence of features and behaviour of ground material on efficiency, performance and usefulness of the biomaterial comminution/grinding process. The basis for the improvement of the functionality of a grinding device is an analysis of the potential of existing solutions and a determination of the scope of effective design features of the working unit within the permissible area. The criteria may be fulfilled by objective-oriented control of the design features of the multi-disc unit. In order for these actions to be effective, relevant relationships need to be explored and a mathematical description needs to be developed for the flow of ground grains through the working space of a multi-disc grinder, as a result variable of the structure and the operation of a working unit.

TOMPOROWSKI A. **Strumień wydajności wielotarczowego rozdrabniania ziaren ryżu.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 150–153.

Poszukiwania rozwiązań konstrukcyjnych zespołów rozdrabniających ziarna zbóż, prowadzące do energooszczędnych procesów produkcyjnych uzasadniają podjęcie badań nad doskonaleniem teorii i konstrukcji rozdrabniaczy. Istotny wpływ na wydajność, funkcjonalność i sprawność procesu rozdrabniania ziarna ryżu mają trudne do opisania zjawiska zachodzące w przestrzeni roboczej rozdrabniacza. Pomimo, że dostępne są opracowania na temat podstaw funkcjonalności i badań rozdrabniaczy wielotarczowych, jak dotychczas nie podejmowano próby opisu wpływu cech i zachowań rozdrabnianego materiału na wydajność, sprawność i użyteczność procesu rozdrabniania biomateriałów. Podstawą do poprawy funkcjonalności działania maszyny rozdrabniającej jest przeprowadzone rozpoznanie możliwości istniejących rozwiązań oraz określenie zakresu, skutecznych w przetwórstwie, cech konstrukcyjnych zespołu roboczego z obszaru dopuszczalnego. Spełnienie kryteriów może być osiągnięte między innymi na drodze celowego sterowania cechami konstrukcyjnymi zespołu wielotarczowego. Aby jednak działania te przyniosły planowane korzyści, konieczne staje się poznanie zależności oraz opracowanie opisu matematycznego przepływu rozdrabnianego ziarna przez przestrzeń roboczą rozdrabniacza wielotarczowego, jako zmiennej wynikowej konstrukcji i działania zespołu roboczego.

LINGAITIS L P, MJAMLIN S, BARANOVSKY D, JASTREMSKAS V. **Prediction methodology of durability of locomotives diesel engines.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 154–159.

The article testifies that technical maintenance and repair terms as well as durability can be predicted accordingly to the maintenance parameters of the diesel locomotives. It is determined that fixing fuel consumption and capacity of diesel locomotives and taking in comparison with limit values allows to set a performance date for technical maintenance. Introduced suggested aspects of interrepair resource of the diesels dependent on comparable fuel consumption and evaluating their operating probability without failure for the durability prediction of diesel locomotives. Currently, the most common are three strategies: until failure, scheduled – premonitory and adaptive (diagnostic). When the quantity of necessary technical maintenances is known for the specific kind of diesel locomotives it is possible to determine interrepair resource depending

LINGAITIS L P, MJAMLIN S, BARANOVSKY D, JASTREMSKAS V. **Metodologia prognozowania trwałości silników diesla w lokomotywach.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 154–159.

W artykule wykazano, że częstotliwość przeglądów technicznych ¡ remontów spalinowozów z silnikami diesla można prognozować analizując parametry eksploatacyjne. Obecnie najbardziej rozpowszechnione są trzy strategie: do awarii, planowo-wyprzedzająca i adaptacyjna (diagnostyczna). W konkretnych warunkach zarządzania gospodarczego na pierwsze miejsce wysuwa się specyfika użytkowania spalinowozów, o zaraz po niej – normatywne wymagania techniczne, reglamentujące eksploatację spalinowozów. Ustalono, że poprzez odnotowywanie zużycia paliwa oraz mocy spalinowozów można określić czas eksploatacji, po upływie którego konieczne będzie przeprowadzenie przeglądu technicznego. Przedłożona została teoretyczna zależność okresu międzyremontowego diesli od porównawczego zużycia paliwa, wykorzystywana do oceny

on comparative and required per hour consumption of fuel and predict their durability taking into account probability of operating without failures.

prawdopodobieństwa bezawaryjnej pracy oraz zaproponowana metodyka prognozowania trwałości spalinowozów z silnikami diesla. Znając właściwą dla danej marki spalinowozu liczbę przeglądów technicznych, można oszacować okres międzyremontowy w zależności od godzinnego i porównawczego zużycia paliwa oraz uwzględniając ich prawdopodobieństwo bezawaryjnej pracy, w ten sposób prognozując ich trwałość.

CHŁOPEK Z. **Testing of hazards to the environment caused by particulate matter during use of vehicles**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 160–170

The study presents results of tests on emissions of fractions of PM10, PM2.5 and PM1 dusts. For modeling of emissions of fractions of PM2.5 and PM1 particles, results of empirical tests were used as carried out in air quality supervision stations located in the agglomeration of the city of Brno. The results of modeling of emissions of fractions of PM2.5 and PM1 particles did not make it possible to make unequivocal conclusions, which proves that the discussed problem has to be treated statistically. However, a significant relation between models of emissions of fractions of particulate matter and sources of emissions of dusts and conditions for distribution of the same were observed.

CHŁOPEK Z. **Badania zagrożenia środowiska cząstkami stałymi podczas eksploatacji pojazdów samochodowych.** Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 160–170.

W pracy przedstawiono wyniki badań imisji frakcji pyłów PM10, PM2.5 i PM1. Do modelowania imisji frakcji cząstek stałych PM2.5 i PM1 wykorzystano wyniki badań empirycznych, przeprowadzonych na stacjach nadzorowania jakości powietrza w aglomeracji czeskiego miasta Brna. Wyniki modelowania imisji frakcji cząstek stałych PM2.5 i PM1 nie umożliwiły sformułowania jednoznacznych wniosków, co dowodzi konieczności statystycznego potraktowania badanego problemu. Stwierdzono jednak istotną zależność modeli imisji frakcji cząstek stałych od źródeł emisji pyłów i warunków ich rozprzestrzenia.

HARDYGÓRA M, KOMANDER H, BŁAŻEJ R, JURDZIAK L. **Method of predicting the fatigue strength in multiplies splices of belt conveyors**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 171–175.

Method of testing the stress distribution in overlap adhesive joints of multiply conveyor belts is presented The impact of strength properties of belts and adhesive rubber on the stress scale and fatigue life of splices were defined. The relations enabling to calculate the strength magnitude and predicting the durability of conveyor's belts splices were given.

HARDYGÓRA M, KOMANDER H, BŁAŻEJ R, JURDZIAK L. **Metoda prognozowania trwałości zmęczeniowej złączy wieloprzekładkowych taśm przenośnikowych**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 171–175.

Przedstawiono metodę badań rozkładu naprężeń w spoinie klejowej zakładkowych złączy taśm przenośnikowych wieloprzekładkowych. Określono wpływ właściwości wytrzymałościowych taśm i gumy klejowej na wielkość naprężeń i na trwałość zmęczeniową złączy. Podano zależności pozwalające na obliczenie wielkości naprężeń i prognozowanie trwałości złączy taśm przenośnikowych.

PARCZEWSKI K, WNĘK H. **Make use of the friction coefficient during braking the vehicle**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 176–180.

In this publication is presented use the tyre-road friction during vehicle braking. Results presented in this publication are based on the road tests of the vehicle equipped in the anti-lock brake system (ABS). Two kinds of tests applied were carried out - the road tests of vehicle making the manoeuvre of braking on the straight section of the road and on the curve of the road. The braking forces and the friction coefficients for the individual wheels of the vehicle were defined on the basis of road tests, including the border values of the friction coefficient.

PARCZEWSKI K, WNĘK H. **Wykorzystanie przyczepności podczas hamowania pojazdu**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 176–180.

W publikacji przedstawiono zagadnienie wykorzystania przyczepności opony do nawierzchni jezdni podczas hamowania. Wyniki prezentowane w publikacji oparto na badaniach drogowych pojazdu osobowego wyposażonego w układ zapobiegający blokowaniu kół. Przeprowadzono dwa rodzaje prób stosowanych do badania wykorzystania przyczepności - badania pojazdu wykonującego manewr hamowania na prostoliniowym odcinku drogi oraz na łuku drogi. Na podstawie badań określono siły hamowania oraz współczynniki przyczepności dla poszczególnych kół pojazdu, w tym wartości graniczne współczynnika przyczepności.

PIENIAK D, NIEWCZAS A, KORDOS P. **Influence of thermal fatigue and ageing on the microhardness of polymer-ceramic composites for bio-medical applications**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 181–188.

Studies presented in this paper, concern polymer-ceramic composites applied in the conservative dentistry. The aim of the study was to evaluate a long-term impact of the humid environment and cyclic thermal loads on the microhardness of new silorane-based composites and two methacrylate-based composites. The composite samples were subjected to normal saline environment with cyclically variable temperatures (5°C and 65°C), using a special thermal shock simulator. Microhardness was measured with Vicker's method before the fatigue test and after a series of 4000 thermal cycles. It is known that microhardness of silorane-based composite in opposite to methacrylate-based composites not decrease under the influence of cyclic thermal loads. It was found slight increase of microhardness under conditions of conducted tests. The ageing studies were also conducted consisting in microhardness evaluation of the composite samples in 6 months period. During that time the samples were kept in normal saline. The studies of hardness were carried out after each month of the exposure time. No long-term impact of normal saline environment with constant temperature on the microhardness of the studied materials has been noticed.

PIENIAK D, NIEWCZAS A, KORDOS P. **Wpływ zmęczenia cieplnego oraz starzenia na mikrotwardość kompozytów polimerowo – ceramicznych do zastosowań biomedycznych**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 181–188.

Badania prezentowane w niniejszej publikacji dotyczyły kompozytów polimerowo-ceramicznych stosowanych w stomatologii zachowawczej. Celem pracy była porównawcza ocena wpływu długotrwałego oddziaływania wilgotnego środowiska oraz cyklicznych obciążeń cieplnych na mikrotwardość nowego kompozytu bazującego na siloranach oraz dwóch tradycyjnych kompozytów bazujących na związkach metakrylanu. Próbki z kompozytów poddano oddziaływaniu środowiska soli fizjologicznej o cyklicznie zmiennych temperaturach (5°C i 65°C) wykorzystując specjalny symulator szoków termicznych. Wykonywano pomiary mikrotwardości metodą Vickersa przed rozpoczęciem testu zmęczenia cieplnego oraz po serii 4000 cykli termicznych. Wykazano, że w przeciwieństwie do tradycyjnych kompozytów stomatologicznych mikrotwardość kompozytu bazującego na siloranach nie zmniejsza się pod wpływem cyklicznego oddziaływania szoków termicznych odpowiadających warunkom fizjologicznym jamy ustnej. W warunkach przeprowadzonych badań stwierdzono nieznaczny wzrost tej mikrotwardości. Przeprowadzono również badania starzeniowe polegające na ocenie mikrotwardości próbek kompozytów przez okres 6 miesięcy. W tym okresie czasu próbki przechowywano w soli fizjologicznej. Pomiary mikrotwardości wykonywano po każdym miesiącu ekspozycji. Wykazano, że długotrwałe oddziaływanie środowiska soli fizjologicznej w warunkach stałej temperatury nie zmienia mikrotwardości żadnego z badanych materiałów.

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Andrzej LOSKA

REMARKS ABOUT MODELLING OF MAINTENANCE PROCESSES WITH THE USE OF SCENARIO TECHNIQUES

UWAGI O MODELOWANIU PROCESÓW EKSPLOATACYJNYCH Z WYKORZYSTANIEM TECHNIK SCENARIUSZOWYCH*

This article aims at presenting the results of research use of modelling of exploitation processes in practical applications (industrial). Firstly, there has been made an identification and of solutions in this area, particular attention was paid equally to the problems associated with processes modelling in the context of wider organizational and technical approach. Basing on the performed studies, of both basic (theoretical) and industrial character, the research problem has been defined. It concentrates on the difficulties of using exploitation process models in relation to the maintenance organization in an industrial enterprise, because of their "flat" nature. Based on the developed research problem, there has been proposed a way of its solution by applying scenario techniques. Secondly, following a review of the state of knowledge (literature) in the context of exploitation scenario building, there has been prepared and presented a detailed research procedure, that will result in the development of methodology for creation of exploitation scenarios, including the way of their use in practice. The article is funded by National Science Centre in Poland under the project no. 5636/B/T02/2011/40 titled: "The use of scenario methods in exploitation processes modelling".

Keywords: *exploitation, maintenance, maintenance scenarios, exploitation processes, modelling.*

Celem artykułu jest zaprezentowanie wyników przeprowadzonych badań w zakresie sposobów wykorzystania metod modelowania procesów eksploatacyjnych w zastosowaniach praktycznych (przemysłowych). W pierwszej kolejności dokonano identyfikacji i klasyfikacji stosowanych w tym zakresie rozwiązań, zwrócono przy tym uwagę na problemy związane z modelowaniem procesów w aspekcie szerszego ujęcia organizacyjno-technicznego. W oparciu o przeprowadzone badania, które miały charakter zarówno podstawowy (teoretyczny), jak i przemysłowy, sformułowano problem badawczy. Jego istota sprowadza się do trudności wykorzystania modeli procesów eksploatacji w odniesieniu do funkcjonujących organizacji utrzymania ruchu przedsiębiorstw przemysłowych ze względu na ich „płaski" charakter. W oparciu o sformułowany problem badawczy zaproponowano sposób jego rozwiązania poprzez zastosowanie do modelowania procesów eksploatacji technik scenariuszowych. Następnie po dokonaniu przeglądu stanu wiedzy (literatury) w aspekcie budowy scenariuszy eksploatacyjnych, opracowano i przedstawiono szczegółowo procedurę prowadzenia badań, których efektem będzie opracowanie metodologii tworzenia scenariuszy eksploatacyjnych, z uwzględnieniem sposobu praktycznego ich wykorzystania. Artykuł jest wynikiem realizacji części badań w ramach projektu badawczego, finansowanego ze środków Narodowego Centrum Nauki nr 5636/B/T02/2011/40 pt.: Wykorzystanie metod scenariuszowych w modelowaniu procesów eksploatacyjnych.

Słowa kluczowe: *eksploatacja, utrzymanie ruchu, scenariusze eksploatacyjne, procesy eksploatacyjne, modelowanie.*

1. Introduction

Both in the theory of exploitation of technical systems, as well as in its practical application, much attention is paid to the problem of modelling. Current tasks of technical departments of most of industrial enterprises exceed traditional framework for planning, execution and settlement of maintenance works, particularly in terms of rationalization and optimization of decision-making processes both in short and long term.

In terms of rapid development of strategies and methods of maintenance management, as well as IT tools used for acquisition, collection and processing large amounts of data describing variety of technical facilities and conditions of their operation,

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

it seems to be possible and necessary to carry out the exploitation research related primarily to the development of the way of making optimal strategic decisions concerning, among others, issues technically, organizationally and commercially reasonable terms and conditions for maintenance tasks, withdrawal of objects from exploitation, long-term practices within exploitation philosophies or scopes of works.

This requires the construction of appropriate models of both technical objects, events, and exploitation processes carried out in an enterprise. These models should accurately reflect selected aspects of exploitation "reality" and must be based on foundations of modelling theory.

This article represents the next stage of research conducted on the possibility of support of exploitation decision making process in the industrial enterprises by the author at the Institute of Production Engineering of Silesian University of Technology. The research leads to develop a method of processes modelling, both their technical aspects as well as non-technical considerations of maintenance tasks (such as organizational, economic), which will use such models in practice.

2. Practical considerations of classical methods of exploitation processes modelling

It is assumed that the exploitation process is a set of structured operations, performed by technical objects overt their lifetime. Course of individual operations is determined by individual characteristics of objects and their organizational and technical environment, resulting in uniqueness of individual exploitation processes.

In order to identify and define the research problems considered in the article, it is necessary to identify and classify the exploitation processes precisely. The basis for such classification may be a way of describing (modelling), which determines the realization of particular tasks related to this process and regarding decision making as well. According to such criteria of classification, there are two basic ways to describe (models) exploitation processes [7]:

a) the exploitation process model as a sequence of events, by which certain tasks are undertaken and realized on the basis of information about specific events occurring at different moments of time (fig. 1),

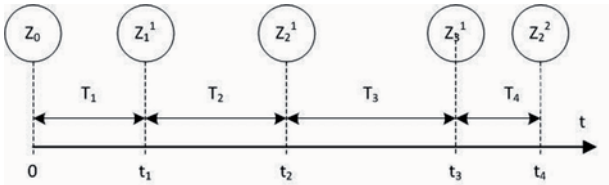

Fig. 1. The exploitation process model as a sequence of events [7]. Zij - exploitation events, Ti - time interval between events, ti - moments in which events occur

b) the exploitation process model as a series of states, by which maintenance tasks are undertaken and realized basin on momentory conditions of the object identified in equal intervals (fig. 2).

Considering the exploitation process model as a sequence of events, one can distinguish two types of possible events: intended and unintended ones. Each type of event determines consequently the procedure, reflecting different principles of

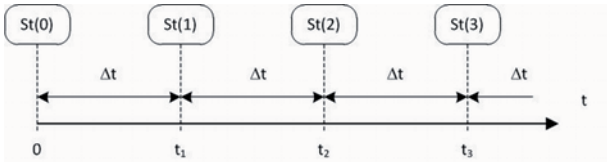

Fig. 2. The exploitation process model as a series of states [7]. St(i) - identified technical conditions, Δt - time interval between the moments of identification of the technical condition, ti - moments of identification of the technical condition

maintenance of facilities, comprised the maintenance strategy. Using the process model as a series of states to identify decision making in maintenance requires periodic (constant in time) control of technical conditions of the object and taking into account different procedures.

Exploitation practice shows that description of exploitation process related to specific item of technical objects requires most frequently simultaneous use of models discussed above. For example, technical objects, for which technical condition monitoring activities are carried out to (related to the exploitation process model as a sequence of states), may be subject to breakdown (events associated with exploitation process model as a sequence of events).

The aforementioned way of modelling exploitation processes in industrial practice results in development and implementation of general and dedicated solutions taking forms of operational strategies. In particular, basing on the relationship between exploitation processes and the way of decision-making in organizational and technical exploitation systems, it can be stated that most common decisions result from use of one of the following maintenance strategies:

1. breakdown maintenance strategy (BM), based on the exploitation process model as a sequence of unintended events,
2. preventive maintenance strategy, based on the exploitation process model as a sequence of unintended intended events (PM),
3. predictive maintenance strategy, which is based on the exploitation process model as a series of states (PM).

In industrial practice by linking different strategies with decision-making process regarding specific technical objects (and not necessarily the entire technological setting), all three strategies create maintenance policy of the company, where any of them is a dominant ona (is the basis for decision-making in relation to the majority or the most important technical objects), and the rest is supplementing it.

3. Identification of research problems and proposals for solutions

Exploitation process models, presented in the previous section and described in the literature, allow to solve important practical problems concerning use and maintenance of machinery and equipment. However, the above mentioned capabilities are subject to certain constraints, resulting from the character of these methods. The main constraint of this type is number of characteristics (parameters) possible to include in the model, that describe condition of the object/diagnostic signal or event. Such restriction significantly influences the accuracy of identification of a specific condition or event. It is also difficult to comprise qualitative features and non-technical aspects (organ-

izational and economic), which significantly affect the implementation of various maintenance tasks.

The most important constraints of the described ways characterizing the exploitation processes include:

- significant simplification of the models of processes in relation to organization, using technical objects, which are the subject of modelling,
- flat nature of the models showing the cause-effect relationships in a unidimensional way without taking into account the interaction with the environment in the form of additional non-technical aspects (eg. organizational or economic),
- difficulties with including qualitative characteristics and non-technical aspects (organizational and economic) in this type of models, which significantly affect the implementation of particular maintenance tasks (including maintenance management area).

The restrictions mentioned in the article hinder satisfaction of the needs related to effective use of typical models for the needs of decision making optimization in relation to the operating of technical objects by maintenance organizations of industrial enterprises.

Proceeding from the existing state of knowledge in the area and the conditions mentioned above, there can be formulated the main research problem of this article:

currently used models and methods of modelling have important restrictions which do not allow for effective use in optimization of decision-making related with operating of the technical objects and thus they are not an effective solution for evaluation and improvement of efficiency of maintenance management.

Solution to the problem of optimizing the decision-making process may be the use of scenario methods, using a multi-threaded picture of reality at simultaneously possibility to look ahead of current time.

Scenario techniques belong to the forecasting methods that have been used in economic sciences for forecasting and strategic management. In technical sciences They have yet to be recognized.

Among several methods to create scenarios, in this case, the best seems to be the method proposed by H. Kahn, who called it as scenariowriting. This method consists of description of events and indication their logical and coherent consequences in order to determine the way of development of an object or situation.

The exemplary point of reference can be past or the current technical condition. The main emphasis is put on these events and situations, that could form the basis of future condition or sequence of events. In this way one gets a set of possible events or, in other words, images of the future.

Beside many ways of creating scenarios with the use of various methods, one can distinguish a limited number of types or variants in the described methodology. In this particular methodology, there are several types or variants. For considered area, possible, appropriate and reasonable to use are two of such types, which correspond to the needs and possibilities of exploitation process modelling [23]. Basing on specific hypotheses one determines possible events being an effect of current state or situation. This is called research scenario. This type of scenario corresponds to maintenance planning problems which are directly related to defining the maintenance strategy. In specific situations it is possible to use anticipatory scenario (fig. 3b), in which identified relations allow to specify the effects of the situation. This type of scenario provides the basis of analysis of past events, in particular failure analysis, where the most important element is to determine the reasons of the situation or failures in maintenance work.

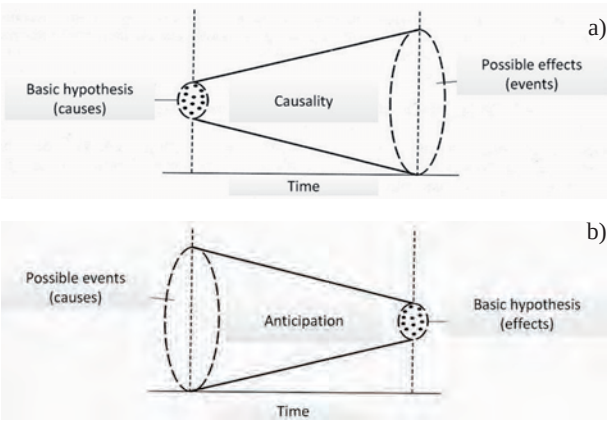

Fig. 3. Types of scenarios: a) research scenario, b) anticipatory scenario [23]

It can be noticed that, the method of construction of scenarios has much in common with the forecasting techniques. Starting from the current situation (a set of features describing exploitation processes), one can determine the factors influencing the future situations that are known. Relating these factors to the nearest future causes a slight change, while in longer periods, these changes may be significant. This is reflected both in changes in particular factors as well as in the influence of changes to individual objects or systems. Through the use of scenario methods for modelling of exploitation processes, one can show the way and scope of achieving possible alternative scenarios describing the effects of taken decisions.

As a part of further research it is proposed to use the events and processes scenarios, which provide qualitatively new approach in the area of modelling exploitation processes for the needs of effective decision making/maintenance management.

Key elements of the scenario methodology and features of exploitation area determine the necessary set of activities (detailed objectives), which implementation allows to solve the determined research problem. These activities include:

- defining the need and basis for scenario/collection of possible scenarios generation based on specific exploitation models, which may result from the reliability criteria, in this case (eg. a set of quantitative exploitation indicators),
- determining the internal and formal structure of the description of the scenario (identifying a set of parameters, the quantitative elements and features, defined as qualitative components of the situation/event),
- filling in scenarios for the object as such by mapping its environment (that is, by analogy, the author of the article proposes to describe the "scenery" in which scenario is “going on” - in addition to the same scenario),
- solution to the problem of practical use of scenarios in maintenance works, and optimization of decision-making processes relating to operating technical systems, taking into account multivariant issue of possible events

and behavioral simulation of objects in shorter and longer term.

4. The importance of exploitation process modelling with the use of scenario techniques

The problem of use of scenario techniques in exploitation occurs incidentally in the literature. It is mainly related to individual descriptions of case studies of scenarios in selected events (eg. in [24]). Detailed analysis of the literature, both domestic and foreign has shown that studies on the use of scenarios for the complex strategic aspects of the exploitation of technical objects are conducted primarily at the Institute of Production Engineering of the Silesian University of Technology. This is reflected in publications [8, 13, 16, 15, 18].

In terms of the issues discussed in the article, there are separate publications describing various elements associated with this topic, in particular:

1. modelling of selected elements of exploitation,
2. scenario methods and techniques,
3. computer aided maintenance management with strategic approach.

The first area is described quite extensively in terms of modelling the various elements of exploitation processes. Valuable in this area is [13], where the classification and review of the major exploitation models was carried out. Other items the literature describe a more or less detailed the various groups of exploitation models (event models eg. [7, 27], diagnostic models eg. [1, 2, 27, 28], technical objects and assets models [13, 19, 7], or exploitation process models [7, 13, 27, 22, 26].

The second area is widely described in the literature mainly from the viewpoints of economics, particularly in terms of strategic management [3, 4, 5, 6, 23]. The third area is described mainly in trade magazines, particularly in [17].

The results of the review of existing knowledge can be summarized in two aspects:

1. From the perspective of national and international publications and other studies, there are references to methods and issues which are parts of the proposed solution.
2. In complex terms, scenario techniques used for exploitation processes modelling can be considered a new issue not published both domestically and abroad.

5. The concept of research on the development of methods for the use of scenarios techniques in exploitation processes modelling

The research initiated and carried out by the author to develop the use of scenarios in exploitation processes modelling includes a wide range of work, both fundamental (theoretical) as well as industrial and developmental. On the one hand, this research is aimed at developing a methodology for construction of exploitation scenarios, as the basis and method of modelling and optimization of exploitation processes, and, on the other hand, at preparation of practical tools to use developed methodology in industrial environments.

Diagram of concept of carrying out such research is shown in fig. 4. Its individual components are described in the following paragraphs.

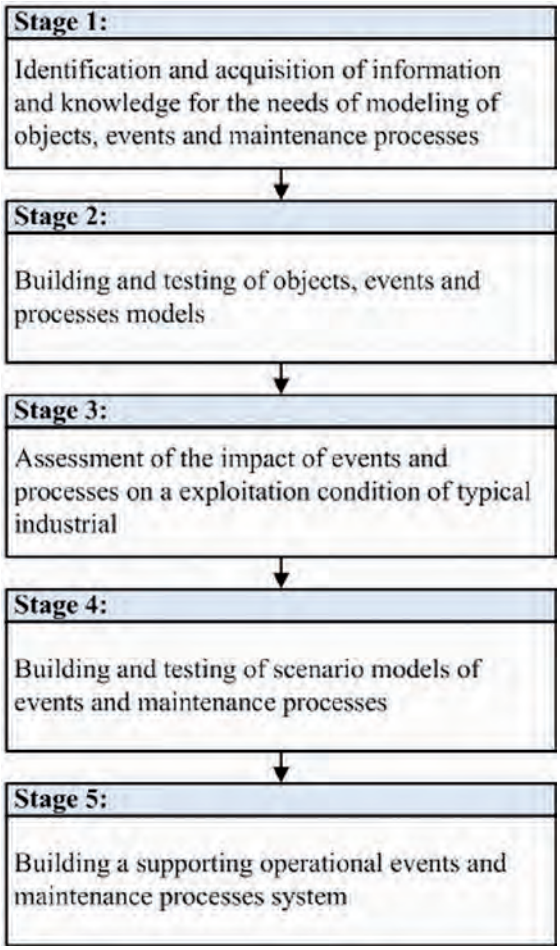

Fig. 4. Concept diagram of research

5.1. Stage 1: Identification and acquisition of information and knowledge for the needs of modelling of objects, events and exploitation processes

The first step of research is to acquire and collect an appropriate repository of information and knowledge about objects and all the technical and nontechnical "circumstances" of their operation, which form potential subject and scope of exploitation scenarios. The quality of the scenario, and thus the accuracy of forecasts results from the possibly large diversity and level of detail of information, therefore searching and acquiring should be orderly. The basis of such arrangement are the reasons based on the three levels related to the operations of selected objects: technical, organizational, decision-making and information exchange.

1. Technical level includes a set of features of the objects and performed with use of them. These activities, which aim at getting information of this type concern:
   - identification of complexity of technical objects which are the subject to modelling,
   - arrangement of maintenance procedures carried out on previously identified technical objects,
   - inventory of maintenance resources (labor, parts, tools, external services).
2. Organizational and decision-making level includes factors resulting from the way of functioning of the typi-

cal maintenance department, both internally as well as for external environment in wider context. The basis for this can be one of the models: a model of maintenance management [7] or the BCM model (Business Centered Maintenance) [9]. In this case, there are identified typical characteristics of standard maintenance department, allowing to gather a large amount of information and create knowledge repository for development of appropriate models, and exploitation scenarios.

3. The information exchange level includes criteria related both to the way of information flow within a typical maintenance organization, and to/from units of the external environment. Special attention is needed to identify the structure of information flow, which should begin with identification and distinction of the object that is maintenance unit (fig. 5).

Fig.5. Diagram of standard maintenance organization in the relationship with the environment

Such an object is a generalized and simplified model of information flow between the considered organizational unit and external entities. External units are both ones that are included in the organizational structure of the company (technical system), as well as ones which are outside of these structures. Inventory of the information flow should include identification:

- input and output of information,
- structure of information flow within the maintenance organization unit.

Research under this phase must be related to real existing enterprises, to take into account features that result from different industries. It is assumed that the information and knowledge will be collected simultaneously with performing the analyses starting from the exploitation activities and functions, through technical objects identifying and modelling, formulating strategic and prevention plans, specifying the organizational aspects, by defining elements of control in the end.

The result of the stage 1 should be a set of information and knowledge related to the functioning of a typical standard maintenance organization unit including computer tools (eg. CMMS/EAM systems or process modelling tool - ARIS Toolset).

5.2. Stage 2: Building and testing of objects, events and processes models

The objective of research carried out within this stage is to build models of objects, events and exploitation processes. These studies must be carried out based on the results of stage 1 – repository of information and knowledge about objects and exploitation processes.

Due to the high diversity of models used in the area of exploitation, they will be built and organized on the basis of a diagram illustrating relationship between selected exploitation characteristics (fig. 6).

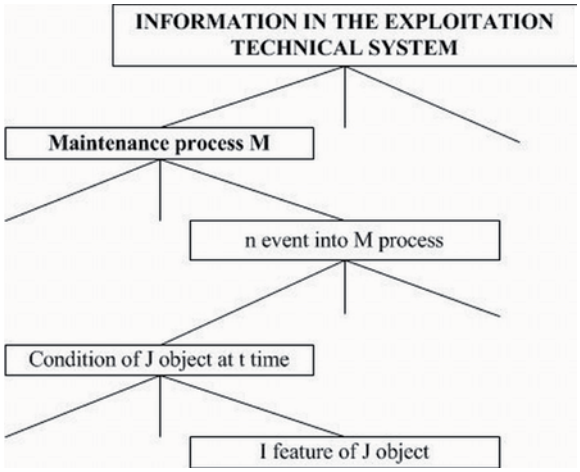

Fig.6. Hierarchical structure of exploitation information [7, 12]

Each of the levels may include a set of models, which is characteristic for aspects of the exploitation of technical systems, discussed here. Due to the hierarchy of exploitation aspects arrangement, causing dependencies between superior and inferior elements, building and ordering the models will be done starting from the lowest level. According to the layout, it can be assumed that:

- in the modelling of technical objects (object characteristics) it is necessary to use methods of structural and functional modelling, as well as methods of group and individual modelling,
- for exploitation events, it is necessary to model intended and unintended events on the basis of the existing tools in this area (event cards, event trees, logic trees, etc.) [2, 12] taking into account specificity of decision making process as a result or effect of a particular situation,
- exploitation processes will be the subject to modelling with the use of process maps and computer tools (eg. Aris Toolset), which allows to perform a simulation in relation to the prospective behaviour of technical objects.

The result of implementation of research in this stage will be technical and organizational set of models, as the basis of exploitation scenarios and system supporting operational events and exploitation processes.

5.3. Stage 3: Assessment of the impact of events and processes on a exploitation condition of typical industrial enterprise

Research in this stage will be carried out with the assumption, that the exploitation condition of industrial companies (from a technical point of view) determined by rank indicators divided into specified classes) will allow to determine the effects of particular events and processes in the enterprise.

The subject of research will cover primarily identification of the classes that are basis for identifying the indicators of rank, using proposed set of measures allowing for quantitative evaluation of operating technical objects and functioning of servicing and maintenance department. Because of wide variety of this type of measurements, the aim of research in this area is assessment of their suitability, and then selection of these that will reflect the efficiency, quality and reliability of operation of analyzed technical objects best. Then, based on

models developed in stage 2, for each identified class there will be performed identification of particular events and processes and their impact on the state of and enterprises. This requires an extensive work, that will classify technical and non-technical (organizational, economic) factors of events and processes, influencing the company condition. That outlined study will be carried out in three ways:

- by introducing a "trial" object failure and simulating possible effects,
- by detailed analysis of cause and effect analysis of past events and activities realized as a result of this (exploitation processes), organized with including models that arise from Root Cause Failure Analysis (RCFA) methodology,
- by detailed analysis of current events and their effects from which the information will complement the research material (occurring along with the research).

After arranging the results of research and developing of cause-effect lists, events and processes will be assigned to the appropriate rank indicator.

5.4. Stage 4: Building and testing of scenario models of events and exploitation processes

During this stage, starting from the results of research done within the previous stages, there will be built exploitation process models, by introducing some elements of scenario methodology. It will be then possible to include multi-aspect nature of exploitation processes management and optimal decision-making. Due to specificity of exploitation, there will be taken into account two types of scenarios [4, 23]: scenarios of possible events and simulation scenarios.

This stage will be implemented in two steps:

1. Based on the selected way of scenarios creating, there will be designed a set exploitation scenarios for selected technical and organizational area. Selection of the area will be determined by the results of research carried out in the previous stages, in particular the developed objects, events, processes models (stage 2) and research on their influence on particular events and processes in the enterprise (stage 3).
2. Based on a set of developed scenarios of events and processes, there will be developed guidelines for use of scenario techniques as a basis for modelling exploitation events and processes. This will allow to make strategic decisions about This will allow to make strategic decisions about exploiting technical objects and functioning of maintenance department.

The result of the research in this stage will be a set of exploitation processes models built using scenario methods along with the guidelines that define their use in medium-and long-term planning and implementation of maintenance tasks.

5.5. Stage 5: Building a system supporting operational events and exploitation processes

The aim of the research in this stage will comprise development of principles for building a system supporting operational events and exploitation processes and building such a system, basingd on the results of previous stages. As a starting point for this research it is assumed that the system will consist of two layers:

- data and knowledge acquisition layer about the events and exploitation processes, in the form of components ensuring communication with data and knowledge sources in the enterprise information system,
- exploitation decision support layer, in the form of subsystem of control of flow related to events and processes, including exploitation scenarios, as a set of components of a system supporting operational events and exploitation processes.

The result of the research in this stage will be a prototype system supporting operational events and exploitation processes, which action will confirm practical feasibility of the assumptions in this research.

6. Summary

Taking into account the multi-aspect and multivariant nature of maintenance management process, reflected by the possibility of optimization seems to be more realistic in terms of scenario than in classical terms. The shape of the model and a set of criteria must take into account a wide range of technical and nontechnical aspects with as well as their connections “inside” modelled processes and with their closer and farther environment. It may be possible provided that an appropriate scenario building method is used to describe existing exploitation situation. The limit of complexity of the scenario description seems to be not in the same method but in the capabilities of the tools - particularly computer tools - used for practical applications of this method.

The presented method of modelling exploitation processes is a key element of the author’s research carried out in the Institute of Production Engineering of the Silesian University of Technology. Justification for undertaking this subject can be specified in two fields:

1. in the exploitation theory,
2. in the area of methods and supporting tools in industrial practice.

The first area, according to the author, due to unreasonable lack of greater interest in the use of scenario techniques in the field of engineering sciences, despite the fact that these techniques have been known for many years and applied in the field of economic sciences. According to the author, the research discussed here can create added value for the area of machinery and technical object exploitation.

The second area emerges from practical and long-term author’s experience in functioning of maintenance departments in a wide variety of industries (food, automotive, paper, chemical, water and sewage, etc.). Currently, the most important exploitation problems of engineers relate to long term planning, including moments of the replacement of worn and damaged components and whole objects, in terms of the need to continually costs reducing. These problems do not occur in technical isolation, but there must be also taken into account organizational, economic, and normative-legal aspects of the enterprise. Until now, these problems were solved in two distinct ways:

- technical, that is based on indicators of reliability and supplemented in some cases by the results of diagnostic tests,
- organizational and economic, that is based on indicators of cost of the enterprise’s technical activities.

Use of scenario techniques in modelling of exploitation processes can be an effective tool for solving problems of planning and implementation of maintenance tasks in many industrial enterprises and therefore will enable implementation of specific actions for:

- implementation of modern maintenance management philosophy (TPM, RCM, WCM),
- building of intelligent system supporting operational events and exploitation processes,
- developing exploitation procedures in relation to the enterprises being at the design stage,
- performing different analyses (eg. failure analysis),

and above all

- optimizing exploitation decision-making process.

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LIFE TIME PREDICTION USING ACCELERATED TEST DATA OF THE SPECIMENS FROM MECHANICAL ELEMENT

PROGNOZOWANIE CZASU PRACY ELEMENTU MECHANICZNEGO Z WYKORZYSTANIEM DANYCH Z BADAŃ PRZYSPIESZONYCH

In accelerated life testing, products are exposed to stress levels higher than those at normal use in order to obtain information in a short time. In this paper ,we expand the limits of performing accelerated life tests to an aerospace product (supple platinum). Specimens from the IAR 330 Puma helicopter structure, made of supple platinum, were subjected to accelerated life testing, and a significant reduction of the testing time was obtained. A simulation of the accelerated life testing data from the same case study was performed using the Monte Carlo method, with the purpose of comparing the data resulting from the experimental study (accelerated life tests) with the simulated data.

***Keywords**: reliability, lifetime, accelerated life tests, acceleration model, Monte Carlo simulation.*

W przyspieszonych badaniach cyklu życia, produkty poddaje się naprężeniom o wartościach wyższych niż występujące w normalnych warunkach użytkowania, w celu szybszego uzyskania informacji. W przedstawionym artykule poszerzamy granice zastosowań badań przyspieszonych o produkt przemysłu lotniczego (giętka platyna, ang. supple platinum). Próbki z giętkiej platyny pochodzące z elementu konstrukcji śmigłowca IAR 330 Puma poddano badaniom przyspieszonym otrzymując znaczne skrócenie czasu badania. Dla otrzymanych danych z badań przyspieszonych przeprowadzono symulację metodą Monte Carlo, w celu porównania danych eksperymentalnych (z badań przyspieszonych) z danymi symulacyjnymi.

***Słowa kluczowe**: : niezawodność, cykl życia, badania przyspieszone, model przyspieszenia, symulacja Monte Carlo.*

1. Introduction

The obtaining information regarding the reliability of mechanical products is usually done either by following the behaviour of the products during operation or during the reliability tests. In the real time operation we carefully record all the phenomena that occur during the product's use. A study based on this information represents only a "historical" study, its value being only that of collection experimental data or screening factors that can lead to a low reliability of the products. The information gathered from the operation usually refers to products or equipments suffering from the wear process, so that at the moment of the conclusions they might not be that important for the improvement of some aspects regarding the design and manufacturing of products, as a requirement of reliability [1, 10]. Considering the main requirement of reliability - the increase of performance of the industrial products, in direct connection with the scope of the study - it is necessary to extend a significant importance to reliability tests. A reliability test is represented by an experiment performed to determine the parameters of reliability for a well-defined product. The main reliability parameters during reliability tests is mean time to failure (MTTF), knowing that, based on the existing relations between reliability parameters, they can be easily deduced from one in other. It is required to specify that in order to apply the statistical methods of estimation of the reliability parameters, is recommended to know the low of distribution for the mean time to failure [21].

Many of the mechanical products produced today for complex technical systems have very high reliability under normal use conditions. The questions then arise of how to make the optimal choice between several types or designs of a device and how to collect information about the corresponding life distributions under normal use conditions. A common way of tackling these problems is to expose the products to sufficient overstress to bring the mean time to failure down to an acceptable level. Thereafter, one tries to "extrapolate" from the information obtained under over stress to normal use conditions. This approach is called Accelerated Life Testing (ALT) or overstress testing [1, 5, 6, 12, 13, 15, 19, 21]. In these tests, reliability practitioners may force the product to fail more quickly than it would under normal use conditions. Accelerated failure time modelling is one part of the quantitative accelerated life testing. The interest of this theory is to know the influence of any given stress on the life duration of an item. The technique of accelerated life testing enjoys both intuitive appeal and objective support from the physics of failure, and can be implemented in various ways; experimental aims are, however, usually phrased in statistical terms. For instance, the practitioner may wish to

estimate a specified percentile of life or the probability of failure within a given warranty period of an item operating under design stress.

The primary purpose of an ALT is to estimate the life distribution and quantities of interest at a use condition. This estimation involves extrapolation from higher stress levels by using an acceleration model, and thus includes the model error and statistical uncertainty. Sometimes, the model error outweighs the statistical one. The model error may be reduced or eliminated only by better understanding the failure mechanisms and using a more accurate model, whereas the statistical uncertainty can be reduced by carefully selecting a good test plan. A typical test plan is characterized by the stress levels, the number of test units allocated to each level, and their censoring times. The most commonly used ALT in modern manufacturing industry is the constant-stress ALT (CSALT) where stress applied to a sample of units is constant. A typical parametric model of CSALT consists of two components: (1) a lifetime distribution that models the time-to-failure at a constant-stress level; and (2) a stress-life model that quantifies the manner in which the lifetime distribution changes a cross different stress levels. There are different types of ALT plans in use, which include subjective, traditional, best traditional, statistically optimum and compromise plans [4, 6, 8, 9, 17, 19, 20].

Pursuing the previously stated main purpose of the accelerated life tests, we need a model that relates life to accelerating stress, such as temperature, humidity, and voltage. Such models, usually called acceleration models, can be classified into the following three types: physical models; quasiphysical models; empirical models. Among the most important acceleration models (life-stress) we can mention the following: Arrhenius, Eyring, Inverse Power Law; Life - Thermal Cycling, Life - Voltage, Life - Vibration, Life - Humidity, Life - Temperature - Humidity [2, 5, 8, 13, 15, 21].

Accelerated life testing [7,11, 13, 16, 21] is used in electronics, (resistors, lasers, liquid crystal displays, electronic bounds, switches, circuit breakers, relays, cells and batteries) in the study of metals and composite materials, but also for certain components and mechanical assemblies (automobile parts, hydraulic components, tools, bearings). In aerospace industry, the accelerated life testing is used to test certain components: the engine, the oil pumps, the landing gear, onboard electronic equipment and stiffening components (strips, spear).

As a result of the critical study above on the accelerated life tests, the scope of the paper becomes evident, which is: the theoretical and experimental study regarding the management of accelerated life tests for a product from the field of aviation (supple platinum), in order to reduce the testing time and obviously of the material costs related to this kinds of tests.

2. Case study

In this paper, accelerated life tests will be implemented and performed on a vital component from the structure of the IAR 330 Puma helicopter, following all the stages that are necessary to the execution of such tests. Starting from the constructive and functional analysis of the tested product and of the experimental bench, then proceeding with the optimization and the design of the accelerated life test plans and finalizing with the statistical processing of the experimental data using software that is specific to accelerated life tests. For a validation of the accelerated life tests we used the Monte Carlo simulation method for the data in accelerated conditions. The purpose of using this method is to make a comparison between the data from accelerated conditions that resulted from the Monte Carlo simulation and the experimental data.

2.1. The necessity of implementation of accelerated life tests in the mechanical product's testing

If a mechanical product requires, for example, 10^8 cycles to cause a failure from fatigue in normal use condition, by using an accelerated life test we can obtain the same result in 10^5 cycles. The design of the accelerated life test and the interpretation of data require the understanding of the relation, in the course of the destructive process considered, between the level of stress and the failure rate. The result of these accelerated life tests is the reliability estimated by statistical and mathematical means, using specific software. Thus, for the design of the accelerated life tests plans and for the processing of statistical data obtained from the quantitative accelerated life test in this paper we used the ALTA 7 (Accelerated Life Testing Data Analysis) software.

In the case study of this paper, we applied a cyclical mechanical stress. During the cyclical stress the most frequently used are the metallic components and systems and the phenomenon is fatigue. The degradation by fatigue involves a variety of aspects regarding to: the type of stress; the shape of the part; the quality of the part that will be processed; the environment of the part's operation. The accelerated life tests where the main degradation phenomenon is fatigue are very important in the industrial field and especially in the aerospace industry [7, 11, 14, 18], with application on the components in the structure of airplanes and helicopters.

The introduction of accelerated life tests in the aviation is necessary, because the fatigue tests can have the operating time of millions of cycles until the failing of components occurs (the helicopter blade, the supple platinum, command rods, the wing and the landing gear). That is the reason why the accelerated life tests represent a method by which the testing time of components from the aerospace field is shortened and thus leading to optimizing of the testing system.

2.2. Constructive and functional of supple platinum

The french helicopter constructors introduced the system for reducing the vibrations like supple platinum. Supple platinum (Fig. 1) is made of a titanium alloy and is placed between the inferior part of the main transmission box and the mechanical board at the Puma IAR 330 helicopter. Supple platinum is a vital part and has the role to reduce the vertical vibrations produced by the main rotor's blade.

2.3. The structure of the test bench

Due to its configuration, supple platinum cannot be subjected to stress tests. That's why the tests are being made on specimens, with standardized shapes and dimensions, made of the same material as supple platinum (a titanium alloy known in the aviation as TA 10).

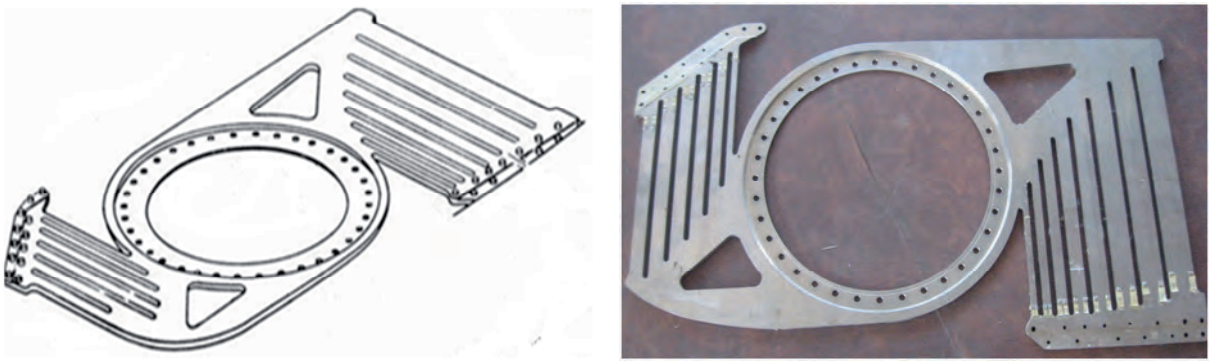

Fig. 1. Supple platinum

The tests of the specimen made of supple platinum consists of the repeated stress using a bending force, on a test bench that includes: a fixation device for the specimen - the specimen is embedded at one end, and at the other end we apply a displacement (arrow) on vertical; the device for the tensioning of the specimen - the main function of the device is to introduce a displacement at the free end of the specimen; the energy installation - that is composed of an engine which produces the mechanical energy for production at displacement at the free end of the specimen; the command installation - has the role to turn off and on the engine during the testing of the specimen; the electronic installation - is composed of an apparatus that reads frequencies and a cycle counter. The test bench used for the fatigue testing of specimens is presented in figure 2.

Fig. 2. The test bench for the fatigue testing of specimens

The data acquisition system is composed of: Hottinger measuring device with 6 channels, Hottinger LC 11 strain gauges, apparatus that show the frequency of stresses and a cycle counter.

2.4. Plan and accelerated test conditions of test specimens

The experimental research has been performed on specimens made out of supple platinum, specifically from removed portions that result from the technological processing. Figure 3.a shows the constructive model of the specimen used in accelerated life tests and, also, the placement of strain gages. On the specimens are mounted and connected in half-bridge 2 strain gages used to measure the specific strain. The placement of this strain gages is described in figure 3b.

Poor accelerated life test plans waste time, effort and money and may not even yield the desired information. Before starting an accelerated life test, it is advisable to have a plan that helps in accurately estimating reliability at operating conditions while minimizing test time and costs. To design the plan for the accelerated life tests of the specimen made out of supple platinum it is necessary to establish the following parameters:

A) The acceleration model: for accelerated life tests where the failure mechanism is a mechanical one (the fatigue in the case of accelerated life tests for the specimens made out of supple platinum), the most adequate one is the IPL model; The inverse power law (IPL) model is commonly used for non-thermal accelerated stresses and is given by:

$$L(V) = \frac{1}{KV^n} \tag{1}$$

where L represents a quantifiable life measure, such as mean life, characteristic life, median life, B(x) life, etc; V represents the stress level; K is one of the model parameters to be determined, (K > 0); n is another model parameter to be determined.

The failure rate under normal operating conditions is:

$$\lambda(t, V) = \beta KV^n \cdot (KV^n t)^{\beta-1} \tag{2}$$

B) The number of specimens subjected to accelerated life tests: for accelerated life testing we used 20 specimens made from supple platinum;

C) The distribution law of the number of cycles until failure used in accelerated life testing: the Weibull distribution was chosen to test the specimens;

D) The stress under normal condition and in accelerated condition: the bending force in normal testing conditions is 50 daN and the maximum bending force is 70 daN (according to the specimens' test chart).

E) The accelerated life test plan: for the accelerated life testing of the specimens made from supple platinum we chose 3 levels best compromise plan. The test plan was realised using the ALTA software, introducing the aforementioned parameters.

The ALTA 7 software generates an optimum testing report, where the levels of accelerated life testing and the number of specimens tested at every accelerated stress level are specified. The testing parameters resulted from the design of the accelerated life testing plan for the specimens made from supple platinum are as follows: 3 levels of testing: 60, 64, 70 daN;

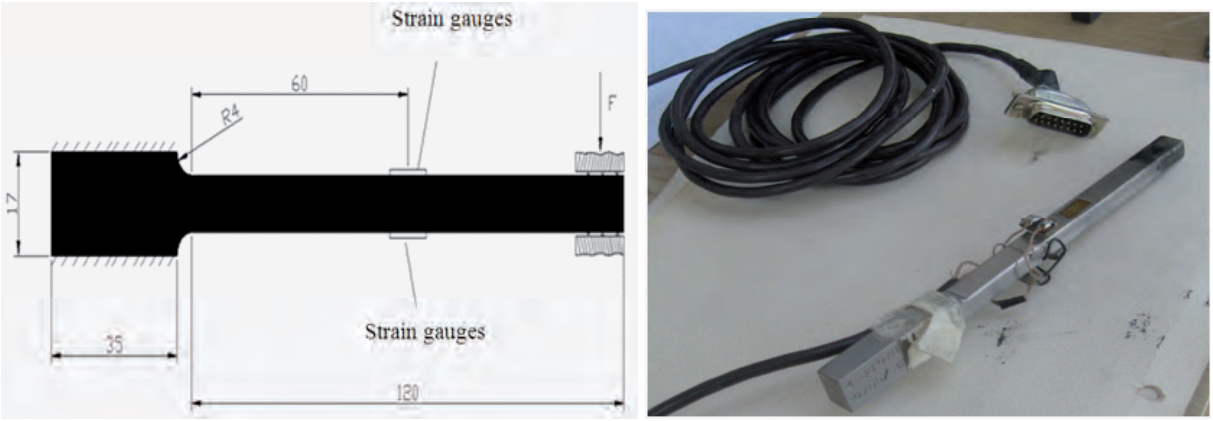

Fig. 3. The specimen made of supple platinum: a) the specimen's constructive model, b) the experimental model

the number of tested specimens corresponding to the level of acceleration: 9, 5 and 6 specimens.

2.5. The statistical processing of experimental data

For the results obtained from the accelerated life testing of the specimens for the 3 levels of accelerated stress we verified the hypothesis that the distribution law of the number of cycles until failure is Weibull (the Kolmogorov - Smirnov test was used). For this verification, we measured the spacing between empirical distribution function of the sample and the cumulative distribution function of the reference distribution. We compared these results with a level of confidence of the Kolmogorov – Smirnov test. Following the statistical processing of the experimental data for the 3 levels of stress the Weibull distribution was accepted.

For the determination of the mean number of cycles to failure and of the reliability parameters under normal testing conditions (F=50 daN) for the specimens made from supple platinum, the experimental data resulted from accelerated conditions have been processed using the ALTA7 software. We calculated the three parameters corresponding to the IPL-Weibull model using the maximum likelihood estimation method for the data from the accelerated regime introduced in the ALTA7 software. The following values of parameters resulted: β=7.283; k=4.04267E-18; n=6.788. We determined the acceleration factor corresponding to the IPL model. This is determined for every level of acceleration of the bending force. The accelerated levels are: La1=60 daN, La2=64 daN, La3=70 daN, and the normal testing level is Lu=50 daN. By calculating the product of the calculated values of the acceleration factors and the number of cycles to

Tab. 1. The determination of the number of cycles to failure in normal conditions

Num.	The number of cycles to failure in accelerated conditions	Acceleration factor	The number of cycles to failure in normal conditions
1	141453	3.447	487711
2	157243		542153
3	169634		584875
4	182723		630005
5	201634		695207
6	206256		711143
7	219634		757269
8	231238		797278
9	247234		852430
10	112787	5.343	388874
11	119462		411889
12	123300		658866
13	139498		745421
14	152087		812692
15	50231	9.818	268414
16	56922		304168
17	67037		658200
18	73008		716826
19	78025		766085
20	85341		837917

Table 2. The dependence between the numbers of cycles in normal conditions – Reliability - Unreliability – Failure Rate

The number of cycles to failure in normal conditions	Reliability R(t)	Unreliability F(t)	Failure Rate $\lambda(t)\cdot 10^{-6}$
268414	0.999	0.001	0.020
304168	0.998	0.002	0.044
388874	0.989	0.011	0.204
411889	0.984	0.016	0.293
487711	0.945	0.055	0.847
542153	0.885	0.115	1.648
584875	0.808	0.192	2.654
630005	0.693	0.307	4.233
658200	0.604	0.396	5.573
658866	0.602	0.398	5.609
695207	0.472	0.528	7.859
711143	0.413	0.587	9.062
716826	0.392	0.608	9.527
745421	0.287	0.713	12.181
757269	0.247	0.753	13.450
766085	0.218	0.782	14.465
797278	0.131	0.869	18.587
812692	0.096	0.904	20.964
837917	0.054	0.946	25.403
852430	0.036	0.964	28.297

failure in accelerated conditions we determined the number of cycles to failure in normal testing conditions (Table 1) for the specimens made from supple platinum from the structure of the IAR 330 Puma helicopter.

We determined the reliability parameters (the reliability function, unreliability and the rate of failure) depending on the number of cycles to failure in normal testing condition (Table 2).

Using the calculated values (the number of cycles in normal testing conditions), the reliability function 3D (Fig. 4a) and the failure rate 3D (Fig. 4b) were plotted.

The main purpose of accelerated quantitative tests is to determine the life time in normal testing conditions. Using the data resulted from accelerated life tests we can determine the mean number of cycles to failure of the specimens made from supple

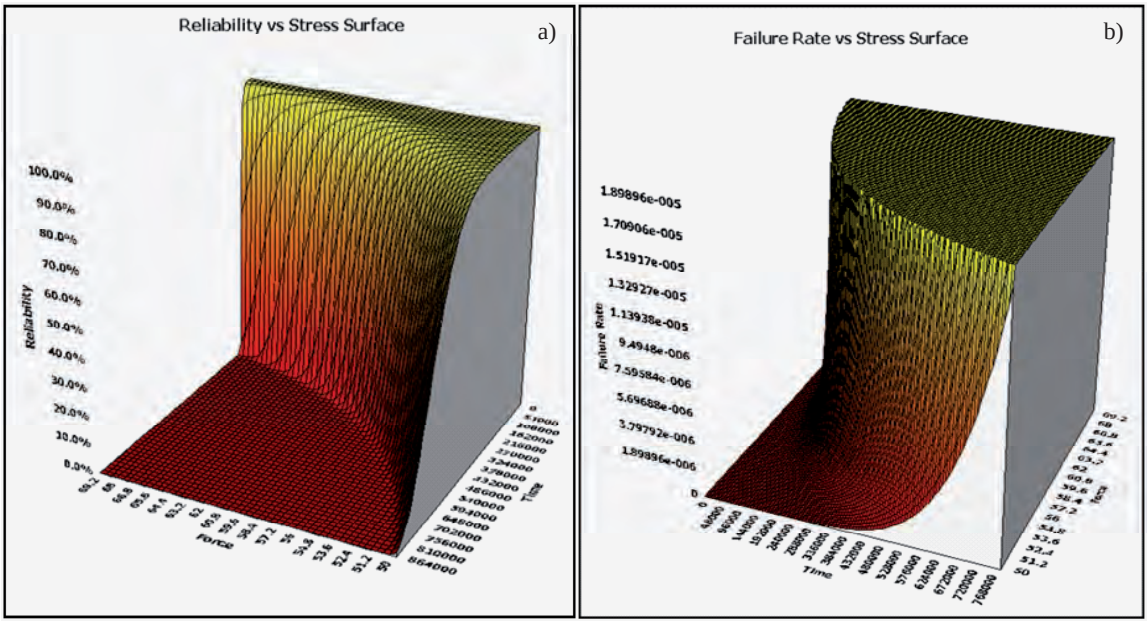

Fig. 4. Reliability parameters: a) reliability function, b) failure rate

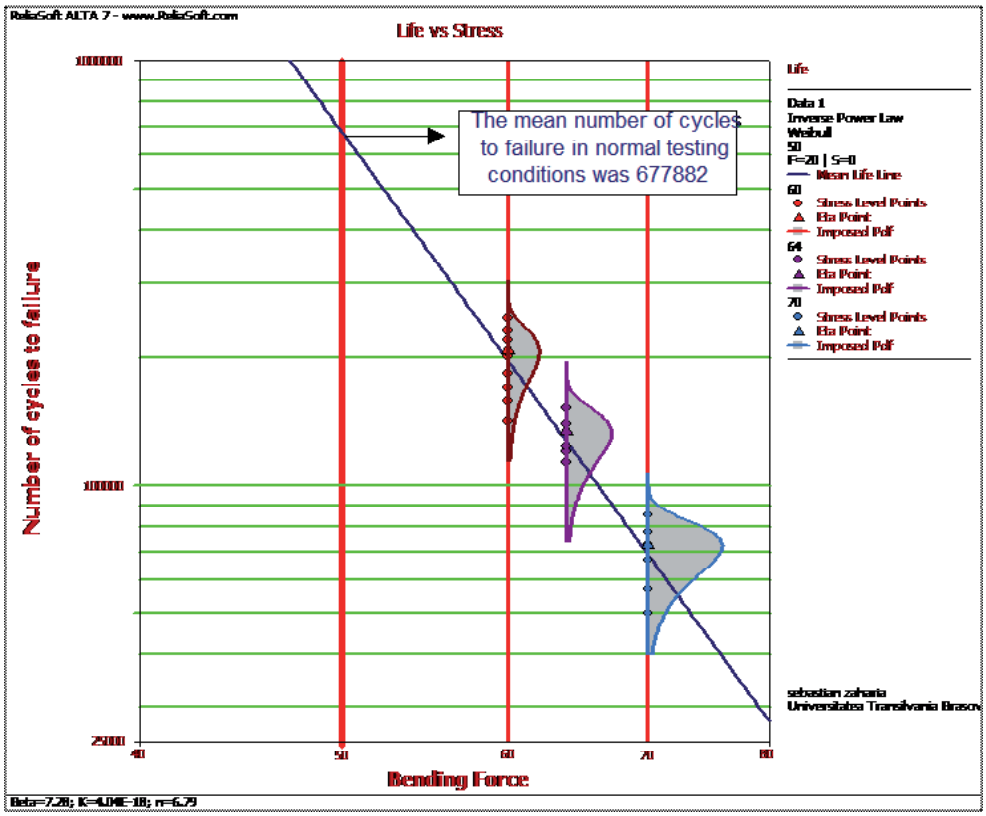

Fig. 5. The determination of the number of cycles to failure of the specimens in normal testing conditionst

platinum in normal testing conditions. The mean number of cycles to failure is determined using the relation of the mean time to failure from table 1.

The mean number of cycles to failure for the tested specimens was of 677882. Life versus stress plots is the most important plot type in accelerated life testing analysis. Life versus stress plots are widely used for estimating the parameters of life-stress relationships. Any life measure can be plotted versus stress in the life vs. stress plots available in ALTA 7. In figure 5, by drawing a line through the mean number of cycles to failure for the 3 levels of acceleration (60 daN, 64 daN and 70 daN) and marking the point of intersection of this line with the vertical line at the normal level of stress of 50 daN, we found out the mean number of cycles to failure in normal testing conditions.

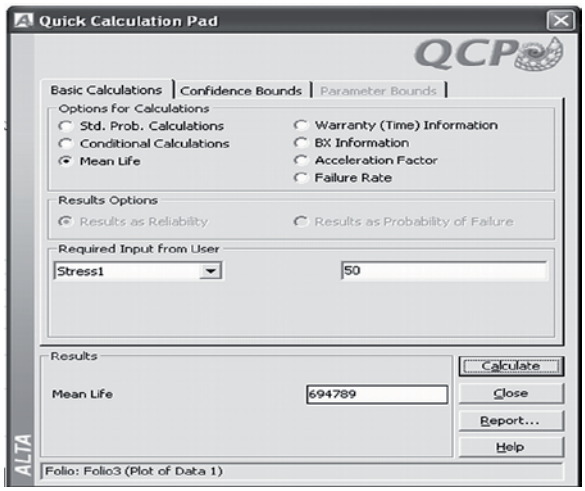

Fig. 6. The calculation of the mean number of cycles to failure in normal testing conditions for the specimens of supple platinum with the Monte Carlo method using QCP

The mean number of cycles to failure of the specimens in normal testing conditions given by the manufacturer at the approval of the vital element supple platinum is 700000 cycles, whereas the mean number of cycles to failure obtained from the accelerated life tests was of 677882 cycles. By adding the number of cycles to failure resulted from the accelerated life tests, this is of 2814747. The total number of cycles to failure in normal testing conditions is 12627432. The main purpose of the accelerated life tests on the specimens made from supple platinum from the structure of the IAR 330 Puma helicopter, to reduce the number of cycles using the accelerated life tests, was validated. Using the accelerated life tests on the specimens made from supple platinum from the structure of the IAR 330 Puma helicopter, the number of cycles to failure has been reduced by 4.5 times, making this result responsible for significant reductions of the material costs.

2.6. The application of the Monte Carlo method for the simulation of data in accelerated conditions (for supple platinum - a component of the IAR 330 Puma helicopter)

Using the Monte Carlo method we simulated N stages of a product with the help of an acceleration model (Inverse Power Law) and statistical distribution (Weibull) which are suited to the analyzed case study. Using the previously determined parameters (β=7.283; k=4.04267E-18; n=6.788) and the three accelerated levels (60, 64 and 70 daN), we simulated with the

help of ALTA7 software the values for the number of cycles to failure in accelerated conditions.

Following the simulation of accelerated data using the Monte Carlo method for the specimens from supple platinum from the structure of the IAR 330 Puma helicopter, we obtained the value of 694789, which represents the mean number of cycles until failure (Fig. 6), which is close to the value of 677882, which represents the mean number of cycles to failure of the specimens tested in accelerated conditions in the previously presented abovementioned experiment. The Quick Calculation Pad (QCP) provides you with a quick and accurate way of gaining access to some of the most frequently requested reliability results.

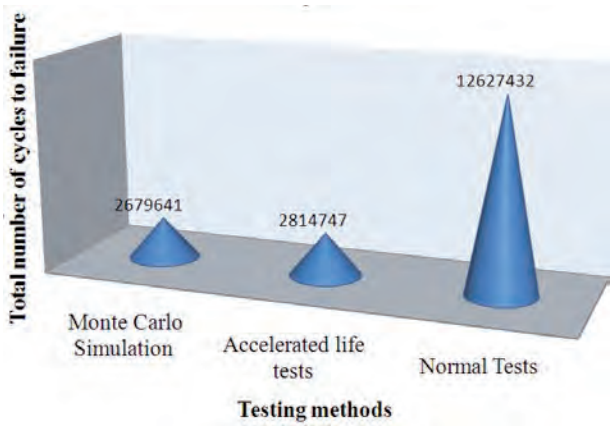

Fig. 7. Significant reduction of time using accelerated life tests

3. Conclusion

At some industrial products (from the aviation, nuclear and electronic fields), for which a high reliability is estimated, the determination of the life time and of the reliability parameters, under normal stress conditions, implies a long testing period. For this reason we opted for the accelerated life testing methods. These are tests being performed at more intense stress conditions, compared to the normal stress conditions, with the purpose of intensifying the degradation processes and, as an economic result, the shortening of the period and costs related to the testing, while preserving the same failure modes and mechanisms.

The implementation of accelerated life tests on the products from the aviation field has produced a significant reduction of the testing time. For the case study under analysis, figure 7 shows the number of cycles to failure from: accelerated life tests, the simulation with the Monte Carlo method and the data from the normal testing conditions. We can observe that, by using the accelerated life tests, the testing time has been reduced by 4.5 times. Given the fierce competition existing on the aviation industry market and considering the reduction in testing time and therefore the optimizing of the products' life cycle, many companies will implement and develop various methods of obtaining data as fast as possible regarding the reliability and quality of the products.

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APPLICATION OF FEM IN THE ANALYSIS OF THE STRUCTURE OF A TRAILER SUPPORTING FRAME WITH VARIABLE OPERATION PARAMETERS

WYKORZYSTANIE MES W ANALIZIE STRUKTURY NOŚNEJ RAMY NACZEPY O ZMIENNYCH PARAMETRACH EKSPLOATACYJNYCH*

This work presents a numerical analysis of the structure of a trailer frame of adjustable length and an increased load capacity designed for the transportation of oversize loads. The study was aimed at developing adequate numerical FEM models which would allow identification of the effort of the structure and the state of strain under operating loads. The analysis was carried out using ABAQUS/Standard, a numerical tool which enables calculations in the geometrically non-linear range with the use of the incremental–iterative Newton–Raphson method. As a result of the analysis, trouble areas in the frame were found in which dangerous stresses occurred. This enabled modification of the structure, leading to a reduction of the stresses to a safe level.

Keywords: *finite element method, supporting frame, strength calculations, trailer, oversized transport.*

W pracy zaprezentowano numeryczną analizę konstrukcji ramy naczepy o zmiennej długości i podwyższonej nośności przeznaczonej do transportu ładunków ponadnormatywnych. Prowadzone badania miały na celu opracowanie adekwatnych modeli numerycznych MES umożliwiających identyfikację wytężenia konstrukcji oraz stanu odkształcenia w warunkach obciążeń eksploatacyjnych. Zastosowanym do analizy narzędziem numerycznym był program Abaqus/Standard, umożliwiający prowadzenie obliczeń w zakresie geometrycznie nieliniowym z wykorzystaniem przyrostowo-iteracyjnej metody Newtona-Raphsona. W wyniku przeprowadzonych prac ustalono newralgiczne obszary ramy w których występowały niebezpieczne naprężenia. Umożliwiło to modyfikację konstrukcji pozwalającą na zmniejszenie naprężeń do bezpiecznego poziomu.

Słowa kluczowe: *metoda elementów skończonych, rama nośna, obliczenia wytrzymałościowe, naczepa, transport nienormatywny.*

1. Introduction

Design of modern structures is a complex task that requires taking account of numerous material and mechanical features when optimizing the geometry of the structure being designed. This concerns, in particular, critical structural elements, whose load capacity determines the strength of the entire supporting system. The process of designing such elements necessitates the use of modern tools which make it possible to search for the best design solutions [10–12]. A contemporary tool that provides a wide range of possibilities of analyzing the strength parameters of a structure being designed is CAE numerical software, which uses the finite element method [3–6, 8]. Such software currently finds broad application in many branches of industry, in particular the aerospace, aircraft and automotive industries.

A group of supporting structures that have to meet high strength and stiffness requirements are the frames used in the modern means of transport. Among design solutions that are subjected to the action of particularly high operating loads are frames of trailers for the transportation of oversize or overweight loads. Designing of this type of structures requires taking account of the various operating configurations of the trailer which make it possible, when necessary, to extend the length and width of the load deck [9–10]. A change of the configuration of the structure during its operation considerably affects the change in the character of its loading, which requires additional consideration in the process of designing and construction of the structure.

This study presents a conception of a central frame whose length can be changed over a wide range depending on the operating needs. A solution based on two mating thin-wall box beams was adopted in which frame length was adjusted by mutual sliding of the load-bearing members in and out of each other. In the calculations, structural details were taken into account, such as process holes, which could have a significant effect on the assessment of the stress-strain state of the structure of the frame. The calculations were done us-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

ing the Abaqus/Standard software, a modern numerical tool that uses the finite element method in the geometrically and physically non-linear range [1, 2, 6, 8].

2. Goal and scope of the study

The aim of the study was to assess the strength and stiffness of the design solution developed for a trailer support frame intended for the transportation of long loads of up to 45 tons. In the adopted concept of the frame, consisting of two independent parts – front and rear, length could be easily changed by sliding the front part of the frame in and out of its rear part. This enabled adjustment of the length of the frame to the transported load. The new structural solution required precise analysis of the state of strain and effort, which was conducted using the finite element method.

Prior to FEM calculations, the bending moments acting on the trailer frame were determined analytically for different combinations of its length and distribution of the transported load. The analysis covered only those cases which were deemed probable and permissible (e.g., loading of a maximally extended frame with a point force, of a value corresponding to the maximum permissible load weight, applied in the middle of its length was considered unlikely and was also listed in the trailer user's manual as impermissible). On the basis of the above considerations, cases for FEM analyses were chosen (Fig. 1).

Because the analysis of the structure was carried out in the range of operating loads, thus not allowing permanent deformations to develop in structure members, a decision was taken to adopt a linear elastic material model. Taking into consideration the contact interactions applied to the numerical model and the possibility of occurrence of large deformations, it was decided that the calculations should be carried out in the geometrically non-linear range using the incremental–iterative Newton–Raphson method [2, 6, 8].

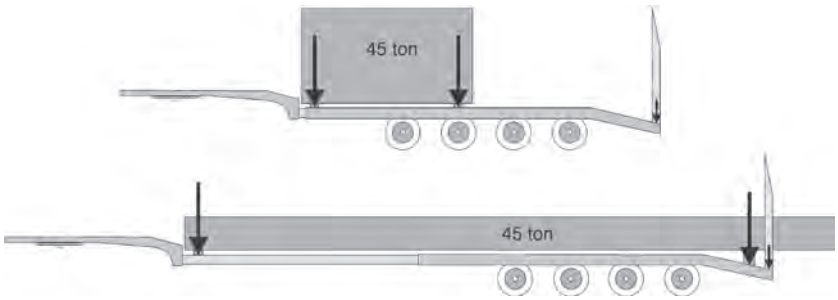

Fig. 1. Schematic diagrams of loading of a retracted (a) and an extended (b) frame with a load

3. Development of a numerical FEM model

Two configurations of frame operation were considered: a retracted frame configuration and a maximally extended frame configuration. In both variants, the same design and material parameters were used. The structure of the frame was designed so that its rear part, being the basic element of the structure for which the boundary conditions are determined by the vehicle suspension system, should simultaneously provide support for the front part, the movable element of the frame. The length of the frame could be changed by sliding the front part in and out of the rear part structure of the frame. A general view of the numerical model of the frame is shown in Fig. 2

The loading of the numerical model consisted of the structure's own weight as well as point mass loading deriving from the weight of the load of 45 tons, additionally taking into account 20% of dynamic surplus. A schematic diagram of the distribution of the external load in the form of point masses for the two frame configurations is shown in Fig. 2.

The structure of the spatial discrete model of the frame was based on shell-type elements having six degrees of freedom per element node [1]. In the joining area between the front and rear part of the frame, a solution was adopted which consisted in using flexible cushions which enlarged the mating area, and, by the same token, eliminated adverse local edge pressures in the zone of the joint. The mutual interactions between the front and the rear part of the frame were reproduced by defining contact interactions between the mating elements.

4. Boundary conditions of the discrete model

The principal task in developing a discrete model of the structure of the frame was to reproduce the operating conditions of the air suspension, which ensures identical reactions for each trailer wheel axle during operation of the vehicle. It was decided that the control arm would be reproduced by means of beam elements of specific stiffness for which different support conditions were defined in the front and rear node of the model of the control arm. The connection between the control arm and the frame in the front node ensured rigid transfer of load from the suspension onto the structure of the frame, allowing the arm only to rotate relative to the wheel axles. The rear node of the control arm was connected with the frame via an spring reproducing the air bag of the air suspension. The stiffness of the element modelling the air bag was selected so as to ensure similar reactions in the axles of all trailer wheels. The support of an individual wheel was realized by depriving the middle node of the control arm (in the connection node between beam elements) of the possibility of displacement in the direction of the X axis – Fig. 3a.

For the front part of the frame, support of the kingpin was defined by disabling displacement of kingpin nodes in the direction of the Y and Z axes – Fig. 3b. Moreover, in the direction of the X axis (vertical movements of the kingpin), support of nodes was introduced in the form of elastic response of an appropriately specified stiffness. Additionally, for the entire model, axial symmetry conditions were defined (along the axis of the frame – the Y axis) by depriving the nodes located on the model's symmetry axis of the possibil-

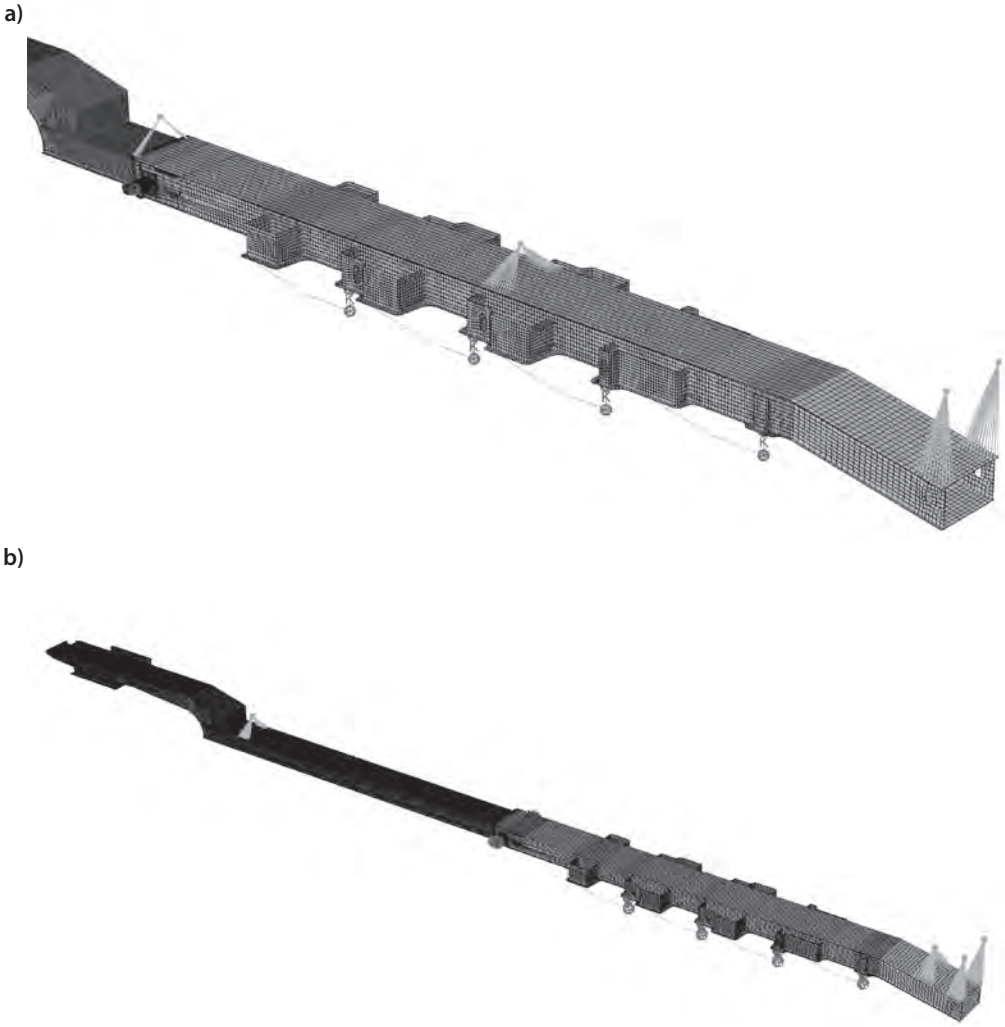

Fig. 2. Discrete models of the frame indicating the manner in which external loading was modelled: a) retracted configuration, (b) extended configuration

ity of displacement in the direction of the Z axis and rotation relative to the X and Y axes. Elimination of these degrees of freedom ensured stable work of the model without unwanted displacements of the structure in the direction crosswise to its axis (sideways) – Fig. 3b.

5. Results of numerical analysis

The numerical calculations conducted in this study made possible evaluation and comparison of the state of strain and effort of the structure of the frame for both of the considered operating variants – the retracted and maximally extended frame. The obtained maps of distribution of H-M-H reduced stresses in the elements of the structure pointed to the areas in which those stresses considerably exceeded the adopted yield point of the material Re = 360 MPa. The most adverse stress gradients occurred in the sliding part of the frame and in the joining zone between the two load-bearing members, both in the case of the retracted and the extended configuration of the frame – Fig. 4.

The very high levels of reduced stress occurring in some areas required elimination, which called for a better design solution. Therefore, modifications of structural details were introduced in the current solution. They primarily involved a change in the location of the process holes in the side walls of the frame, which were a source of dangerous stress gradients. The openings were removed and replaced with one hole in the lower beam wall. Moreover, flat bars for the reinforcement of the side walls of the frame were introduced in the risk zone and reinforcing ribs in the gooseneck were added – Fig. 5. As a result of such activities, successive variants of the structure were being developed, which were then subjected to FEM analysis. The newly introduced modifications made possible elimination of the trouble zones in the supporting system. Fig. 6. shows the results of FEM calculations for the final variant of the structure.

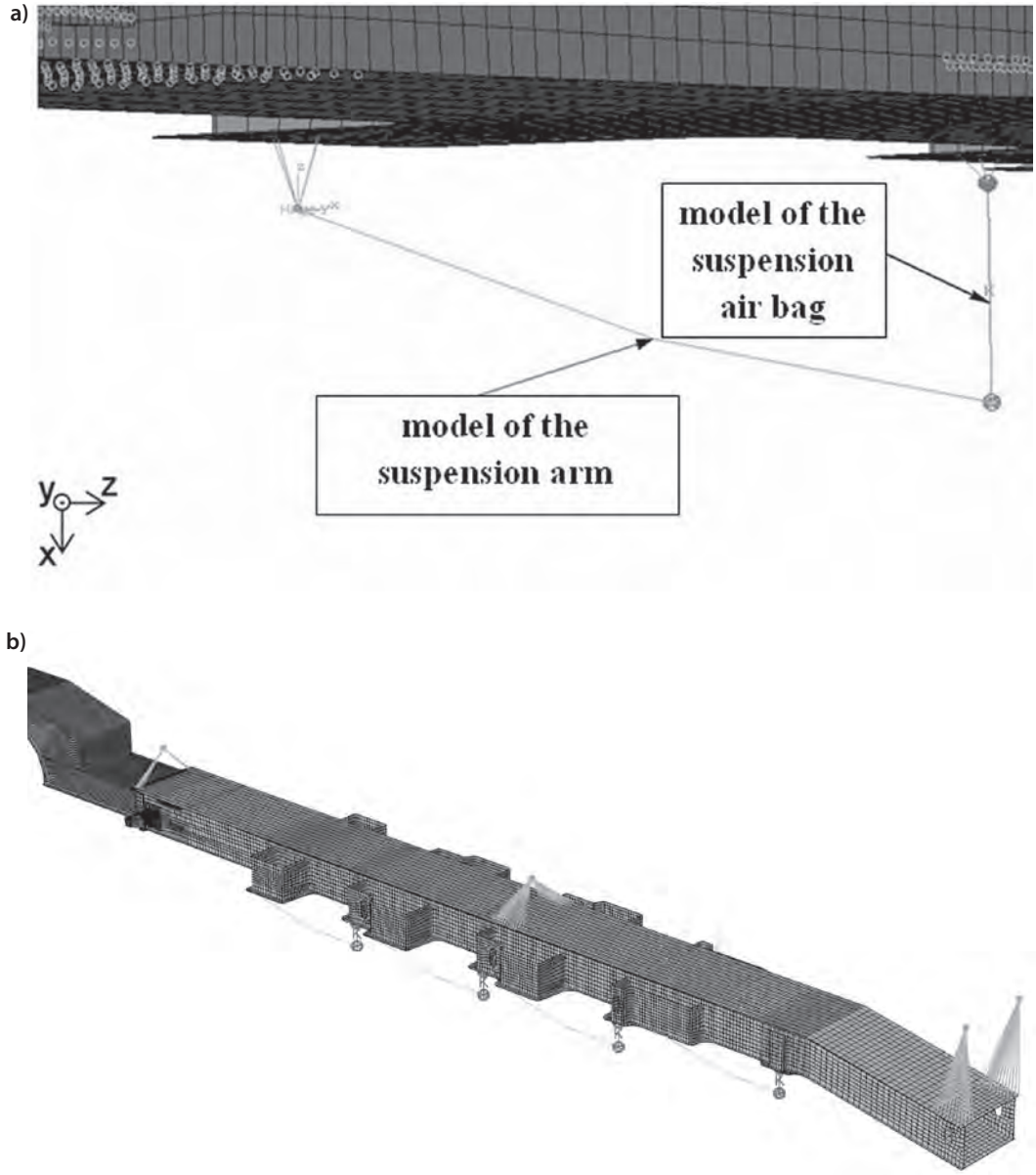

Fig. 3. Boundary conditions of the FEM model: a) model of the wheel suspension, b) support of the frame's kingpin and the model's axial symmetry conditions

6. Conclusions

The numerical analysis of the structure of the support frame of a trailer conducted in this study enables evaluation of the adequacy of the newly developed design solution, allowing identification of the trouble areas determining the strength of the entire structure. This is extremely important in cases where, in the process of looking for new design solutions, too many unknown design parameters occur at the stage of designing complex load-bearing members. The knowledge of stress distribution in the critical elements is then an issue of primary importance, and the application of the finite element method allows analysis of the effort of a structure as early as the design stage [6, 8, 9].

Use of numerical FEM calculations in the design process enables fast and effective introduction of indispensable modifications of structural details, leading to the creation of successive, ever more adequate design variants which, ultimately, make it possible to develop an optimum solution.

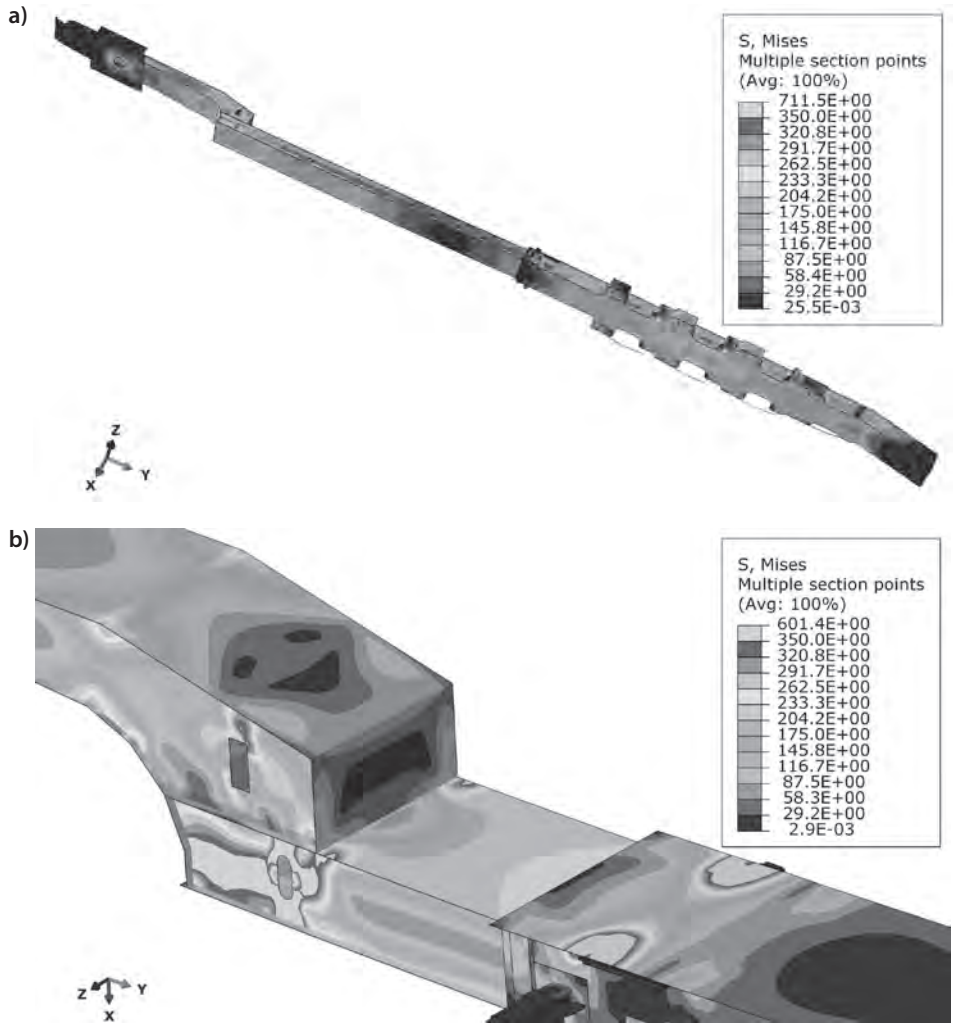

Fig. 4. H-M-H stress distribution in the model of the frame: a) retracted frame – general view, b) extended frame – detail of the joining zone

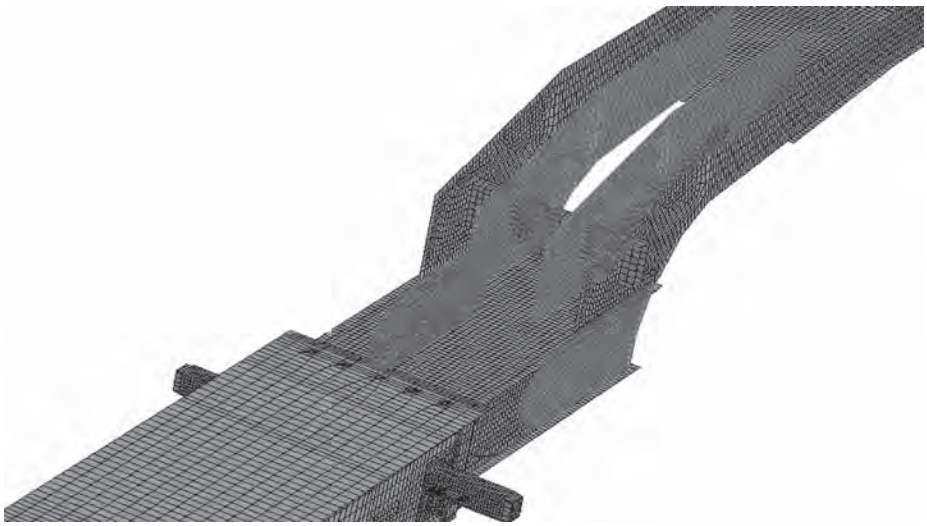

Fig. 5. Cover plates and ribs reinforcing the front part of the frame

Fig. 6. H-M-H stress distribution in the modified model of the frame: a) general view b) detail of the front part of the frame

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UNCERTAINTY ANALYSIS METHOD BASED ON A COMBINATION OF THE MAXIMUM ENTROPY PRINCIPLE AND THE POINT ESTIMATION METHOD

METODA ANALIZY NIEPEWNOŚCI OPARTA NA POŁĄCZENIU ZASADY MAKSYMALNEJ ENTROPII I METODY OCENY PUNKTOWEJ

Uncertainty is inevitable in product design processes. Therefore, to make reliable decisions, uncertainty analysis incorporating all kinds of uncertainty is needed. In engineering practice, due to the incomplete knowledge, the distribution of some design variables can not be determined. Furthermore, the performance function is highly nonlinear, therefore, the high order moments of the performance function are needed to calculate the probability of failure accurately. In this paper, an uncertainty analysis method combining the maximum entropy principle and the bootstrapping method is proposed. Firstly, the bootstrapping method is used to calculate the confidence intervals of the first four moments for mixed random variables and sample variables. Secondly, the high order moments of limit state functions are estimated using the reduced dimension method. Thirdly, to calculate the probability density function (PDF) and cumulative distribution function (CDF) of the limit state functions, an optimization model based on the maximum entropy principle is formulated. In the proposed method, the assumptions that the distribution of the random variables are known and the calculation of the sensitivity for limit state function with respect to the Most Probable Point (MPP) are avoided. Finally, comparisons of results from the proposed methods and the MCS method are presented and discussed with numerical examples.

Keywords: *uncertainty analysis, bootstrapping , moments, maximum entropy principle.*

Niepewność jest nieodłącznym elementem procesów projektowania produktu. Dlatego też podejmowanie niezawodnych decyzji wymaga analizy niepewności, która uwzględniałaby wszystkie rodzaje niepewności. W praktyce inżynierskiej, z powodu niepełnej wiedzy, wyznaczenie rozkładu niektórych zmiennych projektowych nie jest możliwe. Co więcej, funkcja stanu granicznego jest wysoce nieliniowa, co sprawia, że do poprawnego obliczenia prawdopodobieństwa uszkodzenia potrzebna jest znajomość momentów wyższych rzędów tej funkcji. W niniejszej pracy zaproponowano metodę analizy niepewności łączącą zasadę maksymalnej entropii z metodą bootstrapową. W pierwszej części pracy wykorzystano metodę bootstrapową do obliczenia przedziałów ufności czterech pierwszych momentów dla zmiennych losowych typu mieszanego oraz zmiennych z próby. Następnie, wyznaczono momenty wyższych rzędów funkcji stanu granicznego przy użyciu metody redukcji wymiarów. Po trzecie, w celu obliczenia funkcji gęstości prawdopodobieństwa (PDF) oraz dystrybuanty (CDF) funkcji stanu granicznego, sformułowano model optymalizacji oparty na zasadzie maksymalnej entropii. Proponowana metoda nie wymaga założenia znajomości rozkładów zmiennych losowych ani obliczania wrażliwości dla funkcji stanu granicznego w odniesieniu do najbardziej prawdopodobnego punktu awarii. W końcowej części artykułu porównano na podstawie przykładów numerycznych wyniki otrzymane za pomocą proponowanej metody oraz symulacji Monte Carlo (MCS).

Słowa kluczowe: *analiza niepewności, bootstrapping, momenty, zasada maksymalnej entropii.*

1. Introduction

Uncertainty exists in the whole life-cycle of a product. Therefore, to make reliabile decisions, the representation, quantification, and propagation of uncertainty are needed in design processes, which have been widely studied in many advanced research fields.

Uncertainty analysis is to evaluate the cumulative distribution function (CDF), probability density function (PDF) of a performance function formulated by mutually independent random varaibles. The CDF of the performance function can be evaluated with a multidimensional integral. However, in practice it is very difficult or even impossible to obtain an analytical solution to the probability integration. Many research have been develpoed for approximating the probability integration.

Mainly, there are three approximation approaches for uncertainty analysis including (1) simulation method, (2) agent models method, and (3) analytical method. The most direct re-

liability analysis method is Monte Carlo simulation (MCS) [5, 18, 19]. However, the efficiency of MCS is very low for high dimension problems or when the requirement of design accuracy is high. The main merit of the agent methods [7, 11, 12] is easy to solve. However, the accuracy of the agent methods usually does not meet engineering requirements. Analytical methods focus on simplifying the multi-dimensional integral calculation. The first order reliability method (FORM) and second order reliability method (SORM) [3, 6, 8, 9, 22] were widely used by first order or second order Taylor expansion of the performance function at the most probable failure point (MPP). In the MPP based analysis methods, the random variables were needed to be transformed into standard normal distribution, and the sensitivity analysis was required in both the FORM and SORM. Further, the MPP search was an iterative optimization process, which might be trapped into local optimum. The accuracy of the two methods was determined by the non-linearity of the performance function. When the performance function is highly non-linear, the results calculated with the two methods may cause huge errors. Another altenative analytical method [10, 15, 20] for uncertainty analysis have been developed with dimension reduced method combined numerical integration methods. Rahman and Xu [20] proposed a univariate dimension reduction method for multi-dimensional integration using moment based quadrature rule. Huang and Du [10] presented an uncertainty analysis method based on the combination of dimension reduction integration and saddlepoint approximation. In their method, all the random variable should be transformed into standard normal distribution, and the Gauss-Hermite integration was used to calculate the moments of the limit state functions. Lee and Choi, et al [15] developed an inverse analysis method using MPP based dimension reduction for reliability based design optimization. In their method, the MPP calculation was needed and all the random variables were transformed into standard normal distribution.

Maximum entropy principle as a measure of uncertainty has beed developed rencently for uncertainty analysis and reliability based design optimization. As the performance function is highly nonliear or the MPP is not unique, the high order moments of the performace function are needed for estimating the CDF of the performance function accurately. Kang and Kwak [14] applied the maximum entropy principle to reliability based design optimization with the improved moment based quadrature rule. Li and Zhang [16] presented the combined reliability analysis approach with dimension reduction method and maximum entropy principle. The moment based quadrature rule was used to calculate the moments of the performance function. Sung and Kwark [21] proposed reliability bound analysis method based on maximum entropy method with respect to the first truncated moment. Ching and Hsieh [4] developed an estimation method to calculate the confidence interval of the probabilty of failure for the performance function with maximum entropy principle. Volpe and Bagan [23] analyzed the Maximum entropy PDFs and the moment problem of random variables under near-Gauss distribution. A constrained optimization problem is needed to solve in the maximum entropy principle based uncertainty analysis methods. Abramov [1-2] proposed BFGS methods to solve this nonliear optimization problem.

In the above related work, the distribution of the random variables were assumed to be known, and were needed to transform into standard normal distribution. In this paper, an uncertainty analysis method combined maximum entropy principle and bootstrapping method is proposed. When the distribution of some random variables can not be exactly determined, the high order moments of limit state functions are estimated by bootstrapping method. Confidence intervals of the probability density function (PDF), and cumulative distribution function (CDF) of performance functions are calculated based on maximum entropy principle.

The structure of this paper is as follows. In the second section of this paper, the bootstrapping method to estimate distribution information of uncertainty variables is introduced. The process to calculate moments of limit state functions are provided in the third section. An optimization model based on maximum entropy principle is formulated in the forth section. Numerical examples are analyzed using the proposed method in the fifth section. Finally the conclusions and disscussion are given in the sixth section.

2. Bootstrapping method to estimate the distribution of the uncertainty variables

A general uncertainty analysis problem as in Eq. (1) is considered in this work. Performance function $y = g(\mathbf{x})$ which is also referred to limit-state function is modeled as the output of mutually independent random variables $\mathbf{x} = [x_1, x_2, \cdots, x_n]$.

$$F(y) = P\left\{y \le y^a\right\} = \int_{g(\mathbf{x}) \le y^a} \cdots \int f(\mathbf{x}) d\mathbf{x} \tag{1}$$

where $F(y)$ is the CDF of the limit state function, y^a denotes a upper bound of the performance function, $f(\mathbf{x})$ is the joint probability density funtion of $\mathbf{x}$.

Bootstrapping method is a statistical method for estimating the sampling distribution of a random by sampling with replacement from the original samples. The steps of bootstrapping method are analyzed as follows.

Given the m sample points $x_{i,1}, x_{i,2,}, \cdots, x_{i,m}$ for a random variable x_i: Step (1) Construct an empirical probability distribution function f_{x_i} from the samples by placing a probability of $1/m$ for each point $x_{i,1}, x_{i,2,}, \cdots, x_{i,m}$ of the samples. Step (2) from the empirical distribution function f_{x_i}, draw a random sample of size m with replacement. Step (3) calculate the statistic of the resample points $T_{x_{i,k}}$. Step (4) repeat step 2 and step 3 k times, where k equals to 1000. Step (5) construct the relative frequency histogram from the k number of T_{x_i} by placing a probability of $1/k$ at each point. $T_{x_{i,1}}, T_{x_{i,2}}, \cdots, T_{x_{i,1000}}$. $T_{x_{i,(1)}}, T_{x_{i,(2)}}, \cdots, T_{x_{i,(1000)}}$ denote the bootstrap values by ranking $T_{x_{i,1}}, T_{x_{i,2}}, \cdots, T_{x_{i,1000}}$ from bottom to top. Then the bootstrap percentile confidence interval at 95% level of confidence would be $[T_{x_{i,(25)}}, T_{x_{i,(975)}}]$. x_i lies within the centered bootstrap 95% percentile confidence interval $[2\bar{x}_i - T_{x_{i,(975)}}, 2\bar{x}_i - T_{x_{i,(25)}}]$.

2.1. Calculation of moments for sample variables

Given n samples of a random variable x_i , the first four moments μ, σ, μ_3, μ_4 of a random variable can be calculated by Eq. (2):

$$\begin{aligned} &E(\bar{x}_i) = \mu \\ &E(\bar{x}_i - \mu)^2 = \frac{\sigma^2}{n} \\ &E(\bar{x}_i - \mu)^3 = \frac{1}{n^2}\mu_3 \\ &E(\bar{x}_i - \mu)^4 = \frac{1}{n^3}\mu_4 + \frac{3(n-1)}{n^3}\sigma^4 \end{aligned} \tag{2}$$

where $\bar{x}_i = \frac{\sum_{j=1}^{n} x_{i,j}}{n}$.

The centered bootstrap 95% percentile confidence interval of a random varaible x_i is calculated by $[2\bar{x}_i - T_{x_i,(975)},\ 2\bar{x}_i - T_{x_i,(25)}]$.

3. Moments estimation for the limit state functions

In engineering practices, the limit state function $g(\mathbf{x})$ is a nonliear function of large input variables $\mathbf{x} = [x_1, x_2, \cdots, x_n]$. The mean of the limit state funtion can be calculated by point estimation method using m^n points. The computational burden is extremely large if n becomes large. In order to reduce the computational burden, a dimension reduced method [24] is introduced to approximate the limit state function which is expressed in Eq. (3):

$$g'(\mathbf{x}) = \sum_{i=1}^{n}(g_i - g_\mu) + g_\mu \tag{3}$$

where $g_\mu = g(\mu_1, \mu_2, \cdots, \mu_n)$ is the performance function value with all input variables taking the mean values. $g_i = g(\mu_1, \mu_2, \cdots, x_i, \cdots, \mu_n)$ denotes the response value with all input variables taking the mean except the ith input variable. From Eq. (3), the computational burden is reduced largely and the number of the function calls is reached $m \times n$. Since x_i is mutually independent, g_i is also mutually independent. The first four moments of the limit state $g(\mathbf{x})$ can be calculated by Eq. (4):

$$\mu_g = \sum_{i=1}^{n}(\mu_i - g_\mu) + g_\mu \tag{4a}$$

$$\sigma_g^2 = \sum_{i=1}^{n}\sigma_i^2 \tag{4b}$$

$$\mu_{3g}\sigma_g^3 = \sum_{i=1}^{n}\mu_{3i}\sigma_i^3 \tag{4c}$$

$$\mu_{4g}\sigma_g^4 = \sum_{i=1}^{n}\mu_{4i}\sigma_i^4 + 6\sum_{i=1}^{n-1}\sum_{j>i}^{n}\sigma_i^2\sigma_j^2 \tag{4d}$$

where μ_i , σ_i , μ_{3i} , μ_{4i} are the first four moments of g_i which can be calculated with the point estimation method of the single variable.

Considering incomplete knowledge of some random variables, the confidence interval of μ_i $[2\mu_i - T_{\mu_i,975},\ 2\mu_i - T_{\mu_i,25}]$ can be calculated by bootstrapping method.

4. Maximum entropy principle for calculation of CDF and PDF

Entropy has been widely studied for uncertainty analysis and reliability design optimization since entropy was analyzed by Jaynes [13] as a measure of uncertainty . Maximum entropy method is developed to estimate the probability distribution of a random variable by maximizing the entropy subject to constraints supplied by the moments of the random variable.

Generally, Eq. (5) and Eq. (6) are used to calculate the entropy for both the discrete and continuous variables respectively:

$$H(x) = -\sum_{i=1}^{n} p_i \ln p_i \tag{5}$$

$$H(x) = H(p(x)) = -\int_x p(x)\ln p(x) \tag{6}$$

where p_i is the probability of the discrete variable x_i, and $P(x)$ is the PDF of the continuous variable x_i.

4.1. Optimization formulation to calculate PDF and CDF

Maximum entropy formulation of a function can be expressed by Eq. (7):

$$\begin{aligned} &\max: H = -\int_R f(g(\mathbf{x}))\ln f(g(\mathbf{x}))dg(\mathbf{x}) \\ &\text{s.t.}\ \int_R f(g(\mathbf{x}))dg(\mathbf{x}) = 1 \\ &\quad \int_R g(\mathbf{x}) f(g(\mathbf{x}))dg(\mathbf{x}) = \mu_g \\ &\quad \int_R (g(\mathbf{x}) - \mu_g)^r f(g(\mathbf{x}))dg(\mathbf{x}) = \mu_g^r \end{aligned} \tag{7}$$

where R is the integral domain, μ_g is the mean value of $g(\mathbf{x})$, and μ_g^r is the rth central moment for the limit state function $g(\mathbf{x})$.

Lagrange method can be used to solve problem in Eq. (7) and the Lagrange multipliers are denoted as $(\lambda_0, \lambda_1, \cdots, \lambda_n)$, and the maximum entropy formulation for the PDF can be expressed in Eq. (8) , which is the optimal solution to Eq. (7):

$$f(g(\mathbf{x})) = \exp(\lambda_0 + \sum_{i=1}^{n}\lambda_i(g(\mathbf{x}) - \mu_g)^r) \tag{8}$$

4.2. Calculation of the probability of failure for limit state function

The steps to calculate probability of failure for limit state functions based on maximum entropy approach can be summered as follows.

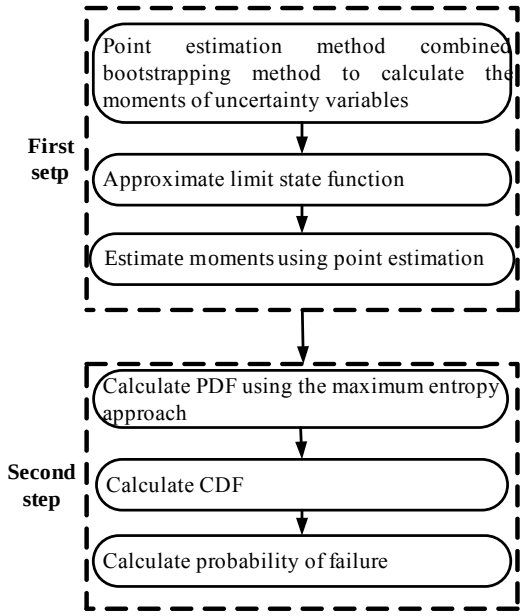

Fig. 1. Flowchart of the proposed method

(1) The first four moments of random variables are calculated by point estimation method combined bootstrapping method.
(2) Estimate moments of the limit state functions where only one random variable is involved, shown in Eq. (2).
(3) Estimate moments of the limit state function where n random variables are involved, shown in Eq. (4).
(4) Estimate PDF of the limit state functions according to Eq. (7) and Eq. (8).
(5) Calculate CDF and probability of failure.

The flowchart of the calculation process is shown in Figure 1.

5. Numerical examples

5.1. Disk edge design

The disk edge design problem used in [20] is expressed as in Eq. (9):

$$y = M_b = g(x) = \sqrt{\frac{fs}{3\times 385.82\delta(N\frac{2\pi}{60})^2(R^3-R_0^3)(R-R_0)}} \quad (9)$$

where $\mathbf{x}=[f,s,\delta,N,R,R_0]^{\mathrm{T}}$; f is the material utilization; s is the tensile strength limit; δ is the density; N is the rotor speed; R is the outer radius; and R_0 is the inner radius.

Table 1. Distributions of random variables

Variable	Distribution type	Parameter 1	Parameter 2
f	Sample	-	-
s	Sample	-lb/in^2	-
δ	Normal	0.28 lb/in^3	0.30 lb/in^3
N	Normal	21,000 rpm	1,000 rpm
R	Normal	24 in	0.5 in
R_0	Normal	8 in	0.3 in

The distributions information of the variables are given in Table 1.

The samples of design variable f and s are displayed as follows:

f=[0.9598 0.8596 0.8850 0.9389 0.9304 0.9346 0.9751 0.9649 0.9474 0.9725 0.8936 0.9767 0.9730 0.9796 0.9728 0.9511 0.9638 0.8676].

s=[215560 215800 224130 215880 218690 219900 220500 226770 226890 212110 211250 219830 217280 214640 214710 222540 218570 216010].

According to the method proposed in Section 2, the confidence interval of moments for the limit state function are shown in Table 2.

Table 2. Confidence interval of moments for the limit state function

First moment	Second moment	Third moment	Fourth moment
[2.1317, 2.88]×10^{-5}	[5.376, 7.2734]× ×10^{-10}	[1.3634,1.8446]× ×10^{-14}	[3.4772,4.7044]× ×10^{-19}

The PDF of the limit state function at the lower bound and upper bound can be expressed as Eq. (10) and Eq. (11) according to the maximum entropy approach:

$$f_{lower}(g) = \exp(0.5153 - 1.26\times 10^6 \times g - 3.79\times 10^7 \times g^2 + 8.76\times 10^{15}\times g^3 - 2.39\times 10^{20}\times g^4) \quad (10)$$

$$f_{upper}(g) = \exp(8.8779 - 4.46\times 10^5 \times g - 1.0036\times 10^9 \times g^2 + 1.032\times 10^{16}\times g^3 - 2.1549\times 10^{20}\times g^4) \quad (11)$$

The comparisons for the PDF and CDF of the limit state function from the proposed method and MCS are displayed in Fig. 2 and Fig. 3, respectively.

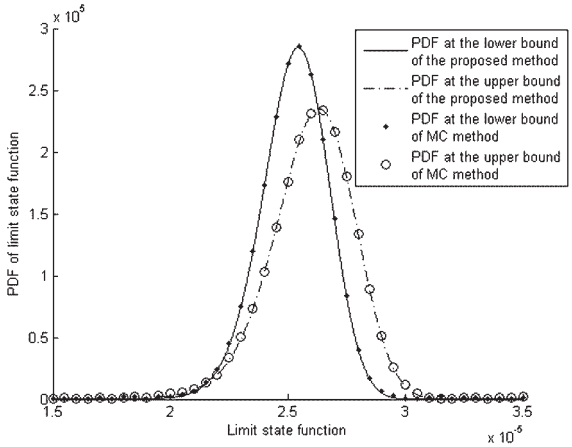

Fig. 2. PDF of the limit state function for disk edge design

5.2. Fortini's clutch problem

The second example is the over running clutch assembly known as Fortini's clutch [17]. The contact angle y in is de-

Table 3. Distribution information for variables

Variable	Distribution type	Mean value[mm]	Deviation[mm]	Parameters
x_1	Beta	55.29	0.0793	q=r=5.0
x_2	Normal	22.86	0.0043	
x_3	Normal	22.86	0.0043	
x_4		Sample		

The samples of design variable are listed as follow.

$\mathbf{x}_4$ = [154.4042,107.4187 115.6844 145.8643 156.3655 156.9087 109.7149 193.6139 158.2305 212.9646 205.6109 383.8824 231.2218 130.8089 110.0401].

termined by the independent random variable, x_1, x_2, x_3, x_4 as shown in Eq. (12). The distribution of design variables is displayed in table 3.

$$y = \arccos\left[2x_1 + (x_2 + x_3)/2x_4 - (x_2 + x_3)\right] \qquad (12)$$

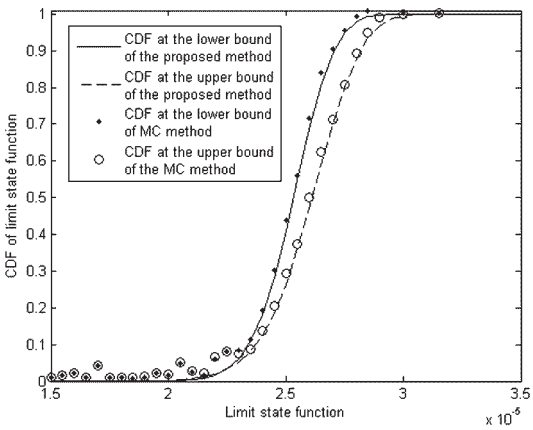

Fig. 3. CDF of the limit state function for disk edge design

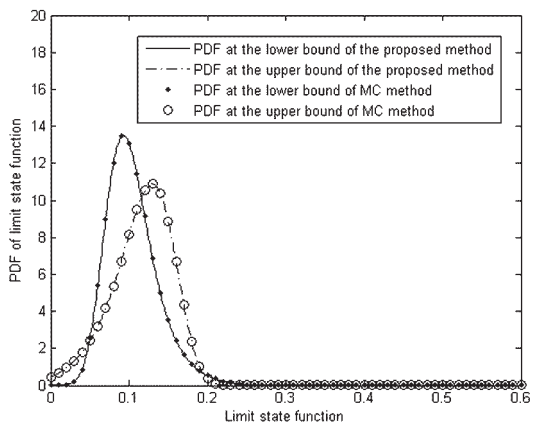

Fig. 4. PDF of the limit state function for clutch

The confidence interval of the first four moments for the limit state function are given in Table 4. And the PDF of the limit state function at the bounds are expressed by Eq. (13) and Eq. (14).

The comparisons for the PDF and CDF of the limit state function from the proposed method and MCS are displayed in Fig. 4 and Fig. 5, respectively.

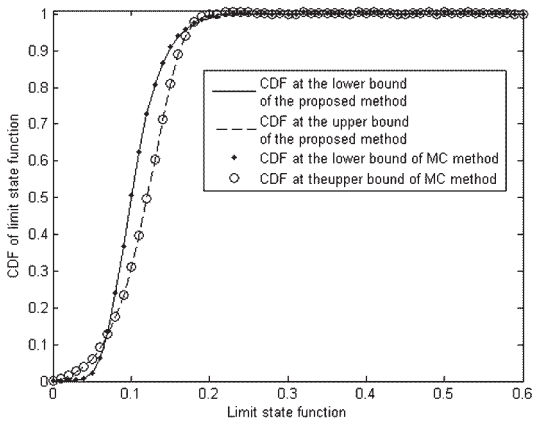

Fig. 5. CDF of the limit state function for clutch

6. Conclusions

In this paper, an uncertainty analysis method with bootsrapping method combined maximum entropy method is proposed. The exact distribution functions of some random variables are not determined using a limited mumber of observations. Therefore, the bootstrapping method is used to estimate the confidence intervals for the stochastic moments of the random variables. Further, the confidence interval of PDF and CDF for the limit state functions are calculated using maximum entropy approach.

In the proposed method, neither derivative nor the MPP search are needed. And the random variables are not needed to be transformed into standard normal distribution. The comparison of results form the proposed method with MC method presents the accuracy of the proposed method.

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CONDITION-BASED MAINTENANCE OPTIMISATION WITHOUT A PREDETERMINED STRATEGY STRUCTURE FOR A TWO-COMPONENT SERIES SYSTEM

OPTYMALIZACJA ZALEŻNEGO OD STANU TECHNICZNEGO UTRZYMANIA URZĄDZEŃ DLA DWUSKŁADNIKOWEGO SYSTEMU SZEREGOWEGO NIE WYMAGAJĄCA Z GÓRY USTALONEJ STRUKTURY STRATEGII

Most existing research on maintenance optimisation for multi-component systems only considers the lifetime distribution of the components. When the condition-based maintenance (CBM) strategy is adopted for multi-component systems, the strategy structure becomes complex due to the large number of component states and their combinations. Consequently, some predetermined maintenance strategy structures are often assumed before the maintenance optimisation of a multi-component system in a CBM context. Developing these predetermined strategy structure needs expert experience and the optimality of these strategies is often not proofed. This paper proposed a maintenance optimisation method that does not require any predetermined strategy structure for a two-component series system. The proposed method is developed based on the semi-Markov decision process (SMDP). A simulation study shows that the proposed method can identify the optimal maintenance strategy adaptively for different maintenance costs and parameters of degradation processes. The optimal maintenance strategy structure is also investigated in the simulation study, which provides reference for further research in maintenance optimisation of multi-component systems.

Keywords: *semi-Markov decision process, condition-based maintenance, multi-component system.*

Większość badań nad optymalizacją utrzymania systemów wieloskładnikowych bierze pod uwagę jedynie rozkład czasu życia elementów składowych. Kiedy przyjmie się dla systemów wieloskładnikowych strategię utrzymania urządzeń zależną od ich bieżącego stanu technicznego (condition-based maintenance, CBM), struktura strategii staje się złożona w związku z dużą liczbą stanów składowych oraz ich kombinacji. W konsekwencji, często przyjmuje się pewne z góry ustalone struktury strategii utrzymania przed optymalizacją utrzymania systemu wieloskładnikowego w kontekście CBM. Opracowanie takich z góry ustalonych struktur strategii wymaga jednak specjalistycznego doświadczenia, a i tak brak dowodów na optymalność tych strategii. W artykule zaproponowano metodę optymalizacji utrzymania szeregowego systemu dwuskładnikowego, która nie wymaga wcześniej ustalonej struktury strategii. Proponowaną metodę opracowano na podstawie semimarkowskiego procesu decyzyjnego (SMDP). Badanie symulacyjne pokazało, że za pomocą proponowanej metody można ustalać optymalną strategię utrzymania w sposób adaptacyjny dla różnych kosztów utrzymania oraz parametrów procesów degradacyjnych. Za pomocą symulacji badano także optymalną strukturę strategii utrzymania, jako punkt odniesienia dla przyszłych studiów nad optymalizacją systemów wieloskładnikowych.

Słowa kluczowe: *semimarkowski proces decyzyjny, condition-based maintenance, system wieloskładnikowy.*

1. Introduction

Most practical engineering assets are multi-component systems, i.e., they have more than one component. During optimising the maintenance of these multi-component systems, one needs to consider three interactions among components: economic dependence, stochastic dependence, and structural dependence. Economic dependence means that the cost of grouping maintenance can be different from the sum of individual maintenance costs. Stochastic dependence implies that degradation processes of different components influent each other. Structural dependence means that a certain group of components are connected together and should be replaced together. The three interactions make the maintenance strategy optimisation of a multi-component system much more complex than that of a mono-component system.

Various approaches have been developed to optimise the maintenance strategy of multi-component systems [9]. However, most of these approaches were based on the lifetime distribution of system components [5, 10-12]. Only few papers

discussed the maintenance optimisation for multi-component systems in the context of CBM. Van Der Duyn Schouten proposed two types of maintenance strategies for multi-component systems [15]. In that paper, an essential condition of a whole system replacement was that the number of components in the doubtful state exceeded a threshold. Gürler further optimised the threshold of the doubtful state based on the research of Van Der Duyn Schouten [3]. Castanier developed a more flexible maintenance strategy; the state dependent inspection interval was adopted in the research [1]. Based on the research by Castanier, Naini considered both preventive replacement and imperfect preventive maintenance to optimise the maintenance strategy of a two-component system [8]. In that paper, the inspection interval was simplified as state independent. These existing approaches to optimising the CBM strategy of multi-component systems largely predetermined maintenance strategy structures. The optimality of these predetermined structures have not been proofed or discussed. Furthermore, identifying an appropriate predetermined maintenance strategy structure also requires expert knowledge and experience that is not always available in reality. Therefore, a maintenance optimisation method that does not require a predetermined strategy structure is more applicable in reality and can be more cost-effective.

This paper proposes a maintenance optimisation approach for multi-component systems without a predetermined strategy structure using the semi-Markov decision process (SMDP). When maintenance strategy optimisation is carried out based on the Markov decision process (MDP) or the SMDP, the optimal maintenance structure can be identified simultaneously with the optimal strategy. Therefore, the MDP and the SMDP are widely used in the maintenance strategy optimisation and the optimal strategy structure investigation of mono-component systems [2, 7, 14, 18]. However, the application of SMDP to multi-component systems is still inadequate. A critical reason is that the health state of a multi-component system is difficult to be expressed, which makes the construction of the relative cost functions for SMDP become challenging. This paper divides the degradation process of a multi-component system into three stages, i.e., normal, partially failed, and completely failed. A SMDP is then developed for the maintenance optimisation of a two-component system. In addition, the optimal maintenance strategy structure of the two-component system under various situations is also investigated.

The body of this paper is organised as follows: Section 2 introduces the formulations of the degradation process of a two-component system and the costs of related maintenance activities. After that, a SMDP for the two-component system is developed in Section 3. The performance of the proposed maintenance optimisation method is investigated by simulation studies in Section 4. Section 4 also investigates the structure property of the optimal maintenance strategy for the two-component system.

2. Description of the System

2.1. The Degradation Model

A two-component system is investigated in this paper. The degradation processes of both components are assumed to follow the stationary Gamma process that are formulated as

$$. \lambda^u(t+\Delta t)-\lambda^u(t) \sim Ga(a_u \cdot \Delta t, \xi_u) \quad u=1,2 \qquad (1)$$

Here, $\lambda^u(t)$ denotes a degradation indicator of Component u at time t, and $Ga(a_u \cdot \Delta t, \xi_u)$ presents the Gamma distribution with the shape parameter $a_u \cdot \Delta t$ and the scale parameter ξ_u. When the process $\lambda^u(t)$ exceeds a failure threshold L_u, Component u fails. Component u is in a perfect health state when $\lambda^u(t)=0$. The Gamma process is monotonically increasing, which is consisted with the irreversible degradation process of most engineering assets. Therefore, the Gamma process is widely used in degradation modelling [16, 17]. The degradation processes of the two components are assumed to be independent from each other, i.e. the stochastic dependence is not considered in this paper.

The two components are assumed to be connected in series, and the whole system suffers from a failure when one of the two components is failed. The failure of the system cannot be detected immediately. However, operating the system in a failure condition will cause an additional cost, and the normal component still degrades even if the system is operating in a failure condition. A practical example of this scenario is a production line that consists of two machines, and each machine produces a certain part of a product. If one machine fails to produce qualified parts, the final product cannot meet the specifications and the production line is considered as failed. However, the failure of the production line may be not detected until an inspection is conducted on the two machines or final products.

2.2. Maintenance Related Costs and Durations

In this paper, three types of maintenance activities are considered, i.e., inspection, preventive replacement, and corrective replacement. The inspection is assumed to be able to completely reveal the state of the two components. Each inspection entails a cost C_i. Inspections are scheduled according to the health state of the two components to avoid unnecessary inspections. A preventive replacement action for Component u is conducted at a cost C_{pu}, while the cost of corrective replacement for Component u is C_{cu}. The preventive replacement cost is lower than the corrective replacement cost, i.e., $C_{pu} < C_{cu}$. In this paper, both the preventive and corrective replacement can bring a component to an "as good as new" state ($\lambda^u(t)=0$). Any preventive replacement or corrective replacement activity brings about a system set-up cost C_s. The set-up cost is caused by the dismantling and the reassembly of the system, or production losses during the system maintenance. The set-up cost is incurred only once for a group of replacement actions performed simultaneously. For example, correctively replacing the whole system costs $C_s + C_{c1} + C_{c2}$. Subsequently, economic dependence exists between the two components if $C_s > 0$. Besides the cost of maintenance activities, running the system in a failure state will cause an additional cost c_d per unit time. The cost rate c_d is assumed to be significant and therefore leaving the system failure after an inspection is not optimal.

In this paper, the expected cost incurred by failure and maintenance activities per unit time is adopted as the criterion of maintenance optimisation. The durations of replacement and inspections can be ignored compared to the life time of components. Resources to carrying out inspections and replacement activities are assumed to be always adequate. The minimum reliability and availability constrains are not considered in this research as well.

3. The Semi-Markov Decision Process Approach

3.1. The Representation of System States and Transitions

Different from a mono-component system, the failure of the two-component system can be caused by the failure of one component or the failures of both the two components. The optimal maintenance action and relative costs in the SMDP under the two situations may be different. Consequently, the states of the two-component system are divided into three types, i.e., normal, partially failed, and completely failed. The normal system state implies that both the two components are running in a normal state. The partially failed system state means that one component is failed, while the other component is still in a normal state. In the completely failed situation, both the two components are in a failure state.

To apply the SMDP, the continuous degradation process of Component u is discretised into M_u different states. The state of Component u at time epoch t is then represented by $x_t^u = 1,2,\ldots,M_u \quad u=1,2$, where the state $x_t^u = 1$ denotes the "as good as new" state and the state $x_t^u = M_u$ stands for the failure state. By combining component states, the system state at time is given by:

$$x_t = \begin{cases} \left(x_t^1 - 1\right)\cdot\left(M_2 - 1\right) + x_t^2 & x_t^1 < M_1, x_t^2 < M_2 \\ \left(M_1 - 1\right)\left(M_2 - 1\right) + x_t^2 & x_t^1 = M_1, x_t^2 < M_2 \\ M_1\left(M_2 - 1\right) + x_t^1 & x_t^1 < M_1, x_t^2 = M_2 \\ M_1 M_2 & x_t^1 = M_1, x_t^2 = M_2 \end{cases} \tag{2}$$

Equation (2) divides the system states into four subsets: when $x_t^1 < M_1, x_t^2 < M_2$, the system is in a normal state; when $x_t^1 = M_1, x_t^2 < M_2$, the system is partially failed, and the failed component is Component one; when $x_t^1 < M_1, x_t^2 = M_2$, the system is failed, and the failed component is Component two; when $x_t^1 = M_1, x_t^2 = M_2$, the system is completely failed. To facilitate the formulation of the SMDP, the state of an individual component given the system state is presented as:

$$x_t^u = g_u\left(x_t\right) \quad u = 1,2 \tag{3}$$

After discretisation, the degradation process x_t^u becomes a continuous time discrete state Markov Chain, and the transition matrix during an interval Δt can be approximated as:

$$\left(\mathbf{P^u}\left(\Delta t\right)\right)_{ij} = p_{i,j}^u\left(\Delta t\right) = \Pr\left(LL_j^u \le \lambda^u\left(t+\Delta t\right) \le UL_j^u \middle| \lambda^u\left(t\right) = \frac{LL_i^u + UL_i^u}{2}\right), \tag{4}$$

where, UL_i^u and LL_i^u denote the upper limit and the lower limit of the i th state of Component u, respectively. The degradation indicator before discretisation, i.e., $\lambda^u\left(t\right)$, follows the Gamma process as in Equation (1). Consequently, Equation (4) can be calculated according to the property of the Gamma process. Because the two components degrade independently, the transition matrix for the system is obtained as:

$$\left(\mathbf{P}\left(\Delta t\right)\right)_{ij} = p_{g_1(i),g_1(j)}^1\left(\Delta t\right)\cdot p_{g_2(i),g_2(j)}^2\left(\Delta t\right) \tag{5}$$

Similarly, the reliability of the system after Δt given that the current system state is i can be calculated as:

$$R\left(\Delta t|i\right) = \prod_{u=1}^{2}\Pr\left(\lambda^u\left(t+\Delta t\right) \le L^u \middle| \lambda^u\left(t\right) = \frac{LL_i^u + UL_i^u}{2}\right), \tag{6}$$

which can be calculated according to the property of the Gamma process [16]. The expected survival time of the system starting at state i during a time interval Δt can be then derived as:

$$\tau\left(\Delta t|i\right) = \int_0^{\Delta t} R\left(s|i\right)ds \tag{7}$$

3.2. The Relative Cost Functions

The relative cost function that formulates the relative cost of a single step in the long-run decision process is a crucial part of constructing and solving the SMDP [6]. In this paper, the relative cost function is a function of the current system state x_t. When the system is in a normal state, i.e., $x_t^1 < M_1$ and $x_t^2 < M_2$, four alternative maintenance activities are available. One is performing an inspection after a certain period of time. The waiting duration till the next inspection depends on the current state of the two system components. The others are preventively replacing Component one, preventively replacing Component two, and conducting a complete system replacement. The relative cost function for a normal system state can be then written as:

$$V\left(x_t\right) = \min\left\{V_{IN}\left(x_t, n_I\Delta_{ID}\right), V_{PR1}\left(x_t\right), V_{PR2}\left(x_t\right), V_{PRAll}; n_I = 1,2,\ldots,N_I\right\} \tag{8}$$

Here, $V_{IN}\left(x_t, n_I\Delta_{ID}\right)$ denotes the relative cost of performing an inspection after a period $n_I\Delta_{ID}$ when the current system sate is x_t, and $N_I\Delta_{ID}$ is the maximum waiting time for the next inspection. The notation Δ_{ID} can be regarded as the minimum time unit of inspection intervals considered in a maintenance strategy. Theoretically, reducing Δ_{ID} can enhance the accuracy of the optimal strategy. However, in reality, the value of Δ_{ID} should be selected based on the application. An unpractical short Δ_{ID} is not beneficial and makes the strategy difficult to implement. For example, when the maintenance strategy of the engine in a locomotive is investigated, Δ_{ID} can be a week instead of an hour. The function $V_{PRu}\left(x_t\right) \quad u=1,2$ is the relative cost when only Component u is preventively replaced. The variable V_{PRAll} is the relative cost of a complete preventive system replacement.

When the system is partially failed ($x_t^u = M_u, x_t^{i\neq u} < M_i$), there are also two optional strategies. One is replacing the failed component only, and the other is a complete system replacement. The corresponding relative cost function is given by:

$$V\left(x_t\right) = \min\left\{V_{PRu}\left(x_t\right), V_{PRAll}\right\} - C_{pu} + C_{cu} \quad u = 1,2 \tag{9}$$

Because a corrective replacement is performed to Component u, the difference between the costs of a corrective re-

placement activity and a preventive replacement activity should be added to Equation (9).

When the system is failed completely ($x_t^1 = M_1, x_t^2 = M_2$), the only possible maintenance activity is complete corrective system replacement, and the relative cost function is as follows:

$$V(x_t) = C_s + C_{c1} + C_{c2} + V(1) \quad (10)$$

Here, $V(1)$ denotes the relative cost function starting at the "as good as new" system state, i.e., $x_t^1 = 1$, $x_t^2 = 1$.

In Equation (8), the relative cost of conducting an inspection after a given time interval Δt starting at system state $x_t = i$ is calculated as:

$$V_{IN}(x_t = i, \Delta t) = C_i + \sum_{j=i}^{M_1 M_2} V(j)\, p_{i,j}(\Delta t) - \gamma \cdot \Delta t + c_d \cdot \left(\Delta t - \tau(\Delta t | i)\right) \quad (11)$$

,

where, γ is the expected cost incurred by failure and maintenance activities per unit time and $p_{i,j}(\Delta t)$ is an element in the system transition matrix during the time interval Δt. The relative cost of preventively replacing Component one and two given that the current system state x_t is i are given by:

$$V_{PR1}(x_t = i) = C_s + C_{p1} + V(g_2(i)) \quad (12)$$

and

$$V_{PR2}(x_t = i) = C_s + C_{p2} + V\left((g_1(i) - 1) \cdot (M_2 - 1) + 1\right) \quad (13)$$

respectively. The relative cost for a complete system preventive replacement which is state independent can be calculated as:

$$V_{PRAll} = C_s + C_{p1} + C_{p2} + V(1). \quad (14)$$

3.3. The Policy Iteration

After the relative cost functions are constructed, the policy iteration is used to find the optimal maintenance policy that minimises the expected cost per unit time. A policy is denoted as $\delta(A) = B$, where $A = 1, 2, \ldots, M_1 \cdot M_2$ is a certain discretised system state derived by Equation (2) and B is the corresponding maintenance action. For a normal system state, the maintenance action can be chosen from:

$$B \in \{(IN, n_I \Delta_{ID}), PR_1, PR_2, PR_{all}; n_I = 1, 2, \ldots, N_I\}.$$

The first candidate maintenance activity $(IN, n_I \Delta_{ID})$ implies performing an inspection after a duration $n_I \Delta_{ID}$. The other optional maintenance actions PR_1 , PR_2 , and PR_{all} denote preventively replacing Component one, preventively replacing Component two, and complete system preventive replacement, respectively. When only Component u is failed, the maintenance action space becomes $B \in \{CR_u, CR_u + PR_{i \neq u}\}$. Here, the maintenance action CR_u denotes correctively replacing Component u , while the $CR_u + PR_{i \neq u}$ represents correctively replacing Component u and preventively replacing the other component at the same time. For complete failure, the determinate maintenance action is complete system corrective replacement, i.e., $CR_1 + CR_2$.

The general process of the policy iteration is as shown in Table 1. For a more detailed introduction of the policy iteration, readers can refer to [7, 13].

Table 1: The process of policy iteration

Step 1:

Set an initial policy function

The initial policy function is selected by the rule of thumb, and any policy satisfies the conditions discussed at the beginning of Section 3.3 can be adopted as the initial policy.

Step 2:

Calculate the relative costs $\{V(A); A = 2, 3, \ldots, M_1 M_2 - 1\}$ and the expected cost per unit time γ by solving the following system of linear equations that is constructed according to the current maintenance policy $\delta_k(\cdot)$:

$$V(A)=\begin{cases} I_{(IN,n_I\Delta_{ID})}(\delta_k(A))\cdot V_{IN}(A,n_I\Delta_{ID}) \\ +I_{PR_1}(\delta_k(A))\cdot V_{PR1}(A) \\ +I_{PR_2}(\delta_k(A))\cdot V_{PR2}(A)+I_{PR_{all}}(\delta_k(A))\cdot V_{PRAll} & ,2\le A\le (M_1-1)(M_2-1) \\ \\ I_{CR_1}(\delta_k(A))\cdot V_{PR1}(A) \\ +I_{CR_1+PR_2}(\delta_k(A))\cdot V_{PRAll}-C_{p1}+C_{c1} & ,(M_1-1)(M_2-1)<A\le M_1(M_2-1) \\ \\ I_{CR_2}(\delta_k(A))\cdot V_{PR2}(A) \\ +I_{PR_1+CR_2}(\delta_k(A))\cdot V_{PRAll}-C_{p2}+C_{c2} & ,M_1(M_2-1)<A<M_1M_2 \end{cases},$$

where the formulations of , $V_{PR1}(A)$, $V_{PR2}(A)$ and are given by Equations (11), (12), (13), and (14) respectively, and is the indicator function given by:

$$I_B(x)=\begin{cases} 0, & x\ne B \\ 1, & x=B \end{cases} \qquad (15)$$

The relative cost functions when the system is brand new and completely failed are determinate, i.e., and $V(M_1M_2)=C_s+C_{c1}+C_{c2}$.

Step 3:

Calculate the relative costs under different maintenance actions:
$V_{IN}(A,n_I\Delta_{ID})$, $A=2,3,\ldots,(M_1-1)(M_2-1)$, $n_I=1,2,\ldots,N_I$,
$V_{PR1}(A)$, $A=2,3,\ldots,M_1M_2-1$
and
$V_{PR2}(A)$, $A=2,3,\ldots,M_1M_2-1$
given by Equations (11), (12), and (13) using the values of $\{V(A);A=2,3,\ldots,M_1M_2-1\}$ and γ obtained in Step 2.

Step 4:

Obtain the improved policy function $\delta_{k+1}(\cdot)$ using the relative costs calculated in Step 3. The $\delta_{k+1}(\cdot)$ is identified piecewisely as:

When the system is in a normal state, i.e., $1\le A\le (M_1-1)(M_2-1)$, the policy function is:

$$\delta_{k+1}(A)=\begin{cases} (IN,l\cdot\Delta_{ID}), & V_{IN}(A,l\cdot\Delta_{ID})=\min\{V_{IN}(A,n_I\Delta_{ID}),V_{PR1}(A),V_{PR2}(A),V_{PRAll};n_I=1,\ldots,N_I\} \\ PR_1, & V_{PR1}(A)=\min\{V_{IN}(A,n_I\Delta_{ID}),V_{PR1}(A),V_{PR2}(A),V_{PRAll};n_I=1,\ldots,N_I\} \\ PR_2, & V_{PR2}(A)=\min\{V_{IN}(A,n_I\Delta_{ID}),V_{PR1}(A),V_{PR2}(A),V_{PRAll};n_I=1,\ldots,N_I\} \\ PR_{all}, & V_{PRAll}=\min\{V_{IN}(A,n_I\Delta_{ID}),V_{PR1}(A),V_{PR2}(A),V_{PRAll};n_I=1,\ldots,N_I\} \end{cases}.$$

When only Component One is failed, i.e. $(M_1-1)(M_2-1)<A\le M_1(M_2-1)$, the policy function is:

$$\delta_{k+1}(A)=\begin{cases} CR_1, & V_{PR1}(A)<V_{PRAll} \\ CR_1+PR_2, & V_{PR1}(A)>V_{PRAll} \end{cases}.$$

When only Component Two is failed, i.e. $M_1(M_2-1)<A<M_1M_2$, the policy function is:

$$\delta_{k+1}(A)=\begin{cases} CR_2, & V_{PR2}(A)<V_{PRAll} \\ CR_2+PR_1, & V_{PR2}(A)>V_{PRAll} \end{cases}.$$

When both the two components are failed, i.e. $A=M_1M_2$, the whole system should be replaced, and the policy function is therefore predetermined as $\delta_{k+1}(A)=CR_1+CR_2$.

Step 5:

If $\delta_{k+1}(\cdot)=\delta_k(\cdot)$, the optimal maintenance policy $\delta^*(\cdot)$ is obtained as $\delta_k(\cdot)$. Otherwise, go to Step 2 and start a new iteration.

The most time-consuming part of the policy iteration algorithm in Table 1 is Step 2 that entails solving a system of linear equations with $M_1M_2 - 1$ variables. When the numbers of discretised states (i.e. M_1 and M_2) are large, some iterative methods (e.g. the Jacobi method and the Gauss–Seidel method) are required to solve the system of linear equations. Fortunately, according to the stimulation study in Section 4.2, the policy iteration can obtain a satisfactory approximate optimal maintenance strategy when the resolution of component state discretisation is moderate. Consequently, the system of linear equations in Step 2 is simply solved based on the LU decomposition. Another potential factor relates to the efficiency of the policy iteration is the number of possible inspection intervals N_I. A large N_I can reduce the efficiency of Step 3 and Step 4 in Table1. However, the value of does not change the number of variables in the system of linear equations in Step 2 which is the bottle-neck of the whole algorithm. Consequently, the number of optional inspection intervals does not increase the computing time of the policy iteration significantly.

4. The Simulation Study of the Proposed Approach

4.1. Investigation of the Optimal Maintenance Strategy Structures

Markov decision process (MDP) has been adopted to explore the maintenance strategy structure property of mono-component systems and multi-component systems based on lifetime distribution (i.e. two-state assumption) [4, 6]. However, these strategy structure properties cannot be simply extended to the CBM of multi-component systems. The structure of the CBM strategy of multi-component systems is much more complex due to the large number of component states and their combinations. To address this research gap, this study investigates structure properties of the CBM strategy of a continuous-state two-component system. The results can provide guidelines for approximate maintenance optimisation algorithms of multi-component systems in a CBM context. In addition, investigating the strategy structure can also validate the effectiveness of the proposed SMDP approach.

Maintenance Strategy Structures for Different Set-up Costs

The set-up cost is an important element in the maintenance optimisation of multi-component systems. When the set-up cost covers a considerable proportion of the maintenance cost, significant economic dependence among components exists, and the group maintenance should be adopted. Subsequently, the influence of different set-up costs on maintenance strategy structures were studied first. In this part of simulation study, parameters of system degradation processes and maintenance costs were selected without particular physical meaning, and were for illustrative purpose only. The parameters of the system degradation processes were set as follows: $a_1 = a_2 = 1$, $\xi_1 = \xi_2 = 1/3$, and $L_1 = L_2 = 2$. The inspection cost and the failure cost per unit time were assumed as $C_i = 1$ and $c_d = 10$. The shortest inspection interval was Δ_{ID} =0.2, and the corresponding N_I was selected as 15. As discussed in Section 3.2, the selection of Δ_{ID} is application-dependent in reality, and an unpractical short Δ_{ID} is not preferred. The value of N_I is initially selected by the rule of thumb, and may be modified according to the maintenance optimisation results. When the longest inspection interval in the obtained optimal strategy is equal to $N_I \cdot \Delta_{ID}$, a larger N_I should be used so that the policy iteration can access a potential optimal policy with a longer inspection interval.

First of all, a small set-up cost ($C_s = 1$) was considered, and costs for preventive and corrective replacement were selected as: $C_{p1} = C_{p2} = 39$ and $C_{c1} = C_{c2} = 99$, respectively. After the policy iteration, a minimum average cost per unit time $\gamma = 19.4894$ was derived. The result of the policy iteration is presented as the matrix in Figure 1. Each colour standards for a particular type of maintenance action; the numbers in white rectangles are the waiting durations till the next inspection. Because the degradation processes and the maintenance costs of the two components are the same, the policy matrix is symmetrical about the diagonal line. Figure 1 also shows that the optimal maintenance action for a component is not monotonic in State 9. Preventive replacement for the component in State 9 is required, when the state of the other component is below state 6. On the other hand, a further inspection is optimal when the other component is in State 7 and State 8. A complete system replacement is required when both the components are in or above state 9. This unexpected optimal maintenance structure is caused by the economic dependence: When the other component degrades to a state near the preventive replacement threshold, a more economical way is leaving the component in State 9 along and performing complete system replacement later. To demonstrate the effects of this non-monotonic structure, a monotonic strategy in Figure 2 was also adopted, and the average cost per unit time was $\gamma = 19.5157$. Therefore, the non-monotonic strategy in Figure 1 was more cost-effective.

Then a significant set-up cost ($C_s = 20$) was adopted. To maintain the replacement costs for an individual component (i.e., $C_s + C_{pu}$ and $C_s + C_{cu}$) unchanged, the costs for preventive and corrective replacement were selected as $C_{p1} = C_{p2} = 20$ and $C_{c1} = C_{c2} = 80$, respectively. After the policy iteration, the minimum average cost per unit time was calculated as $\gamma = 17.3396$ and the optimal strategy is presented in Figure 3. Finally a more significant set-up cost ($C_s = 30$) was used, and the costs for replacement were $C_{p1} = C_{p2} = 10$ and $C_{c1} = C_{c2} = 70$. Using the policy iteration, the minimum average cost per unit time was obtained as $\gamma = 15.4537$ and the optimal maintenance strategy is shown in Figure 4.

Some conclusions can be drawn from the maintenance optimisation results for the three different set-up costs. Firstly, the cost reduction by introducing opportunistic maintenance is more significant when the set-up cost covers a larger proportion of the total replacement cost. Secondly, the non-monotonic part of the strategy and the threshold for opportunistic replacement is near the "as good as new" state for a large set-up cost. Finally, besides opportunistic replacement, complete system replacement is required when the two components are both near but still below the preventive replacement thresholds. More cost-effective maintenance strategy structures are expected after the non-monotonic properties that are derived by this simulation study are described appropriately.

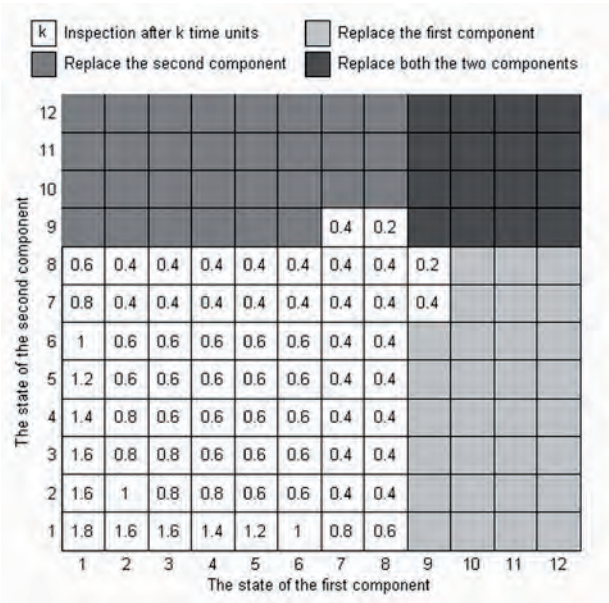

Fig. 1. The optimal maintenance strategy when $a_1 = a_2 = 1$, $\xi_1 = \xi_2 = 1/3$, $C_s = 1$, $C_{p1} = C_{p2} = 39$, *and* $C_{c1} = C_{c2} = 99$

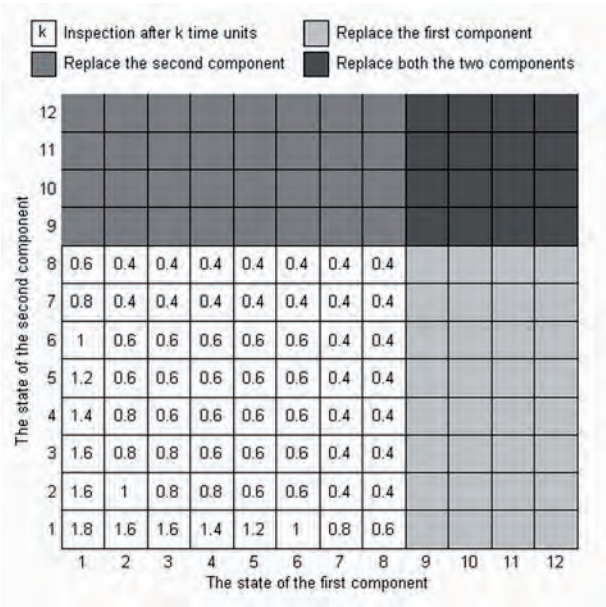

Fig. 2. The monotonic maintenance strategy when $a_1 = a_2 = 1$, $\xi_1 = \xi_2 = 1/3$, $C_s = 1$, $C_{p1} = C_{p2} = 39$, *and* $C_{c1} = C_{c2} = 99$

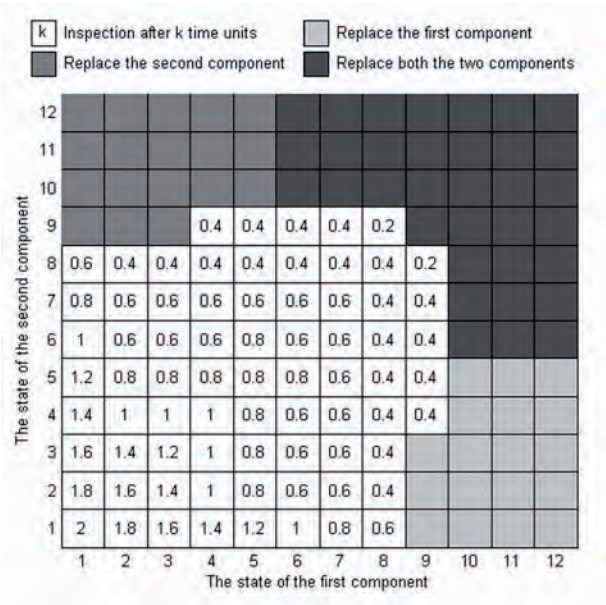

Fig. 3. The optimal maintenance strategy when $a_1 = a_2 = 1$, $\xi_1 = \xi_2 = 1/3$, $C_s = 20$, $C_{p1} = C_{p2} = 20$, *and* $C_{c1} = C_{c2} = 80$

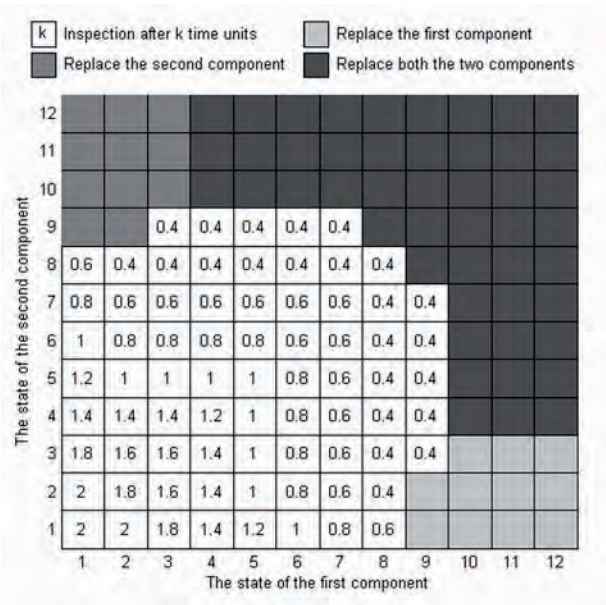

Fig. 4. The optimal maintenance strategy when $a_1 = a_2 = 1$, $\xi_1 = \xi_2 = 1/3$, $C_s = 30$, $C_{p1} = C_{p2} = 10$, *and* $C_{c1} = C_{c2} = 70$

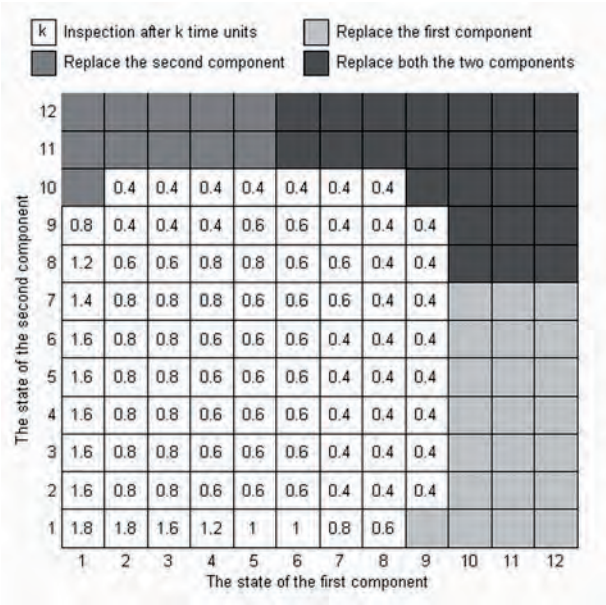

Fig. 5. The optimal maintenance strategy when $a_1 = a_2 = 1$, $\xi_1 = 0.5$, $\xi_2 = 1/6$, $C_s = 20$, $C_{p1} = C_{p2} = 30$, *and* $C_{c1} = C_{c2} = 80$

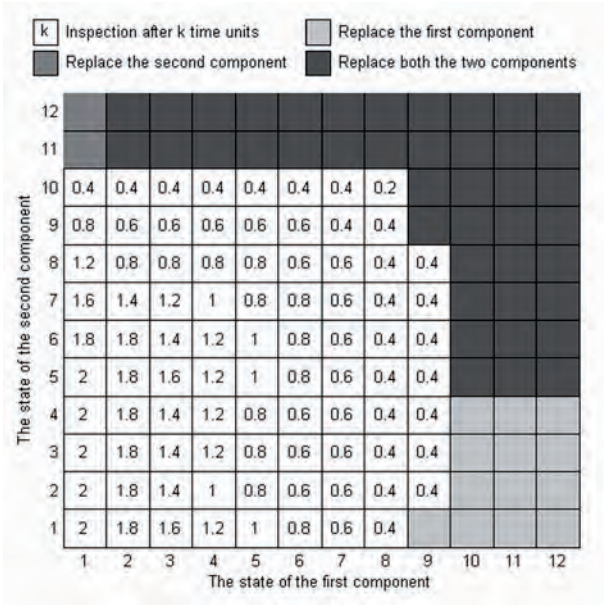

Fig. 6. The optimal maintenance strategy when $a_1 = a_2 = 1$, $\xi_1 = 0.5$, $\xi_2 = 1/6$, $C_s = 47$, $C_{p1} = C_{p2} = 3$, *and* $C_{c1} = C_{c2} = 53$

Maintenance Strategy Structures for Different Degradation Process Parameters

Different from the methods developed in [3, 15], the approach proposed in this paper can process a system whose components follow different degradation processes. This part of simulation study explores the influence of process parameters on maintenance strategy structures. The parameters for the degradation processes of the two components were $a_1 = a_2 = 1$ and $\xi_1 = 0.5$, $\xi_2 = 1/6$. A larger scale parameter ξ_u $u = 1, 2$ indicates a faster degradation process. Therefore, Component one degrades more quickly. Two sets of maintenance costs were used: $C_s = 20$, $C_{p1} = C_{p2} = 30$, $C_{c1} = C_{c2} = 80$ and $C_s = 47$, $C_{p1} = C_{p2} = 3$, $C_{c1} = C_{c2} = 53$. The minimum average cost per unit time for the two situations were $\gamma = 21.4651$ and $\gamma = 18.5801$, respectively. The corresponding maintenance strategies are showed in Figure 5 and Figure 6.

Figure 5 and Figure 6 show that lower preventive and opportunistic thresholds are set for Component one due to the faster degradation process of that component. Consequently, the strategy structures become unsymmetrical about the diagonal line. The difference between Figure 5 and Figure 6 shows that the proposed SMDP can adaptively identify the maintenance strategy structure according to different maintenance costs and degradation process parameters.

4.2. Influence of the Number of Discretised Intervals

The system state space is discretised to perform the SMDP, which can introduce errors into the estimate of average cost per unit time. The discretised system state space also leads thresholds for preventive and corrective replacement to be less accurate. Increasing the number of states can reduce the errors that are brought in by discretisation. However, the consumed memory and elapsed time increase quickly with the resolution of the system state space. Therefore, it is necessary to find a balance between the accuracy of a maintenance strategy and the length of computing time.

In this part of simulation study, different numbers of discretised component states were trailed to investigate the relationship between the effectiveness of the maintenance strategy and the elapsed time of the policy iteration. The effectiveness of the maintenance strategy was evaluated through the average cost per unit time of a simulated degradation process. The parameters of the degradation processes were selected as and ; the costs of maintenance actions were $a_1 = a_2 = 1$, $\xi_1 = \xi_2 = 1/3$, and $C_s = 30$. To explore the effects of the resolution of the component states, four different numbers of discretised component states were adopted, i.e., $M_1 = M_2 = 7$, $M_1 = M_2 = 12$, $M_1 = M_2 = 22$, and $M_1 = M_2 = 32$. For the three different resolutions, the policy iteration was carried out and elapsed durations were recorded. The derived maintenance strategies were applied to a simulated degradation process of 106 unit time length. The simulated average costs per unit time were calculated to compare with the approximated results derived by the policy iteration. The results are demonstrated in Figure 7.

Figure 7 shows that the approximated average costs are lower than the simulated average costs, and the difference between the two costs reduces with the growth of the number of discretised states. The increase of the approximated average costs is caused by the reduction of errors in the policy iteration, and the decrease of the simulated average cost is due to more accurate thresholds in maintenance strategies. Figure 7 also shows that when , adopting a finer resolution of component states cannot save the simulated average cost significantly, while the elapsed time is considerably longer. The simulated average cost per unit time when $M_1 = M_2 = 22$ and $M_1 = M_2 = 32$ were 15.6524 and 15.6398, respectively. The corresponding elapsed

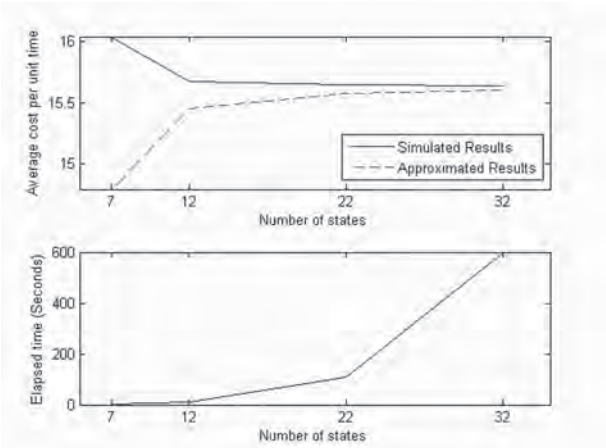

Fig. 7. The simulated and approximated average cost per unit time and the elapsed time

durations were 106.8 seconds and 597.3 seconds. This small variance between the two simulated average costs shows that the proposed approach is able to identify an approximate global optimal strategy for a continuous state two-component system without a predetermined strategy structure.

5. Conclusions

This paper has developed a SMDP approach to optimise the maintenance strategy of a multi-component system without a predetermined strategy structure. The state of the multi-component system has been divided into three different types: normal, partially failed, and completely failed to construct the relative cost function and perform the policy iteration. Compared with other existing approaches, the proposed SMDP do not need to predetermine the maintenance structure and the number of inspection intervals. Therefore, the SMDP developed in this paper is more adaptive and applicable in reality. Furthermore the SMDP divides the long-term degradation process into single time steps. Consequently, the SMDP approach is easier to be carried out in more complex practical situations, e.g., imperfect maintenance, state-dependent maintenance cost, and state-dependent maintenance durations. In addition, the SMDP uses the transition matrix to express the system degradation process. Therefore, the stochastic dependence and the structure dependence can be also processed by the proposed approach when the transition matrix of system states is established.

This research has also explored the structure property of the optimal CBM strategy for a two-component system through a simulation study. The results can provide a guideline to develop an approximate optimal maintenance strategy for multi-component systems. The simulation study also shows that the proposed approach using the SMDP can provide satisfactory optimisation results for a continuous state two-component system. For a more complex multi-component system with intractable number of component state combinations, approximate solving methods for the SMDP can be adopted.

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RELIABILITY ANALYSIS OF MECHANICAL VIBRATION COMPONENT USING FUZZY SETS THEORY

ANALIZA NIEZAWODNOŚCIOWA MECHANICZNEGO ELEMENTU WIBRACYJNEGO Z WYKORZYSTANIEM TEORII ZBIORÓW ROZMYTYCH

The conventional reliability analysis of mechanical vibration component only considers the randomness of vibration but rarely for the fuzziness that may exist. It is therefore difficult to be consistent with the engineering practices. Based on the mechanical vibration theory, a novel fuzzy reliability approach by integrating the fuzzy comprehensive evaluation and fuzzy set theory is proposed in this paper. The fuzzy comprehensive evaluation is used to optimize the fuzzy factors of the reliability analysis of vibration component. With the aim of comparing the performance of the proposed approach with the conventional approach, two engineering examples are presented. The results demonstrate that the proposed approach is better than the conventional approach for its capability of covering fuzzy factors in the engineering problems.

Keywords: *reliability analysis, mechanical vibration, fuzzy reliability, fuzzy comprehensive evaluation.*

Tradycyjna analiza niezawodnościowa wibracyjnego elementu mechanicznego bierze pod uwagę jedynie losowość drgań, rzadko zaś wyjaśnia mogącą występować rozmytość. Taka analiza nie odpowiada zatem praktyce inżynierskiej. Opierając się na teorii drgań mechanicznych, w niniejszym artykule zaproponowano nowatorskie podejście w ramach teorii rozmytej niezawodności, które łączy rozmytą ocenę kompleksową oraz teorię zbiorów rozmytych. Rozmytej oceny kompleksowej użyto do optymalizacji rozmytych czynników analizy niezawodnościowej elementu wibracyjnego. W celu porównania efektywności proponowanego podejścia z efektywnością podejścia tradycyjnego przedstawiono dwa przykłady z dziedziny inżynierii. Wyniki pokazują, że proponowane podejście jest lepsze od tradycyjnego ze względu na możliwość objęcia w problemach inżynierskich czynników rozmytych .

Słowa kluczowe: *analiza niezawodnościowa, drgania mechaniczne, niezawodność rozmyta, rozmyta ocena kompleksowa.*

1. Introduction

Many component failures of engineering systems are related to vibration [12]. The conventional reliability analysis approach is purely based upon the probabilitistic reliability theory and mechanical vibration theory [3-6]. However, it is assumed that components or systems only have two states, either perfect working or completely failed in the conventional reliability theory [1]. The assumption implies that the state of components or systems can be exactly identified and furthermore there are no intermediate states between these two states. Nevertheless, it is widely observed in the engineering practices that the performance of systems may degrade during their lifetime [8, 14]. On the other hand, it is very difficult or even impossible to collect accurate and sufficient failure data in some real systems when quantifying the reliability characteristics, especially for those systems which consist of new components or components with extremely low failure rates [9, 11]. Many uncertainty factors in mechanical vibration could not be covered only with probability theory. To address the issues, a novel fuzzy reliability analysis method by integrating the fuzzy comprehensive evaluation [7] and fuzzy set theory is developed to analyze the reliability of vibration component.

The organization of this paper is as follows. In Section 2, the analysis of mechannical vibration is briefly reviewed. The fuzzy comprehensive evaluation is introduced in Section 3. In Section 4, fuzzy reliability analysis of vibration components is presented. Two engineering examples are followed to illustrate the proposed method in Section 5. Conclusions are provided in Section 6.

2. Analysis of mechanical vibration

The speed when the resonance occurs is called the critical speed. Critical speed analysis is very important and may be quite complex. Due to the randomness of the load and geometrical shape of components, the critical speed of the vibration component could usually not be expressed by a constant, but a special region with a given probability. Hence, the critical

speed has discreteness, which reflects in the special performance. For example, the vibration component has no certain accurate frequency. Amplitude, frequency and phase angle of vibration is not deterministic but random at a given time.

In mechanical vibration theory, the machinery has many critical speeds with different orders in nature. When the running speed is close to the first order critical speed, the state is the most dangerous. Hence we often consider the first order critical speed because the effect of the higher orders could be ignorable. It is required that the running speed does not fall into the resonant region which is determined by the experimental data and the natural frequency of component during the process of calculating vibration of mechanical component. Let n_c and n denote the critical speed and the running speed respectively. Thus the range of running speed has the following properties [2].

If $n < n_c$, then $n < n_c(1-\delta_1)$ and $0 < \delta_1 < 0.3$

If $n > n_c$, then $n > n_c(1+\delta_2)$ and $0 < \delta_2 < 0.3$

where δ_1 and δ_2 are fuzzy factors affecting the reliability of vibration component.

Assume that the critical speed n_c is a random variable with normal distribution, and running speed n is a constant. From the above formulas, in the conventional reliability analysis of mechanical vibration component, when the random variable n_c is over $n/(1-\delta_1)$ or below $n/(1+\delta_2)$, the failure will not occur. When the value of n_c falls into the range from $n/(1+\delta_2)$ to $n/(1-\delta_1)$, the failure will occur. This relationship is illustrated in Fig. 1. In Fig. 1, the dash line represents the characteristic function.

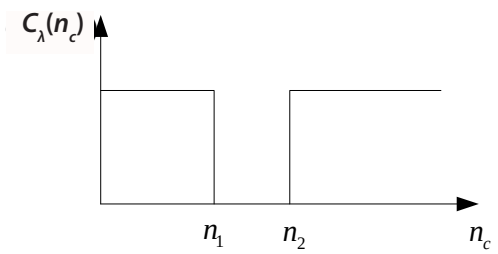

Fig. 1. Characteristic function

The reliability of mechanical vibration component is the probability that no resonance occurs. In other words, the running speed should be not close to the critical speed. The reliability can be computed by:

$$R = \int_{-\infty}^{n_1} f(x)\mathrm{d}x + \int_{n_2}^{+\infty} f(x)\mathrm{d}x \tag{1}$$

where $f(x)$ is the probability density function of the critical speed n_c .

When the critical speed follows a normal distribution with the mean value μ and the standard deviation σ , the reliability is expressed by:

$$R = 1 - [\Phi((n_2-\mu)/\sigma) - \Phi((n_1-\mu)/\sigma)] \tag{2}$$

where $[\Phi((n_2-\mu)/\sigma) - \Phi((n_1-\mu)/\sigma)]$ denotes the failure probability of vibration component.

From the above analysis, it can be concluded that the values of δ_1 and δ_2 are important to reliability analysis of mechanical vibration component because these values directly determine the failure region. Many factors would impact on the selection of the values of δ_1 and δ_2 . Hence, factors associated with the selection of the values of δ_1 and δ_2 must be considered comprehensively. In this paper, the fuzzy comprehensive evaluation is developed to determine the value of δ_1 and δ_2 by considering the fuzziness.

3. Fuzzy comprehensive evaluation

The selection of values of δ_1 and δ_2 involves some different kinds of information of systems. However, when there is no available information, it is usually assumed $\delta_1 = \delta_2 = 0.15$ [10]. In other cases, especially involving much information about influence factors, fuzzy comprehensive evaluation can be used to determine the values of δ_1 and δ_2 via fuzzy transformation principle. The procedure of evaluation is summarized as follows.

3.1. Determine factor set and evaluation set

Let $U=\{u_1,u_2,...,u_n\}$ be a set consisting of m influence factors, which represent the attributes of a system. The set is called a factor set. It should be noted that the factors in the factor set often possess fuzziness.

Let $V=\{v_1,v_2,...,v_n\}$ be a set consisting of n remarks, which could be obtained by accounting for the lower and upper boundaries of V, and it is called the evaluation set. V could be determined by the boundaries of V and the number of steps. The aim of fuzzy comprehensive evaluation is to select the optimal result from the evaluation set based on the factor set. Obviously, for each v_i, there are only two options: belonging to this remark or not. Therefore, the evaluation set is a classic set.

3.2. Constructing fuzzy evaluation matrix

First, let $\tilde{R}_i$ be a single-factor fuzzy evaluation set and be expressed as $\tilde{R}_i = (r_{i1}, r_{i2}, \cdots, r_{in})$, where r_{ij} is the membership degree with respect to the remark v_j in terms of the factor u_i. Then, let $\tilde{R}$ be a fuzzy evaluation matrix and be expressed as:

$$\tilde{R} = \begin{bmatrix} \tilde{R}_1 \\ \tilde{R}_2 \\ \vdots \\ \tilde{R}_m \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$

where $\tilde{R}_i = (r_{i1}, r_{i2}, \cdots, r_{in})$, the ith row in the matrix $\tilde{R}$, is the single-factor evaluation of the ith factor μ_i , which is a fuzzy subset on V. $(U, V, \tilde{R})$ is called a comprehensive evaluation model.

3.3. Comprehensive evaluation

Let $\tilde{W} = (w_1, w_2, \cdots, w_m)$ be a weight set, which can be determined with the experience of experts or designers. The set denotes the different influence on the evaluation of every factor

where w_i represents the weight of the influence factor u_i and $\sum_{i=1}^{n} w_i = 1$ ($w_i \geq 0$).

Based on the single-factor evaluation matrix, the comprehensive effect of every factor with respect to the remark v_j can be denoted by $\tilde{R}_j = \sum_{i=1}^{m} r_{ij}$. However, this approach does not consider the weight of every factor. Then, when $\tilde{W}$ and $\tilde{R}$ are known, fuzzy comprehensive evaluation set $\tilde{B}$ can be obtained by the fuzzy transformation $\tilde{B} = \tilde{W} \circ \tilde{R} = (b_1, b_2, \cdots, b_m)$. The operator '$\circ$' is defined by the equation $b_j = \sum_{i=1}^{n} w_i r_{ij}$ here. However, different models could be obtained depending on other various operation compositions. $v = \sum_{j=1}^{m} b_j v_j \Big/ \sum_{j=1}^{m} b_j$ can be used to denote an evaluation result. Then the values of δ_1 and δ_2 are equal to the evaluation result.

4. Fuzzy reliability analysis of vibration component

The resonant region has a jump in the conventional reliability analysis. However, from the point of practice, there should exist a transition region which can be represented by the fuzzy set. The fuzzy reliability considers the transition region that the conventional approach ignores. Let $[n_1', n_1]$ and $[n_2, n_2']$ denote the transition region of resonance. As shown in Fig. 2, the dash line denotes the membership function of the fuzzy failure.

From Fig. 2, the fuzzy reliability of mechanical vibration component is provided by:

$$R = P(n_c \tilde{\geq} n_2') + P(n_c \tilde{\leq} n_1') = \int_{-\infty}^{+\infty} \mu_1(x) f(x) \mathrm{d}x + \int_{-\infty}^{+\infty} \mu_2(x) f(x) \mathrm{d}x \tag{3}$$

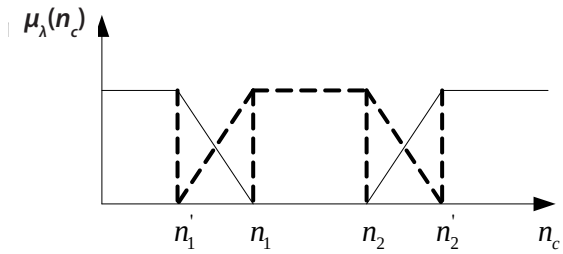

Fig. 2. Membership function

where $\mu_1(x)$ is the membership function when critical speed n_c is greater than n_2' and $\mu_2(x)$ is the membership function when critical speed n_c is less than n_1'. Let $\beta_1 = \frac{n_1' - \mu}{\sigma}$, $\beta_2 = \frac{n_1 - \mu}{\sigma}$, $\beta_1' = \frac{n_2 - \mu}{\sigma}$ and $\beta_2' = \frac{n_2' - \mu}{\sigma}$, the fuzzy reliability is rewritten as:

$$R = 1 - [\Phi(\beta_1', \beta_2') - \Phi(\beta_1, \beta_2)] \tag{4}$$

where

$$\Phi(\beta_1, \beta_2) = \frac{1}{\beta_2 - \beta_1}\{[\beta_2 \Phi(\beta_2) - \beta_1 \Phi(\beta_1)] + \frac{1}{\sqrt{2\pi}}[\exp(-\frac{\beta_2 * \beta_2}{2}) - \exp(-\frac{\beta_1 * \beta_1}{2})]\}.$$

In the fuzzy reliability analysis, other types of membership function could also be used to replace the membership function used here.

5. Case study

5.1. Fuzzy reliability analysis of a shaft

Here a shaft is taken as an example. The manufacturing level and working condition are normal, material quality is good, and importance degree is high. Its running speed is 3000rpm. Then the first order critical speed follows a normal distribution and the mean value and standard deviation are 2640rpm and 145.14rpm respectively. The proposed method will be used to compute the reliability of vibration of the shaft.

Let U ={manufacture level, material quality, work condition, importance degree} and V ={0.1,0.11,0.12,0.13,0.14,0.15}. Then, the evaluation matrix can be constructed as follows:

$$\tilde{R} = \begin{bmatrix} \tilde{R}_1 \\ \tilde{R}_2 \\ \tilde{R}_3 \\ \tilde{R}_4 \end{bmatrix} = \begin{bmatrix} 0.0 & 0.5 & 0.8 & 1.0 & 0.5 & 0.0 \\ 0.0 & 0.2 & 0.4 & 0.8 & 1.0 & 0.5 \\ 1.0 & 0.9 & 0.6 & 0.4 & 0.1 & 0.0 \\ 0.0 & 0.0 & 0.5 & 0.6 & 0.8 & 1.0 \end{bmatrix}$$

Moreover, the weight set $\tilde{W} = (0.26, 0.24, 0.30, 0.20)$ and $\tilde{B} = \tilde{W} \circ \tilde{R} = (b_1, b_2, \cdots, b_6) = (0.3,\ 0.488,\ 0.584,\ 0.692,\ 0.56,\ 0.32)$

Therefore, the values of δ_1 and δ_2 equal to 0.1257 ($v = 0.1257$ by using $v = \sum_{j=1}^{m} b_j v_j \Big/ \sum_{j=1}^{m} b_j$). From Eq. (1), the conventional reliability can be computed by:

$$\begin{aligned} R &= 1 - \{\Phi[\frac{3000/(1-0.12) - 2640}{145.14}] - \Phi[\frac{3000/(1+0.12) - 2640}{145.14}]\} \\ &= 1 - [\Phi(5.299) - \Phi(0.266)] \\ &= 0.606 \end{aligned}$$

From Eq. (3), if the values of δ_1 and δ_2 is considered, the fuzzy reliability should be given by:

$$R = 1 - (0.9998 - 0.5755) = 0.5755$$

5.2. Fuzzy reliability analysis of a suspension system

Suspension system is a very important part for cars and trains [13]. One function of suspension system is to transform force and moment while the other one is to reduce the vibration from the rude road. Therefore, fuzzy reliability analysis for the suspension system in a train with the proposed method is conducted. The frenquency from the actuator is 1.50 Hz by accounting for the road condition. The first order inherent frequency is assumed to be normally distributed with the mean value 0.98 Hz and standard deviation 0.12 Hz. The proposed method is employed to compute the reliability of a suspension system under vibration.

Let U ={design level, manufacture level, installation level, work condition} and V ={0.11,0.12,0.13,0.14,0.15,0.16}. The evaluation matrix could be provided as:

$$\tilde{R} = \begin{bmatrix} \tilde{R}_1 \\ \tilde{R}_2 \\ \tilde{R}_3 \\ \tilde{R}_4 \end{bmatrix} = \begin{bmatrix} 0.0 & 0.3 & 0.6 & 0.8 & 1.0 & 0.8 \\ 0.0 & 0.2 & 0.4 & 0.8 & 1.0 & 0.5 \\ 0.0 & 0.0 & 0.4 & 0.7 & 0.9 & 1.0 \\ 1.0 & 0.8 & 0.5 & 0.2 & 0.0 & 0.0 \end{bmatrix}$$

The weight set is given by $\tilde{W} = (0.32, 0.24, 0.22, 0.22)$ and

$$\begin{aligned} \tilde{B} &= \tilde{W} \circ \tilde{R} = (b_1, b_2, \cdots, b_6) \\ &= (0.22,\ 0.32,\ 0.486,\ 0.646,\ 0.758,\ 0.596) \end{aligned}$$

With $v = \sum_{j=1}^{m} b_j v_j \Big/ \sum_{j=1}^{m} b_j$, we can get $\delta_1 = \delta_2 = 0.1405$.

The conventional reliability could be obtained with Eq. (2):

$$\begin{aligned} R &= 1 - \{\Phi[\frac{1.5/(1-0.12)-0.98}{0.12}] - \Phi[\frac{1.5/(1+0.12)-0.98}{0.12}]\} \\ &= 1 - [\Phi(6.0375) - \Phi(2.994)] \\ &= 0.9986 \end{aligned}$$

If the fuzziness is considered, the fuzzy reliability of the suspension system by using $\delta_1 = \delta_2 = 0.1405$ could be represented as:

$$R = 0.9974$$

By comparing the results from the conventional method and the proposed method, a conlusion that the reliability becomes lower with consideration of fuzziness is arrived.

6. Conclusion

In this paper, a fuzzy reliability analysis approach of mechanical vibration component is developed. By comparing the proposed approach and the conventional approach, a conclusion that the proposed approach is capable of considering the fuzziness and the reliability of vibration component can be computed in a more comprehensive sense. It should be noted that the proposed approach incorporates the fuzzy comprehensive evaluation into fuzzy reliability theory. From the two engineering examples, it is shown that the proposed approach is more suitable for the complicated reliability analysis because it considers not only aleatory uncertainty but also fuzziness in an integrating framework.

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MAINTENANCE DECISION MAKING BASED ON DIFFERENT TYPES OF DATA FUSION

PODEJMOWANIE DECYZJI EKSPLOATACYJNYCH W OPARCIU O FUZJĘ RÓŻNEGO TYPU DANYCH

Over the last decade, system integration is applied more as it allows organizations to streamline business processes. A recent development in the asset engineering management is to leverage the investment already made in process control systems. This allows the operations, maintenance, and process control teams to monitor and determine new alarm level based on the physical condition data of the critical machines. Condition-based maintenance (CBM) is a maintenance philosophy based on this massive data collection, wherein equipment repair or replacement decisions depend on the current and projected future health of the equipment. Since, past research has been dominated by condition monitoring techniques for specific applications; the maintenance community lacks a generic CBM implementation method based on data mining of such vast amount of collected data. The methodology would be relevant across different domains. It is necessary to integrate Condition Monitoring (CM) data with management data from CMMS (Computer Maintenance Management Systems) which contains information, such as: component failures, failure information related data, servicing or repairs, and inventory control and so on. These systems are the core of traditional scheduled maintenance practices and rely on bulk observations from historical data to make modifications to regulated maintenance actions. The most obvious obstacle in the integration of CMMS, process and CM data is the disparate nature of the data types involved, and there have benn several attempts to remedy this problem. Although, there have been many recent efforts to collect and maintain large repositories of these types of data, there have been relatively few studies to identify the ways these to datasets could be related. This paper attempts to fulfill that need by proposing a combined data mining-based methodology for CBM considering CM data and Historical Maintenance Management data. It shows a system integration of physical and management data that also supports business intelligence and data mining where data sets can be combined in non-traditional ways.

Keywords: *data mining, RUL, data fusion, condition monitoring, CMMS.*

W ostatniej dekadzie coraz częściej stosuje się integrację systemów, która pozwala przedsiębiorstwom zwiększać wydajność procesów biznesowych. Nowością w zarządzaniu infrastrukturą techniczną jest zwiększanie efektywności już poczynionych inwestycji w systemy kontroli procesów. Pozwala to zespołom do spraw operacyjnych, utrzymania ruchu oraz kontroli procesów monitorować i ustalać nowe poziomy alarmowe na podstawie danych o stanie fizycznym maszyn krytycznych. Utrzymanie urządzeń zależne od ich bieżącego stanu technicznego (condition-based maintenance, CBM) to filozofia utrzymania ruchu opierająca się na tym masowym poborze danych, wedle której decyzje dotyczące naprawy lub wymiany sprzętu zależą od jego obecnego oraz przewidywanego przyszłego stanu technicznego. Ponieważ dotychczasowe badania były zdominowane przez problem technik monitorowania stanu dla konkretnych aplikacji, nie opracowano ogólnej metody wdrażania CBM opartej na eksploracji (data mining) owych olbrzymich ilości zebranych danych, która miałaby zastosowanie w różnych domenach. Konieczna jest integracja danych z monitorowania stanu (condition monitoring, CM) z danymi dotyczącymi zarządzania pochodzącymi ze skomputeryzowanych systemów zarządzania utrzymaniem ruchu (CMMS), które zawierają informacje na temat uszkodzeń elementów składowych, dane związane z uszkodzeniami, a także informacje dotyczące obsługi lub napraw czy sterowania zapasami. Systemy te stanowią podstawę tradycyjnych praktyk obsługi planowej, a zasadzają się na całościowych obserwacjach dokonywanych na podstawie danych eksploatacyjnych, które pozwalają modyfikować regulowane działania obsługowe. Najbardziej oczywistą przeszkodą w integracji danych CMMS, danych procesowych oraz danych z monitorowania stanu jest rozbieżność ich natury. Dotychczas podjęto jedynie kilka prób rozwiązania tego problemu. Chociaż ostatnio wiele wysiłku włożono w gromadzenie i utrzymanie dużych zasobów tego typu danych, istnieje stosunkowo niewiele badań na temat możliwych sposobów powiązania owych zestawów danych. W prezentowanej pracy poczyniono próbę wypełnienia tej luki proponując metodologię łączoną opartą na eksploracji danych dla celów CBM, która bierze pod uwagę dane z monitorowania stanu i eksploatacyjne dane z zarządzania ruchem. W pracy przedstawiono integrację systemową danych fizycznych i danych z zarządzania, która wspiera także analitykę biznesową (business intelligence) oraz eksplorację danych, gdzie zestawy danych można łączyć w sposób nietradycyjny.

Słowa kluczowe: eksploracja danych, pozostały okres użytkowania (RUL), fuzja danych, monitorowanie stanu, CMMS.

1. Introduction

Maintenance can be considered as an information processing system that produces vast amount of data. However data is not synonymous with information; but that data must be processed with data analytical tools to extract the information, [5]. IT (Information Technology) and AI (Artificial Intelligence) tools development support the unprecedented transformation from the industrial age to the information age in maintenance using these existing and emerging technologies that analyze near real-time assets systems data to provide prediction and response maintenance capability. Several technological advances and initiatives at various levels have made a move toward CBM (Condition Based Maintenance) a reality for today's industry.

The transition to CBM requires a collaborative effort on a massive scale and is contingent on identifying and incorporating enhanced and emerging technologies into existing and future production systems. This will require new tools, test equipment, and embedded on-board diagnosis systems. Even more critical, the transition to CBM involves the construction of data-centric, platform-operating capabilities built around carefully developed robust algorithms. This will allow maintenance personnel in the field, support analysts, and engineers the ability to simultaneously, and in real-time, translate conditional data and proactively respond to maintenance needs based on the actual condition

Nowadays, two main systems are implemented in most maintenance departments: Computer Maintenance Management Systems (CMMS) are the core of traditional maintenance record-keeping practices and often facilitate the usage of textual descriptions of faults and actions performed on an asset. Second one is condition monitoring systems; recently developed Condition Monitoring Systems (CM) are capable of directly monitoring asset components parameters; however, attempts to link observed CMMS events to CM sensor measurements have been fairly limited in their approach and scalability.

A CBM strategy, where the optimal time to schedule a service visit is forecasted based on the condition of the equipment, is often proposed as an answer to the challenge of increase the efficiency and reduces the cost for the service of their equipment over their lifecycle, [10]. However, predictive maintenance approaches are frequently hampered. First, by the lack of knowledge of the features those give a good indication of the condition of the equipment. Second, by the processing power needed for prediction algorithms to forecast the future evolution of the selected features, especially, when large measurements are collected. To overcome these problems, this paper proposes to use data mining to improve the quality of the prognosis. Therefore,

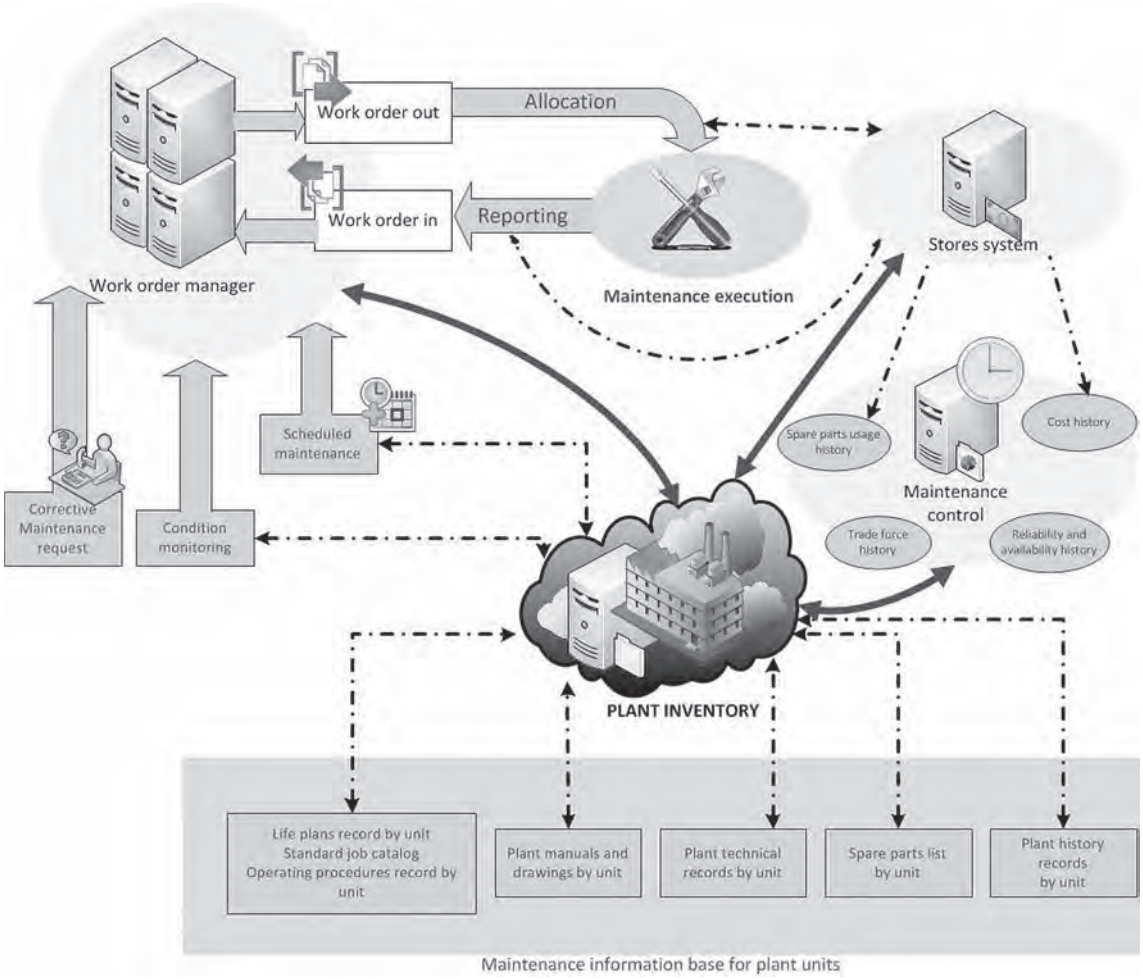

Figure 1. Functional model for maintenance documentation system

the development of future maintenance information systems in order to improve automatic condition monitoring systems enabled by embedded electronics and software in industrial machines, is one of the most important current research problems in this topic.

In this paper, the issues and challenge of this necessary integration of data of different nature are presented. It can be argued that understanding the requirements and constraints in conjunction - from maintenance AI and IT perspectives - is necessary to provide different decisions for different end users.

2. Maintenance historical data

2.1. Existing data in maintenance function

Maintenance documentation system, for recording and conveying information, is an essential operational requirement for all the elements of the maintenance management process. Maintenance documentation can be defined according to [11] as: Any record, catalog, manual, drawing or computer file containing information that might be required to facilitate maintenance work. Simultaneously, a maintenance information system can be defined as: The formal mechanism for collecting, storing, analyzing, interrogating and reporting maintenance information.

The way in which a maintenance documentation system generally functions is shown in Figure 1, a model which has evolved, according to [12], over a number of years through extensive studies of both paper-based and computerized systems, and which therefore illustrates the principal features of both types – features which, inevitably, they have in common. The system can be considered to be made up of the following interrelated modules:

1. Plant inventory,
2. Maintenance information base,
3. Maintenance schedule,
4. Condition monitoring,
5. Maintenance control.

The plant inventory (1) is a coded list of the plant units. This is the main way into the system. The asset data shall be collected in an organized and structured way. The major data categories for equipment are the following:

1. Classification data, e.g. industry, plant, location, system;
2. Equipment attributes, e.g. manufacturer's data, design characteristics;
3. Operation data, e.g. operating mode, operating power, environment.

These data categories shall be general for all equipment classes. Additionally some data specific for each equipment class (e.g. number of stages for a compressor) is needed. Finally, the classification of equipment into technical, operational, safety related and environmental parameters is the basis for the collection of assets data due to the different nature of devices (safety instrumented systems, productive assets, maintenance tools, condition monitoring systems etc.). This information is also necessary to determine if the data are suitable or valid for various applications. There are some data that are common to all equipment classes and some data that are specific for each equipment class.

These plant inventory units are the target for maintenance actions. These actions are basically of two kinds according to [3]:

- Those being done to correct an item after it has failed (corrective maintenance). It is required that for recording the reliability of an item, as a minimum corrective maintenance to correct a failure shall be recorded.
- Those being done to prevent an item from failing (preventive maintenance). A part of this may only be checks. Recording actual preventive maintenance (PM) is recommended to be done, essentially in the same way as for corrective actions. This may give additional information as follows:
  - the full lifetime story of an item (all failures and maintenance);
  - the total resources used on maintenance (man-hours, spare parts);
  - the total down time and hence, total equipment availability, both technical and operational;
  - the balance between preventive and predictive maintenance (inspections, tests) to verify the condition of the equipment to decide if any preventive maintenance is required or not.

Figure 2 shows the main types of maintenance actions being commonly performed.

According to [2] a new maintenance type called "opportunity maintenance" can be included if one considers maintenance of an item that is deferred or advanced in time when an unplanned opportunity becomes available.

Maintenance actions are the result of implemented maintenance program. Choice of applied methodology, ratio preventive-corrective, etc. is always up to maintenance manager who has plant inventory and maintenance information base to construct the model to be used. The maintenance information base (2) is a database of maintenance information, e.g. unit life plans, job catalog, etc. for each of the units. These data are characterised by:

- identification data; e.g. maintenance record number, related failure and/or equipment record;
- maintenance data; parameters characterising a maintenance, e.g. date of maintenance, maintenance category, maintenance activity, impact of maintenance, items maintained;

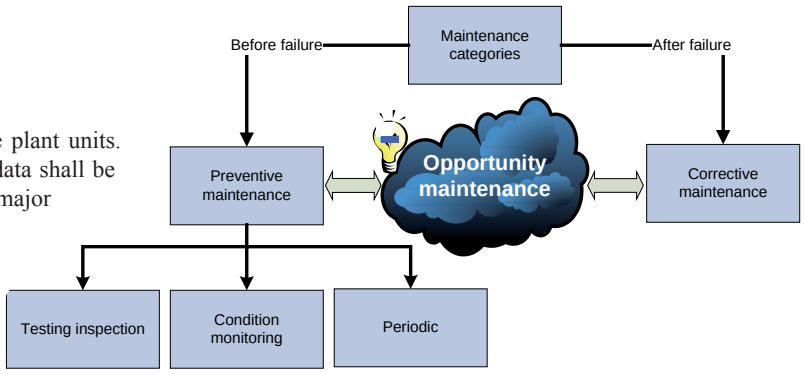

Figure 2. Maintenance actions categorisation

Category	Data to be recorded	Category	Data to be recorded
Identification	Maintenance record	Maintenance resources	Maintenance man-hours, per discipline
	Equipment location		Maintenance man-hours, total
	Failure record		Maintenance equipment resources
Maintenance data	Date of maintenance	Maintenance times	Active maintenance time
	Maintenance category		Down time
	Maintenance priority		
	Interval (planned)		Maintenance delays/problems
	Maintenance activity	Remarks	Additional information
	Maintenance impact on plant operations		
	Subunit maintained		
	Component/maintainable item(s) maintained		
	Spare part location		

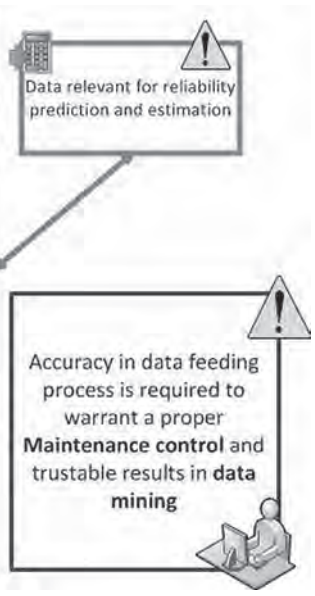

Table 1. Maintenance records recommended meeting most International Standards and general recommendations [9]

- maintenance resources; maintenance man-hours per discipline and total, utility equipment /resources applied;
- maintenance times; active maintenance time, down time.

A common report for all equipment classes should be used for reporting maintenance data. The data required are shown in Table 1. For some equipment classes minor adaptations may be needed. The minimum data needed to meet the objectives of International Standards, Maintenance Association and CMMS manufacturer's recommendations are identified in Table 1.

Recording maintenance actions is crucial for a successful further knowledge extraction that is why all actions performed should be recorded. PM records are mainly useful for the maintenance engineer, but will also be useful for the maintenance engineer wanting to record -or estimate- the availability of equipment, and doing lifetime analysis not only taking failures into account, but also maintenance actions intended to restore the item to "as-good-as-new" condition. PMs are often performed on a higher indenture level (e.g. "package" level); hence there may not be data available that can be related to the items on the lower indenture level. This restriction must be considered when defining, reporting and analysing PM data.

During the execution of PM actions, impending failures may be discovered and corrected as part of the PM activities. In this case the failure(s) shall be recorded as any other failure with the subsequent corrective action done even though it initially was considered to be a PM type activity. The failure detection method shall in this case be referred to as the type of PM being done. It is, however, realised that some failures, generally of minor character, may be corrected as part of the PM and not recorded specifically. The practice on this may vary between companies and should be addressed by the data collector(s) in order to reveal the possible type and amount of failures being included within the PM program.

A final option is to record the planned PM program as well. In this case it is possible to additionally record the differences between the planned and the actual performed PM (backlog), [4]. An increasing backlog will be an indication that the control of the conditions of the plant is being jeopardised and may in adverse circumstances lead to equipment damage, pollution or personnel injury.

Regarding corrective maintenance, failure records are especially relevant for further knowledge extraction so failure data have to be recorded in a proper way to be suitable for further computation. A uniform definition of failure and a method of classifying failures are essential when data from different sources (plants and operators) need to be combined in a common maintenance database.

These failure data are characterised by:

- identification data; e.g. failure record number and related equipment that has failed;
- failure data for characterizing a failure, e.g. failure date, items failed, failure impact, failure mode, failure cause, failure detection method, so on.

The type of failure and maintenance data shall normally be common for all equipment classes, with exceptions where specific data types need to be collected. Corrective maintenance events shall be recorded in order to describe the corrective action following a failure.

Finally the combination of plant inventory and maintenance base information produces the expected maintenance schedule. This schedule is a mixture of available techniques to fulfill stakeholder's constraints and achieve company goals. This mixture is usually composed by some scheduled maintenance and condition monitoring to perform condition based maintenance. The maintenance schedule (3) is a schedule of the preventive maintenance jobs (over a year and longer) listed against each of the units in the life plans. The condition monitoring schedule (4) is a schedule of the condition monitoring tasks, e.g. vibration monitoring listed against each of the units in the life plans. Preventive maintenance records are required to retain the complete lifetime history of an equipment unit.

The system has to plan and schedule preventive jobs (arising from the maintenance schedule), corrective jobs (of all priorities) and where necessary modification jobs. The jobs are carried out by trade-force via hard copy or electronic work or-

ders. Information coming back on the work orders (and other documents) is used to update the planning systems and provides information for maintenance control. The maintenance control system (5) uses information coming from a number of sources, work orders, stores, shift record, etc. to provide various reports for cost control, plant reliability control, etc.

One of the main issues is the integration of these data with the rest of company records such us health and safety, finances, etc.. Up until about 10 years ago most CMMS were stand alone, i.e. they had no electronic linkage with other company software. The most recent computerized maintenance systems are integrated electronically (they are in the same database) with stores, purchasing, invoicing, company costing, payroll and also can have electronic links to project management and condition monitoring software.

2.2. The search of a comprehensive data format

Each mentioned data becomes a database record, e.g. a failure event, shall be identified in the database by a number of attributes. Each attribute describes one piece of information, e.g. the failure mode. It is recommended that each piece of information be coded where possible. The advantages of this approach versus free text are:

- facilitation of queries and analysis of data;
- ease of data input;
- consistency check undertaken at input, by having predefined code-lists;
- minimise database size and response time of queries.

The range of pre-defined codes should be optimised. A short range of codes will be too general to be useful. A long range of codes will give a more precise description, but will slow the input process and may not be used fully by the data collector. Selected codes shall, if possible, be mutually exclusive. The disadvantage of a pre-defined list of codes versus free text is that some detailed information may be lost. It is recommended that free text is included to provide supplementary information. A free-text field with additional information is also useful for quality control of data. This free text box is extremely risky in further data mining process due to difficulties of text recognition and interpretation, see Table 1. Different employees have different skills to describe failures, events and actions and expert systems are not so good to distinguish all these variations.

For all mentioned categories, it is recommended to include some additional free text giving more explanatory information as available and deemed relevant, e.g. include a more verbal description of the occurrence leading to a failure event. This would assist in quality checking the information and browsing through single records to extract more detailed information. However users should be aware of the existing risk in automatic processing of these records.

2.3 Database structure

The data collected shall be organised and linked in a database to provide easy access for updates, queries and analysis. Several commercial databases are available that can be used as main building block for designing a reliability database. Two aspects on organising the structure of data shall be addressed as follows:

- Logical structure: This defines the logical link between the main data categories in the database. This model represents an application-oriented view of the database. The example in Figure 3 shows a hierarchical structure with failure and maintenance records linked to the classification/equipment description (inventory). Records describing preventive maintenance (PM) are linked to the inventory description in a many-to-one relation. The same applies for failures, which additionally have related corrective maintenance records linked to each failure. Each record (e.g. failure) may consist of several attributes (e.g. failure date, failure mode, etc.).
- Database architecture: This defines the design of the database as to how the individual data-elements are linked and addressed. Four model categories are commonly available ranked in order of complexity and versatility:
  - Hierarchical model: Data fields within records are related by a 'family tree-like' relationship. Each level represents a particular attribute of data;
  - Network model: This is similar to the hierarchical model; however, each attribute can have more than one parent;
  - Relational model: The model is constructed from tables of data elements, which are called relations. No access path is being defined beforehand; all manipula-

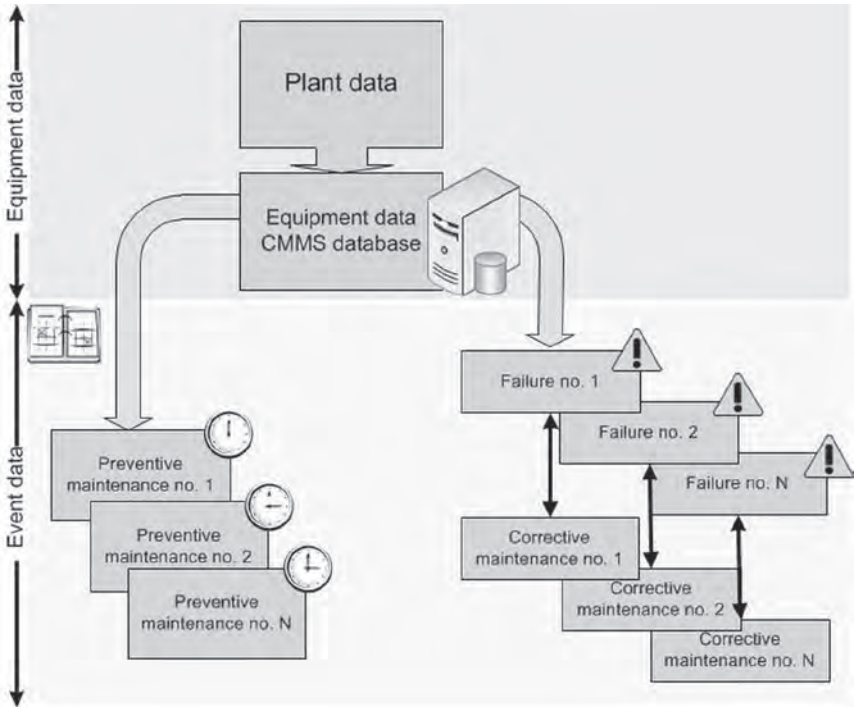

Figure 3. Logical data structure

tion of data in tabular form is possible. The majority of database designs use this concept;
- Object model: Software is considered as a collection of objects that each has a structure and an interface. The structure is fixed within each object while the interface is the visible part that provides the link address between the objects. Object modelling enables the database design to be very flexible, extendable, reusable and easy to maintain. This model seems to be the most popular in new database concepts.

3. Condition Monitoring data and automatic asset data collection

Condition monitoring involves comparing on-line or off-line data with expected values; if necessary, it should be able to generate alerts based on preset operational limits. Health assessment determines if the health of the monitored component or system has degraded, and conducts fault diagnostics. The primary tasks of prognostics involve calculating the future health and estimating the remaining useful life (RUL). In reality, however reliable and effective CBM faces some challenges. First, initiating CBM is costly. Often the cost of instrumentation can be quite large, especially if the goal is to monitor equipment that is already installed. It is therefore important to decide whether the equipment is important enough.

Implementing condition-based maintenance requires the setting of an information system to meet the basic requirements of:
- Collection and processing of large quantity of information not previously available, regarding the condition of each part of a machine.
- Initiate corrective maintenance actions within the lead-time (the period of time between the off-limits condition and an emergency shutdown). In this respect there may be two different situations which the examiner may encounter :
  - The condition of machine is not yet close to breakdown. In this case the normal procedure through the maintenance planning section will be followed.
  - The condition of machine is already well within the lead-time (near to breakdown). In this situation the information must be directly passed on to the maintenance supervision for carrying out emergency corrective maintenance actions.

In order to operate the condition based maintenance program correctly, the maintenance personnel should introduce into the system:
- Condition of machine,
- Part of machine probably defective,
- Probable defect,
- Time during which failure must be repaired.

By scrutinizing and correlating of diagnosis against actual findings during repair work, it will be possible:
- To control the examiner training,
- To improve the correlation between parameters chosen for condition measurement and actual defects found,
- To obtain severity curves specific to each machine.

Making the potential of condition monitoring a reality requires that large amounts of data be collected, monitored, filtered and turned into actionable information. The cheaper and more ubiquitous the computerized monitoring hardware becomes, the greater the volume of data and the more challenging it becomes to manage and interpret. The vast amount of diagnostic data produced by today's smart field devices can be a very important source for accurate documentation of maintenance activities. But the sheer volume and complexity of such information can be daunting and difficult for maintenance personnel to manage. What's needed is an effective means of compiling and organizing the data for day-today utilization by your staff, while preserving and recording significant events for future reference. Data is becoming more and more available.

However, in most cases, this data may not be used due to its bad quality, or even properly stored for several reasons, [13]:
- Project managers do not have sufficient time to analyse the computerised data so they don't care about proper storage;
- The complexity of the data analysis process is beyond the capabilities of the relatively simple maintenance systems commonly used;
- There has been no well defined automated mechanism to extract, pre-process and analyse the data and summarise the results so stored data are not reliable.

Maintenance personnel, not only cope with large amounts of field-generated data, they turn that information to their advantage in a number of ways. Real Time Condition Monitoring (RTCM) systems produce lots of warnings, alarms and reports that can be used by maintenance people for many purposes. In this way, the most important issues are identified and handled quickly.

Ultimate goal is to fully integrate RTCM data with CMMS to generate work orders as needed. That will provide true automation from the time a field device begins to show signs of reduced performance until a work order is printed out in the maintenance department and a technician is dispatched to the scene. In Figure 4, this automation of work order dispatching is shown.

This level of integration of CMMS and CM is feasible due to IT evolution. With the development of open communication protocols, the information accumulated by smart field devices can be captured by asset management software. It's no longer necessary for technicians to carry handheld communicators or laptops into the plant to evaluate the condition of instruments, some of which are quite inaccessible or in hazardous areas, to be followed by manually documenting test results and current device status.

Current applications compile databases of every smart instrument used for process control, including its design parameters, original configuration, maintenance history and current operating condition. With these online tools, technicians can obtain up-to-date information on any device and they never have to make manual entries back into a system. Every event is recognized and recorded, whether initiated by a technician or caused by an external force such as an equipment breakdown or power failure. This process produces one immediate result for shop floor level because work orders can be open and closed helped by devices that collect automatically information and send warning if something wrong happens. Users can refer to recorded alerts to identify any devices that have been problematic over time and what corrective steps may have been taken previously. Automated documentation provides a seamless record of events in a given production area, including communication failures, device malfunctions and process variables

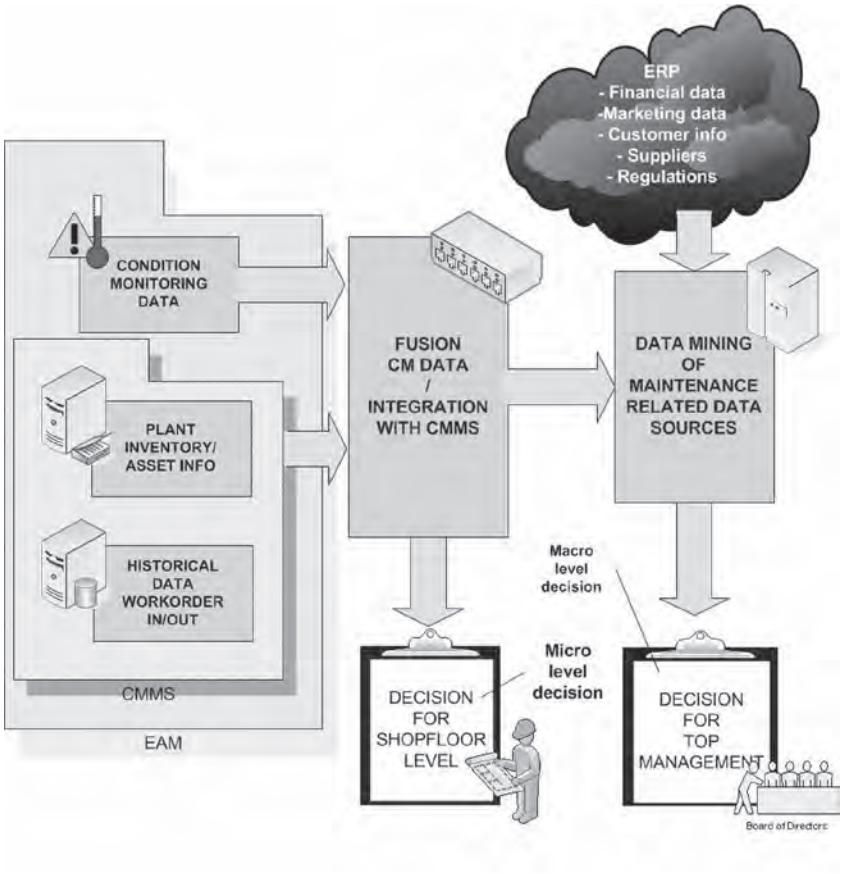

Figure 4.Two step integration of RTCM and CMMS databases

that are out of range. Armed with this information, maintenance personnel are better equipped to understand and resolve nagging repetitive issues to improve the process. If there is an issue, or if maintenance personnel are experiencing a rash of issues, they can go back into the records and get a sense of what's been going on over time. They can search by a specific device or by location.

Since all records are date and time stamped, users can easily determine when and by whom a particular device was changed or tested, including "as found/as left" notations. With this information in a database that cannot be edited, it should never be necessary for technicians to spend time searching for historical information on a device. Since events can also be recorded manually, users can document unusual occurrences affecting the entire plant, such as a lightning strike or power outage, or individual events like device inspections.

This decision level is extremely useful for technicians to take immediate actions. However vast amount of available information can produce new knowledge if it's exploited with proper AI tools due to real physical integration in same database types and locations. Modern CMMS information is stored in very large relational, or tabular, databases. This format is appropriate for an integration investigation since there are a large number of software tools available to query and investigate the tables. For the historical analysis, only certain fields are required, thus allowing for the previously mentioned sensitive data to be removed or filtered. The data subset still contains a full history of component faults and related actions, providing a comprehensive maintenance history profile while alleviating security concerns.

Importing CM data into this relational database is somewhat more challenging but possible, since each type of sensor generates different data classes, sampling rates, and number of compiled indicators. Furthermore, each manufacturer stores the collected information in unique proprietary formats, requiring platform-specific importation software to be written. However most CM software allows the CM data to be exported from the original interface so that it can be expanded and generalized.

Although both the CMMS and the CM data now co-exist within a single database where it can be queried and explored, automating the discovery of linked events requires additional processing. Relating a given maintenance fault or action, which is textual, to sensor data, which is some arbitrary data class type, can only be accomplished through the compilation of overlapping metadata, [14]. The fields which are generated characterize the location and significance of events, creating a quantified set of parameters by which the disparate data can be compared. Metadata for CM records is generated differently depending on the data class involved. One-dimensional and dimensionless quantities can be assigned rarity parameters through statistical distribution analysis, and higher dimensional data requires using neural networks to identify anomalies. Determining rarity is often accomplished through simple single variable statistical analysis, while severity is typically derived from developers recommended threshold values. More complex domain types require more advanced, though typically well-understood analyses such as neural networks which can isolate anomalous points from multidimensional data. It is predicted that through the integration process, more advanced metrics and indicators can be discovered which implement previously unexplored relationships in the data, such as multi-parameter trending. This new discovered knowledge can help maintenance personnel to find out the Remaining Useful Life of the system in order to schedule operation and maintenance processes in function of such relevant information. This information affects replacement of assets, shutdown of the plant, overhauls etc.; so it constitutes the second decision level displayed in Figure 4 which is strongly related to business goals and useless for immediate interventions.

4. Data mining of maintenance historical data for RUL calculation

Condition based maintenance (CBM) is the real target of all maintenance plans to optimize inspections and intervention avoiding wastes of time and money. It has evident benefits, including reducing maintenance cost, increasing machine reliability and operation safety, and improving time and resources management [1]. That is why major improvements can be

achieved in maintenance cost, unscheduled machine failures, repair downtime, spare parts inventory, and both direct and indirect overtime premiums, by using CBM. Although these benefits are well illustrated, two major problems hamper the implementation of predictive maintenance in industrial applications. First, the lack of knowledge about the right features to be monitored and second, the required processing power for predicting the future evolution of features, which is often not available.

Data Mining (also known as Knowledge Discovery in Databases, or KDD) has been defined as "the nontrivial extraction of implicit, previously unknown, and potentially useful information, from data" [6]. Data mining and knowledge discovery can be applied to historical data from the field in order to optimally identify these relevant features for the condition of the equipment and the associated thresholds and contexts. Based on this information, a prediction model is fitted to the live data of the equipment, collected from customer's premises, for predicting the future evolution of these features and forecasting the RUL (remaining useful life) and consequently the time interval to the next maintenance action. To overcome the limited processing power of the machine's processor and data replications costs derived from the huge amount of collected and stored data, the concept of cloud computing comes up, performing prediction through computation of remote located databases.

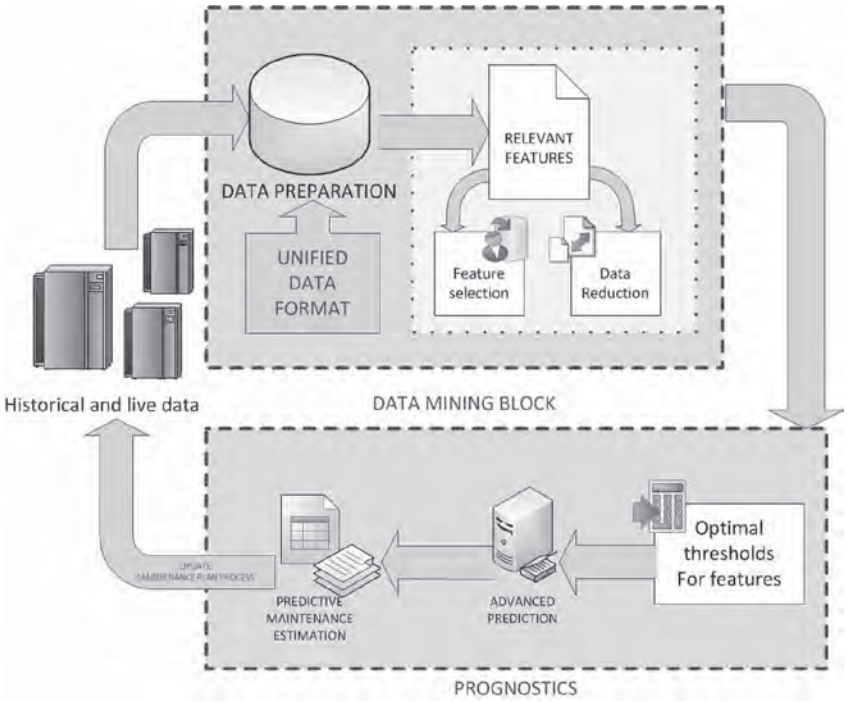

Figure 5. Data mining steps with maintenance data

The lack of knowledge for the proper extraction of right features can be compensated with data mining techniques proved to be useful for relevant features extraction. It has been proved in [8], [15] and [16] that application of data mining techniques to condition monitoring data is very useful for extracting relevant features which can be used as parameters for machine diagnosis and/or prognostics. However, in many other industrial applications, no clear physical understanding of the process is available and therefore to retrieve these relevant features, a clear methodology is required.

This paper proposes the use of data mining for CBM optimization in order to perform an accurate predictive maintenance scheduling. So far, prognostic has been tackled as an independent step from data mining, assuming the prediction of a completely known parameter [7]. On the contrary, in a real integration of data mining and CBM approach, prognostics is an integral part of the flowchart and makes use of the relevant features extracted in data mining step. This approach enables the possibility to compare different features evolution and combine them to improve the accuracy of remaining useful life forecast.

This approach consists of:

- A data mining step on historical data where data preparation, data reduction and relevant features extraction are performed.
- A prognostics step, where optimal thresholds are retrieved using prediction algorithms are applied on live data to estimate the remaining time for the relevant features to reach the thresholds. This remaining life time can be used to establish an optimal predictive maintenance.

Logical data mining process to optimally forecast the predictive maintenance actions is as follows: starting point is the available historical database of machines running whose maintenance performed actions can be altered in function of the result of decision support system regarding scheduling process. In general, such a database exists for almost all machine manufacturers, but only a limited amount of information is currently used.

The next step consists of data preparation, including data transformation from the original to unified data formats and data cleaning such as removing outliers or calculating missing values. Note that the data preparation step may be time consuming since the unified data format should be compatible with the data mining software tool and still retain a physical interpretation of the data.

The real data mining step consists of the data reduction where significant information is found and non relevant information is discarded to reduce significantly the number of attributes in the searching process. After this pruning process, the relevant features are extracted out of the selected.

The final step consists of prognostics, itself divided into two sub steps. First, reliability estimation methods are applied to historical database in order to identify the optimal thresholds of the selected features. Secondly, a prediction algorithm is applied to live data in order to forecast the time to schedule the optimal CBM. The different steps of the data mining approach are summarized in Figure 5.

5. Conclusion

Main benefit from maintenance data integration process is insight into the future establishment of CM and CMMS data format standards. Early integration attempts will identify data structures that are most conducive and useful for long-term storage and searching. With the coordination of CMMS and CM developers, a general set of guidelines for file formats can be established which will enhance the potential for research by the scientific community, greatly increasing the usefulness of CMMS and CM platforms. Following the implementation of an integrated system, the usefulness of CM devices will expand from mere guidance tools to automated diagnostics and prognostics systems. These integrated systems will constantly compare sensor readings to the wealth of historical records and forecast likely maintenance events based upon historical precedence. This will allow for more efficient logistics and component performance evaluation. Furthermore, these systems will identify unexplained or common modes of failure directing the efforts of scientific component testing, the results of which will drive design modifications making the assets increasingly more reliable.

This integration has two steps. First one is integration of technology and standards like MIMOSA are actively contributing to the development of a common hardware and software platform for data storage. Second step is related to the new knowledge extraction as a result of integration performed in first step. For this purpose data mining comes up as a very effective maintenance knowledge tool.

Data mining has become useful over the past decade in maintenance to gain more information, to have a better understanding of the behaviour of running assets, and to find optimal maintenance policies derived from this new knowledge. Today, data mining is no longer thought of as a set of stand-alone techniques, far from the maintenance applications. Enterprises require more and more integration of data mining technology with relational CMMS and CM databases and their business-oriented applications. To support this move to applications, data mining products are shifting from stand-alone, technology to being integrated in the relational databases.

The goal is to find new and interesting patterns in the data and somehow use the gained knowledge in maintenance decisions. The integration of mining results into the operational business is usually done in an ad-hoc manner. With the integration of mining, the focus shifts toward the deployment of mining in business applications. The audience includes the end users in the line of business who need an easy-to-use interface to the mining results and a tight integration with the existing environment.

Simple predictive models, anticipation of assets behaviour, and automatic optimization of maintenance processes by means of data mining become more important than some general knowledge discovery. If the purpose of the model is to increase knowledge of the data, the knowledge gained needs to be organized and presented in a way that the end user, maintenance personnel can use it.

Depending on the maintenance requirements, the deployment phase can be as simple as generating a report or as complex as implementing a repeatable data mining process. However, even if the data analyst does not carry out the deployment effort, the maintenance personnel, i.e. end user, must understand up front what actions need to be carried out to actually use the created models. A right deployment of the model and understanding by maintenance people are necessary to be sure the real benefits are harvested by the company through right maintenance decisions. The final product should manifest itself as an automated maintenance exploration interface. Users should be able to quickly identify possible diagnoses of faults and quickly retrieve historical maintenance actions that were effective in resolving the problem. Such a system would be easily scalable allowing for maintainers to have information on a variety of practices being performed across the field.

In addition to the assurance that these systems deliver top performance, benefits of this integration include increased plant availability and lower maintenance costs because most faults are caught before they can evolve into problems requiring major repairs and/or costly process interruptions and downtime.

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Łukasz JEDLIŃSKI

MULTI-CHANNEL REGISTERED DATA DENOISING USING WAVELET TRANSFORM

ODSZUMIANIE DANYCH REJESTROWANYCH WIELOKANAŁOWO Z UŻYCIEM TRANSFORMATY FALKOWEJ*

In order to obtain information regarding given phenomenon or object, it is usually necessary to register selected measurement signals obtained using sensors. Unfortunately, obtained signals, apart form desired information, contain disturbances caused by, amongst many other, properties of the measurement channel and processes associated with object operation. In many cases it is necessary to measure the same value in different places and/or directions. Thus, there is a demand for a tool improving signal to noise ration of the multi-channel registered signals.Wavelet transform is a relatively new method of data processing used in different fields (e.g. technique and physics). In case of signals it can be used for denoising, compression, trend detection or discontinuity detection. In this work it was used to denoise vibration signals registered by two three-axis sensors. Object of investigation was the bevel toothed gear. Signals denoising was to improve efficiency of the diagnosis of transmission gears teeth damage.

Keywords: *denoising, wavelet transform, artificial neural network, spiral bevel gear.*

W celu uzyskania informacji o interesującym nas zjawisku lub obiekcie najczęściej rejestrowane są wybrane sygnały pomiarowe otrzymane za pośrednictwem czujników. Niestety uzyskane sygnały oprócz pożądanej informacji zawierają również zakłócenia, które są spowodowane m.in. właściwościami toru pomiarowego i procesami towarzyszącymi działaniu obiektu. W wielu przypadkach zachodzi potrzeba pomiaru takiej samej wielkości w różnych miejscach obiektu i/lub kierunkach. Potrzebne są zatem narzędzia do poprawy stosunku sygnału do szumu sygnałów rejestrowanych wielokanałowo.Transformata falkowa jest stosunkowo nową metodą przetwarzania danych, która znalazła zastosowanie w różnych dziedzinach takich jak technika i fizyka. W odniesieniu do sygnałów może być używana do odszumiania, kompresji, wykrywaniu trendu czy nieciągłości sygnału. W pracy tej transformata falkowa została użyta od odszumiania sygnałów drgań zarejestrowanych z dwóch trójosiowych czujników. Obiektem badań była przekładnia zębata stożkowa. Odszumianie sygnałów miało na celu poprawę skuteczności diagnozy uszkodzenia kół zębatych przekładni.

Słowa kluczowe: *odszumianie danych, transformata falkowa, sztuczne sieci neuronowe, przekładnia stożkowa.*

1. Introduction

In the vibroacoustic diagnosis, like in other fields of science, it is desired to improve achieved results [2]. In the recent years one can observe continuous development of the algorithms of diagnostic computing and signal processing methods [3, 11, 16]. Measuring and computer equipment allow signal measurement with much higher accuracy and from many channels simultaneously.

In case of examining complex objects there is a necessity of registering many signals. At the beginning of the investigation more measurement points are selected to avoid losing important information and obtain best measurement points.

Obtained measurement signals always contain disturbances. In a simple signal model [1, 4, 10] it is assumed that signal contains valuable component (contain useful information) and random component (noise). There are many methods of extracting useful information from the signal, e.g. by signal filtration, PCA main components analysis, signal averaging. Among these method it is worth to mention wavelet transform (WT) that has been found to be useful in signal denoising [14]. Generalisation of the denoising using WT for one signal is a procedure proposed in [1] for many signals – it was used in this work.

2. Test stand

An investigated object is a bevel toothed gear. Its body was equipped with two three-axis vibration acceleration sensors marked with 1 and 2 in Fig. 1. X axis of the sensors is parallel to the direction of input shaft axis and Z axis is an axis of output shaft. The vibrations was registered for the gear in good conditions and with damaged surface of teeth due to seizing. More precise description of the test stand can be found in [9].

3. Discrete wavelet transform (DWT)

In case of the Continuous Wavelet Transform (CWT) the wavelet coefficients are computed for each scale what generates large amount of data and requires long computations. Dis-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

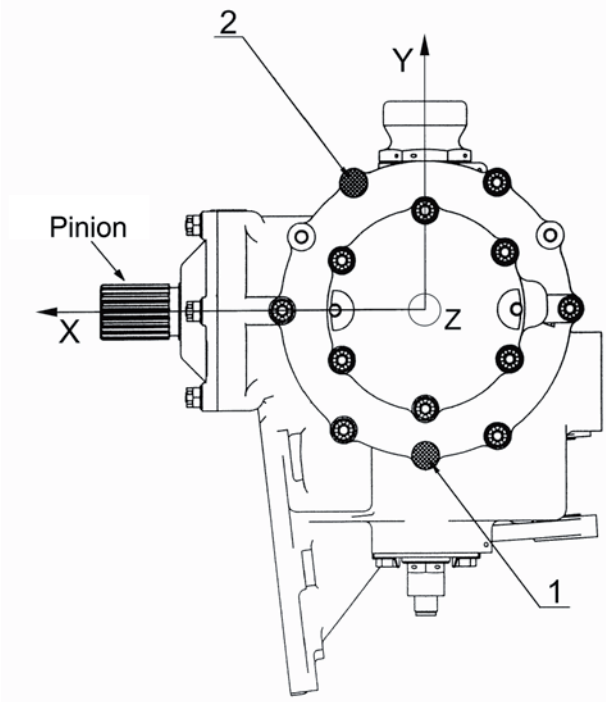

Fig. 1. View of the examined gear with marked position of the vibration sensors

crete Wavelet Transform is based on CWT and allows scale selection. DWT can be defined as [17]:

$$DWT(j,k) = \left|S_0^j\right|^{-1/2} \sum_k x|k|\psi\left(\frac{t - k\tau_0 S_0^j}{S_0^j}\right) \quad (1)$$

where:
$S_0 > 1$, $\tau_0 > 1$,
ψ – basis wavelet,
$x|k|$ – investigate signal,
j, k – positive integers.

For fast and efficient computations of DWT one can use an algorithm introduced by Mallat [12,15], known as multi-resolution analysis (MRA). As a result of its operation we obtain multi-resolution representation of the signal in a form of approximations and details. Complete theoretical basis of the MRA can be found in Mallat's work [12] and the dependency describing it is expressed by formula [17]:

$$x(t) = \sum_\tau S_0(\tau)\phi(t-\tau) + \sum_\tau \sum_{j=0}^{j-1} d_j(\tau)^{j/2}\psi(2^j t - \tau) \quad (2)$$

where:
τ – shift coefficient,
S_0 – scale coefficient,
d_j – wavelet coefficient for j scale,
$\phi(t)$, $\psi(t)$ – scaling and wavelet function.

Details and approximations are computed thanks to filtration with a two-channel set of filters (quadrature reflection filters [5,6]). In order to obtain signal decomposition into a few levels the filtration operation should be iterated (Fig. 2). Using low-pass filter we obtain approximation A_j (low frequency signal component) and using high-pass filter we obtain detail D_j (high frequency signal component)[7]. Fig. 2 shows sample signal registered with 10kHz frequency. Decomposition resulted in signal in 0 – 5kHz range at the first level of approximation A_1 and detail D_1 - range 5 – 10 kHz. If the original signal consisted of 100 samples then the filtration results in obtaining a detail with length equal approx. 100 samples and an approximation with length equal approx. 100 samples. A sum of the resulting signals is approximately twice larger than original signal. To avoid this increment of number of samples decimation is used (removing every second sample from the obtained signal). Then we can perform further decomposition. Usually, an approximation is analyzed in order to obtain next detail and approximation. Signal decomposition is performed for finished number of levels due to signal length or physical sense of obtained details and approximations [18]. Usually, decomposition level does not exceed 8.

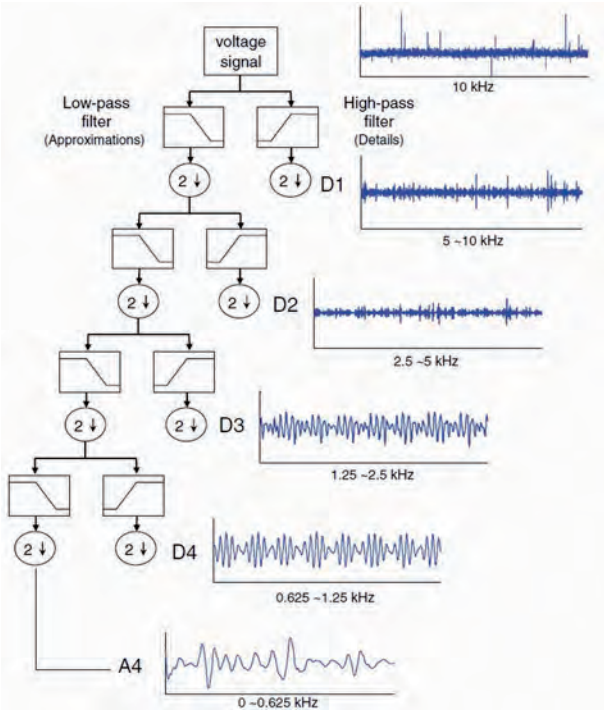

Fig. 2. Signal decomposition using multi-resolution analysis algorithm [17]

Removing irrelevant information (noise) after wavelet decomposition can be realized using a few methods. Next signal approximations contain signal component with lower and lower frequencies, thus the selection of proper approximation as a signal representation is then noise elimination method. Other possibility is simple modification of first detail (or details) by changing wavelet coefficients to zero. These methods of signal denoising are not very precise. More sophisticated denoising algorithms base on zeroing detail wavelet coefficients basing on a criterion calculated separately for each detail. Apart from selection of the proper threshold criterion (below which wavelet coefficients are set to zero) it is also necessary to select a method of threshold realisation. Hard thresholding method realizes denoising process by setting zero value for the elements which absolute value are below threshold value (other elements are not changed). A variation of this method is soft thresholding, in which not zeroed elements are also changed what

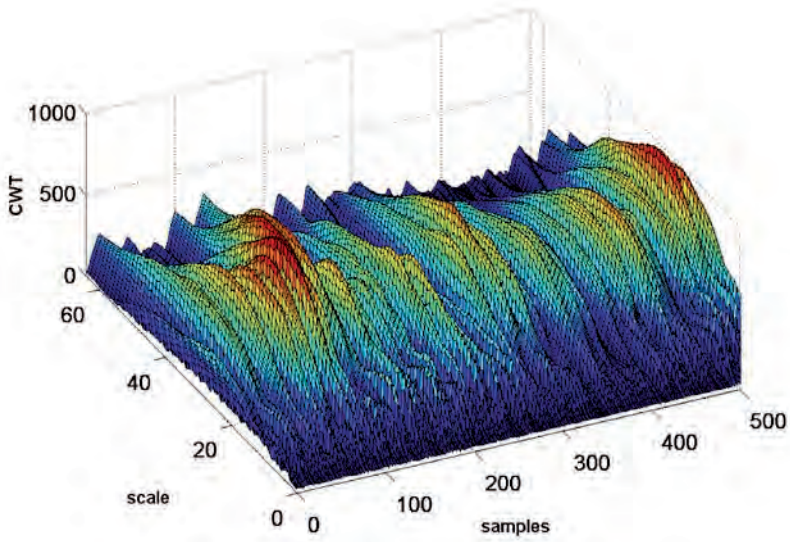

Fig. 3. 3D plot of vibration signal

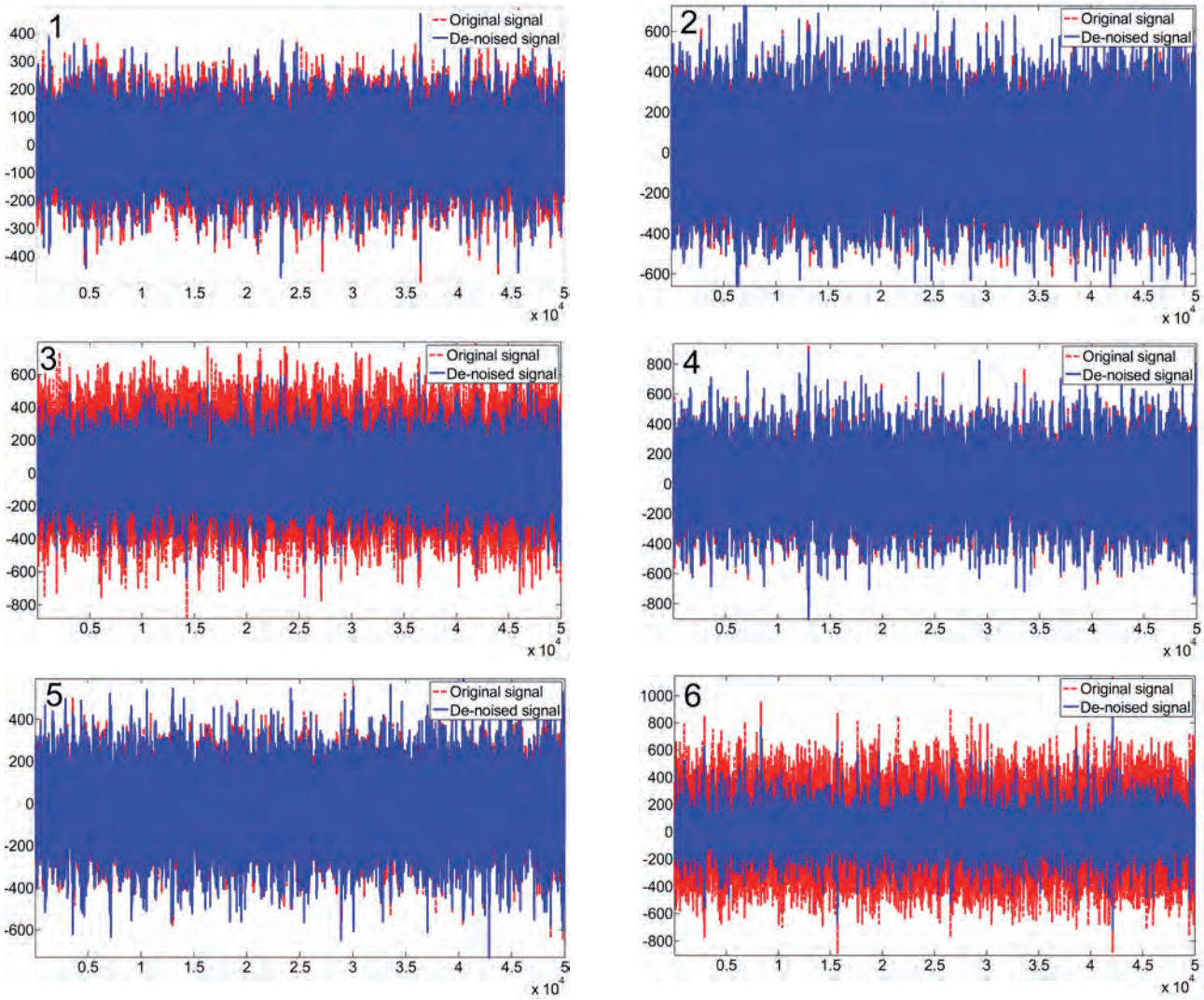

Fig. 4. Vibration signals for the damaged gear from first to sixth channel before and after denoising

eliminates discontinuities in the location where the elements have values equal to threshold value [13]. Signal reconstruction is performed similarly to the decomposition. One should oversample details and approximations before synthesis in the filters (their selection is critical for complete reconstruction of the original signal).

3.1. Denoising procedure

Denoising procedure for the multi-dimensional data is a generalisation of single dimension data denoising. The considerations are in accordance with Aminghafari et al. [1].

Let us assume the following p-dimensional signal model:

$$X(t) = f(t) + \varepsilon(t),\ t = 1,\dots, n \tag{3}$$

where:

$X(t)$, $f(t)$, $\varepsilon(t)$ are of 1x p dimension,

$f(t)$ – signal to be denoising,

$\varepsilon(t)$ – Gaussian noise with unknown covariance matrix $E(\varepsilon(t)^T \varepsilon(t))=\Sigma_\varepsilon$.

Every component $X(t)$ has form for $1 \le i \le p$:

$$X^i(t) = f^i(t) + \varepsilon^i(t),\ t = 1,\dots, n \tag{4}$$

where:

f^i – belongs to certain functional space (most often L^2 or Besov's).

Covariance matrix Σ_ε that is to be additionally defined, shows stochastic dependence between $X(t)$ components and spatial correlation models.

Denoising procedure can be expressed using three steps [1] for the X matrix that has n x p dimensions and consists of p signals (columns of X matrix) in a way that $n>>p$:

- For each column of X matrix perform a wavelet decomposition of J-th degree. In this degree J+1 matrixes $D_1,\dots,D_J$ are obtained – they contain degree detail coefficients from 1 to J of p signals and approximation coefficients A_J of p signals. The matrixes D_j and A_J have dimensions $n2$-j x p and $n2$-J x p;
- Determine the estimator $\hat{\Sigma}_\varepsilon$ of the noise covariance matrix and perform SVD (singular value decomposition) of the $\hat{\Sigma}_\varepsilon$matrix using orthogonal V matrix where $\hat{\Sigma}_\varepsilon = VAV^T$. Then change the basis using transformation matrix V (precisely calculating $D_j V$, $1 \le i \le p$) and perform single-dimensional filtering using threshold $t_i = \sqrt{2\lambda_i \log(n)}$ for the i-th column of the matrix $D_j V$;
- Perform reconstruction of the denoised matrix using simplified details matrix and approximation through basis changed using V^T matrix and reciprocal wavelet transform.

4. Test results

Vibration signals registered during tests were denoised using the procedure described above. Denoising was performed for the signals recorded for transmission in good condition and for damaged one (6 channels were registered). Figure 3 shows a graph of wavelet coefficients which illustrated the change of frequency vibration signal in time.

Denoising results in time domain for the damaged gear are shown in Fig. 4. Basing on the graphs for the axes of sensors according to the direction of output shaft axis one can notice that corresponding signals exhibit the highest level of noise.

Signal decomposition level was equal three and for the basic wavelet the Coiflet 1 was chosen (Fig. 5)

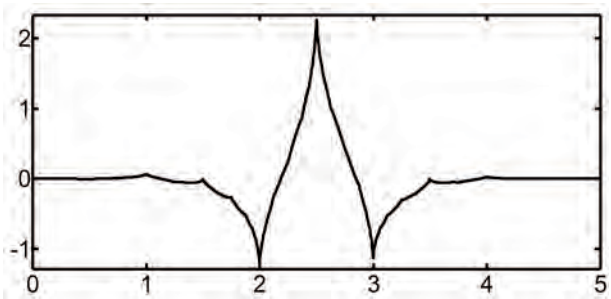

Fig. 5. Wavelet Coiflet 1

For the same criterion of calculating thresholds for the signal details the denoising was realized using soft and hard thresholding. Then the features of signals were computed and eight of twenty of them were selected using an algorithm presented in [8]. Selected features:

- average value,
- RMS value,
- peak value,
- peak factor,
- backlash factor,
- standard deviation,
- energy ratio,
- FM0.

In order to compare the efficiency of signals denoising the same features were computed for the signals without processing. Condition classification was performed using artificial neural network - multi layer perceptron (MLP).

Table 1. Condition classification results for the unprocessed signal

Network name	Quality (learning)	Quality (testing)	Quality (validation)	All trials
MLP 8-4-2	89,88	91,66	91,66	90,41

Table 2. Condition classification results for the denoised signal (soft thresholding)

Network name	Quality (learning)	Quality (testing)	Quality (validation)	All trials
MLP 8-4-2	95,53	95,83	95,83	95,62

Table 3. Condition classification results for the denoised signal (hard thresholding)

Network name	Quality (learning)	Quality (testing)	Quality (validation)	All trials
MLP 8-9-2	97,02	94,44	94,44	96,24

Network classification results are given in the tables above. Classification efficiency for the unprocessed signal reached approx. 90% and for the denoised signal – approx 5% better. Differences between hard and soft thresholding were insignificant.

5. Summary

The work presents a method of denoising vibration acceleration signals registered simultaneously for the same object. Comparison of the signals before and after denoising showed that for both sensors (in the same direction of vibration registration – along the axis of the input shaft) there were the highest amount of noise.

Signal denoising was performed using two methods - soft and hard thresholding. Then the neural network was to recognize gear's condition. Both methods resulted in similar and satisfying output. Classification quality achieved approx 96%. In order to verify efficiency of the method, similar procedure was performed for the original (unprocessed signal). Classification correctness was then smaller by approximately 5%.

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Andrzej TOMPOROWSKI

STREAM OF EFFICIENCY OF RICE GRAINS MULTI-DISC GRINDING

STRUMIEŃ WYDAJNOŚCI WIELOTARCZOWEGO ROZDRABNIANIA ZIAREN RYŻU*

A search for design solutions for grain grinding devices offering energy-saving production processes justify the research into the improvement of the theory and the design of grinders. The efficiency, functionality and performance of the rice grains grinding are significantly influenced by processes, difficult to describe, occurring within the working space of the grinder. Although there are some studies on the principles of the functionality and analysis of multi-disc grinders, an attempt has not been made so far at describing the influence of features and behaviour of ground material on efficiency, performance and usefulness of the biomaterial comminution/grinding process. The basis for the improvement of the functionality of a grinding device is an analysis of the potential of existing solutions and a determination of the scope of effective design features of the working unit within the permissible area. The criteria may be fulfilled by objective-oriented control of the design features of the multi-disc unit. In order for these actions to be effective, relevant relationships need to be explored and a mathematical description needs to be developed for the flow of ground grains through the working space of a multi-disc grinder, as a result variable of the structure and the operation of a working unit.

Keywords: *grinding, biomaterials, efficiency.*

Poszukiwania rozwiązań konstrukcyjnych zespołów rozdrabniających ziarna zbóż, prowadzące do energooszczędnych procesów produkcyjnych uzasadniają podjęcie badań nad doskonaleniem teorii i konstrukcji rozdrabniaczy. Istotny wpływ na wydajność, funkcjonalność i sprawność procesu rozdrabniania ziarna ryżu mają trudne do opisania zjawiska zachodzące w przestrzeni roboczej rozdrabniacza. Pomimo, że dostępne są opracowania na temat podstaw funkcjonalności i badań rozdrabniaczy wielotarczowych, jak dotychczas nie podejmowano próby opisu wpływu cech i zachowań rozdrabnianego materiału na wydajność, sprawność i użyteczność procesu rozdrabniania biomateriałów.Podstawą do poprawy funkcjonalności działania maszyny rozdrabniającej jest przeprowadzone rozpoznanie możliwości istniejących rozwiązań oraz określenie zakresu, skutecznych w przetwórstwie, cech konstrukcyjnych zespołu roboczego z obszaru dopuszczalnego. Spełnienie kryteriów może być osiągnięte między innymi na drodze celowego sterowania cechami konstrukcyjnymi zespołu wielotarczowego. Aby jednak działania te przyniosły planowane korzyści, konieczne staje się poznanie zależności oraz opracowanie opisu matematycznego przepływu rozdrabnianego ziarna przez przestrzeń roboczą rozdrabniacza wielotarczowego, jako zmiennej wynikowej konstrukcji i działania zespołu roboczego.

Słowa kluczowe: *rozdrabnianie, biomateriały, wydajność.*

1. Introduction

An innovative approach to the design studies is based on developing operational objectives, means or techniques that have not yet been integrated into the practice and not to mention into the engineering knowledge. The verification procedures may relate to such problems of the grinding process as dynamics of changes in the initial length of grains, transport of the ground material (grains of various lengths) with a simultaneous quasi-cutting between subsequent discs, a stream of particles leaving the machine with a specific intensity and under specific conditions. Consequently, the knowledge on the grinder design, as a practical and empirical field of science, focuses on not only the current situation but also on the future potential that is currently only conceptual [1, 2, 3, 5].

Purpose of the study: The main purpose of the study is to determine factors, design features, functional features and their influence on the dynamics and efficiency of grain biomaterial (long grain rice) grinding. The analysis carries out with a multi-disc grinder constructed according to a patent held by the University of Technology and Life Sciences in Bydgoszcz [4]. Additional aim of the work was to describe the complexity of the phenomena, process and relationships of the multi-disc grinding.

2. Rice grains comminution model

For the purpose of volumetric efficiency tests, long grains rice of stabilized humidity parameters and standardized grain size were used as the feed material. Therefore, an assumption was made that for the purpose of this study an output model of the feed material (grains) is the ground substance of even size and repeatable constant dimensions of a single grain.

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

It is assumed that in the holes of grinding discs, rice grains take the position along their longer axis, perpendicularly to the intra-disc cutting (shearing) plane.

The orientation of the ground medium ρ_n^m within the operating space of the multi-disc multi-hole grinder is described by the probability distribution of the grain length. Because the material in the holes of the same disc is subjected to the same cutting process in all holes, the indexed state is the number of a disc (n) and the number of a cut (m):

$$\rho_n^m : (0, l_{\max}] \to [0,1], \qquad \int_0^{l_{\max}} \rho_n^m dl = 1. \tag{1}$$

Dislocation of the material to the next disc involves passing through the cutting process stage, n ≤ m. The initial state of the material, in hole of the first disc (all grains are intact) before the first cut equals ρ_0^0 and constitutes an input state of the material that will be described with a certain function focused on l_{max} value.

An input state of the material during the grinding process is changed due to two factors, mechanisms (fig.1): grinding (quasi-cutting) and removal of grains of the desirable or smaller size from the intra-disc spaces of the grinding unit of the device.

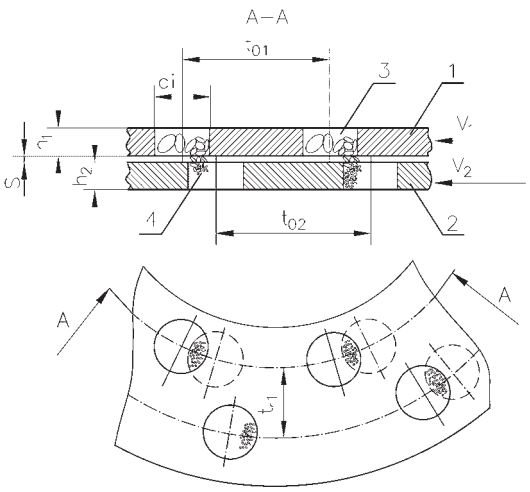

Fig.1. Technique (method and design means) of disc arrangement in the grinder for quasi–cutting of the grain material [2]; 1-previous disc, 2-next disc, 3-input state of the material, 4-next state of the material, d_i – hole diameter, t_{01}, t_{02}, t_{rl} – scale, h_1, h_2 – disc thickness, s – gap, V_1, V_2 – linear velocity

3. Grinding process

When holes of the two adjacent discs meet (fig.2) and their combined section begins to increase (0, max), the next hole is filled with a part of ground material from the previous hole. In order for the cutting process to be efficient and effective, a hole in the previous disc must be completely filled when the combined section of the holes begins to decrease (max, 0).. The three conditions must be fulfilled:

1. The quantity of the material in the previous hole must be always greater than the space available in the next hole. Otherwise, we can imagine that the material moves from a hole of the previous disc to a hole of the next disc without being sheared along the whole length of the device. Because some of the material is removed to the space between discs, the volume of holes in the next disc should always be smaller than in the previous disc (this is achieved through a smaller section of a hole or smaller thickness of a disc, however, there are some design limitations related to stresses that a disc must carry). Thickness (h) of disc n, for the purpose of calculations with be represented by yn,, whereas will represent the height to which the material fills a hole of disc n before k cut.
2. Each point of the section of the next hole should, at a certain moment of the relative motion of the disc, be located within the section of a hole of the previous disc.
3. When a cut is made, a hole in the next disc is closed for transfer to the following disc (there are not arising so-called opening corridors).

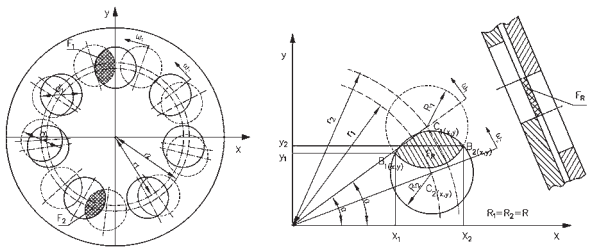

Fig. 2. Sectional area and effective grinding surface for two grinding discs between edges of the grinding holes [2], FR –intra-hole surface area of cut (for example: F1, F2)

The fill of a hole in a layer changes as follows (fig.3):

The analysis shows that k cut after $n-1$ disc occurs earlier than k cut after disc n. With such numbering of cuts, quasi-cuts (for each disc the numbers begins from the first cut), grains may, at each boundary of individual discs, be subjected to cutting identified with the same number.

When a hole is filled, the shared part of the cross-section of the holes begins to diminish – cutting (quasi-cutting) process. According to the initial assumption, each grain within the section of grinding holes is subjected to the cutting process. The orientation of grains in relation to the plane on which the cutting process takes place is random with even distribution. Grains of each length will be disintegrated (ground) with equal probability into two smaller particles, with the total length equal to the length (size) before cutting.

Cutting (to be precise quasi-cutting) always occurs in the material that before the complete filling was in the previous disc. The distribution of grain length, when the grain is cut, in the material that fills the empty space of disc changes according to the following relationship:

$$\tilde{\rho}_{n+1}^m(x) = A_{n,m}\rho_n^m = \left(1 - \frac{x}{y_{n+1} - \tilde{y}_{n+1}^m}\right)\rho_n^m(x) + \frac{1}{y_{n+1} - \tilde{y}_{n+1}^m}\int_x^{l_{\max}} \rho_n^m(l)\,dl, \tag{2}$$

while in the material that remains in disc n:

$$\tilde{\rho}_n^{m+1}(x) = \tilde{B}_{n,m}\rho_n^m = \left(1 - \frac{x}{\tilde{y}_n^m}\right)\rho_n^m(x) + \frac{1}{\tilde{y}_n^m}\int_x^{l_{\max}} \rho_n(l)\,dl, \tag{3}$$

The functions obtained are non-negative being a sum of two non-negative components. When integration is performed from 0 to l, it may be easily established that those are the probability distributions:

$$\int_0^{l_{\max}} \tilde{\rho}_n^{m+1}(x)\,dx = 1 - \frac{\bar{x}}{\tilde{y}_n^m} + \frac{1}{\tilde{y}_n^m}\int_0^{l_{\max}}\int_x^{l_{\max}} \rho_n(l)\,dl\,dx = 1 - \frac{\bar{x}}{\tilde{y}_n^m} + \frac{1}{\tilde{y}_n^m}\int_0^{l_{\max}}\int_0^{x} \rho_n(l)\,dx\,dl = 1 - \frac{\bar{x}}{\tilde{y}_n^m} + \frac{1}{\tilde{y}_n^m}\int_0^{l_{\max}} x\rho_n(l)\,dx = 1 \tag{4}$$

and similarly for distribution $\tilde{\rho}_{n+1}^m$. Therefore, operators $A_{n,m}$ and $\tilde{B}_{n,m}$ are correctly defined stochastic operators.

To simplify the analysis, an assumption was made that after the cutting is completed, the distribution of grain length in disc n+1 is homogeneous (the cut fraction and the fraction situated in the hole before the cut mix), and therefore it is weighted average of ρ_{n+1}^k and ρ_n^k:

$$\rho_{n+1}^m(x) = \frac{\tilde{y}_{n+1}^m}{y_{n+1}}\rho_{n+1}^{m-1} + \frac{y_n - \tilde{y}_{n+1}^m}{y_{n+1}} A_{n,m}\rho_n^m(x) \tag{5}$$

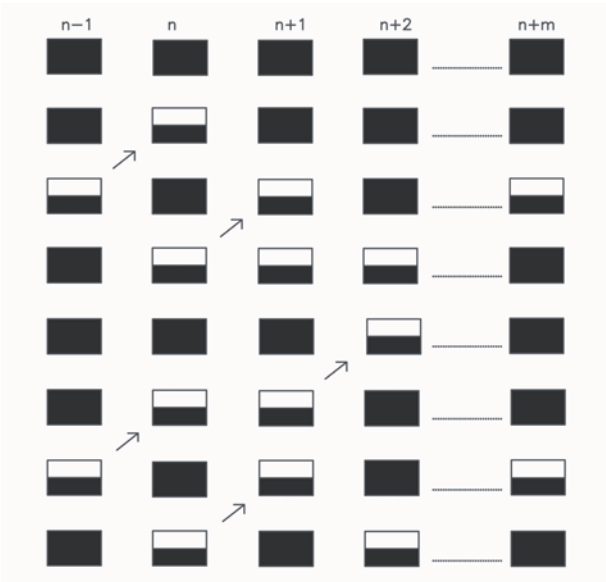

Fig. 3. Diagram showing transport of the material subjected to the grinding process with quasi-cutting between the discs; where indicates a cutting phase

4. Removal process

After the grain is cut, two layers of the material move with respect to one another in the direction of movement of two adjacent discs and gradient of their mutual velocities. Particles of the material are removed from the previous hole (they are subjected to component of force, gravitational force perpendicular to the intra-disc gap), whereas they are not removed from the next hole (because the direction of perpendicular component of gravitational force is away from the gap).

After the cutting, the length distribution is as follows:

$$\tilde{\rho}_n^{m+1}(x) = B_{n,m}\rho_{n,m} = \begin{cases} \tilde{\rho}_n^{m+1}(x)\left(\int_{l_{\min}}^{l_{\max}} \tilde{\rho}_n^{m+1}(x)\right)^{-1} & x \rangle l_{\max} \\ 0 & x \langle l_{\min} \end{cases} \tag{6}$$

Level of material after cut m (before cut m+1) in gap n, is:

$$\tilde{y}_n^{m+1} = \left(y_n - y_{n+1} + \tilde{y}_{n+1}^k\right)\left(1 - \frac{\int_0^{l_{\min}} \tilde{B}_{n,m}\rho_n^m(x)\,x\,dx}{\int_0^{l_{\max}} \tilde{B}_{n,m}\rho_n^m(x)\,x\,dx}\right) \tag{7}$$

In order to obtain the distribution in the whole space of the hole before cut m+1 (after re-fill), the following weighted average must be used:

$$\rho_n^{m+1}(x) = \frac{y_n - \tilde{y}_n^{m+1}}{y_n} A_{n-1,m}\rho_{n-1}^m + \frac{\tilde{y}_n^{m+1}}{y_n} B_{n,m}\rho_n^m \tag{8}$$

Operator is no longer a linear operator as , because it depends on the level of the material that remains in disc n after cut m: , and is a function of the probability distribution in the material (that determines the quantity of material removed from the machine during the cutting process) [6]. For to be treated as linear operators, values of must be treated, at each stage of the procedure, as pre-determined and iterative – corresponding to the results of studies and experiments.

5. Flow of particles leaving the machine

At cut m, the flow of particles leaving the machine through a gap between disc n and n+1 is described with the probability distribution:

$$s_n^m(x) = \begin{cases} \int_x^{l_{\max}} \rho_n(l)\,dl\left(\int_0^{l_{\min}}\int_x^{l_{\max}} \rho_n(l)\,dl\,dx\right)^{-1} & l \langle l_{\min} \\ 0, & l \rangle l_{\min} \end{cases} \tag{9}$$

and its volume equals:

$$V = \left(y_n - y_{n+1} + \tilde{y}_{n+1}^k\right)\frac{\int_0^{l_{\min}} \tilde{B}_{n,m}\rho_n^m(x)\,x\,dx}{\int_0^{l_{\max}} \tilde{B}_{n,m}\rho_n^m(x)\,x\,dx} \tag{10}$$

6. Changes of length distribution in discs

The grain length distribution of disc n after cut m is described with ρ_n^m. Operators used for distribution ρ_n^m in ρ_{n+1}^m and in ρ_n^{m+1} are identified accordingly as $A_{n,m}$ and $B_{n,m}$. Changes of distributions are shown in the efficiency diagram, fig.4.

State ρ_0^0 is known (distribution of grain length for the input material). State ρ_n^m was obtained from operation of the sum of products of operators A and B for state ρ_0^0. The products represent all paths to that state from state ρ_0^0. For example:

ρ_0^0		ρ_0^0		ρ_0^0				
	↘		↘		↘			
ρ_0^0	B0,0 →	ρ_0^1	B0,0 →	ρ_0^2	B0,0 →	ρ_0^3	B0,0 →	⋯
	↘		↘		↘			
ρ_1^0	B1,0 →	ρ_1^1	B1,1 →	ρ_1^2	B1,2 →	ρ_1^3	B1,3 →	⋯
	↘		↘		↘			
ρ_2^0	B2,0 →	ρ_2^1	B2,1 →	ρ_2^2	B2,2 →	ρ_2^3	B2,3 →	⋯
⋮		⋮		⋮		⋮		⋱

Fig. 4. Efficiency-based diagram of grain length distributions – products of quasi-cutting, for specific discs

$$\rho_2^3 = \left(A_{1,2}A_{0,1}B_{0,0} + A_{1,2}B_{1,1}A_{0,0} + B_{2,2}A_{1,1}A_{0.0} \right)\rho_0^0 \quad (11)$$

State ρ_n^m is obtained by application of A operator n times[1] and B operator m times . The path is unambiguously determined by n-element subset of a set of steps within the complete path $\{1, \ldots, m\}$, steps within which A operator operates. The number of such subsets, i.e. the number of products in the sum equals $\binom{m}{n}$. In general, operators A and B do not commutate. It is essential for further analysis to calculate such expressions.

States ρ are positive elements of Banach space[1] L (0, 1), and operators A and B are endomorphisms of that space. For practical reasons, approximate states ρ with positive elements R^d and operators A and B with matrixes d×I. Physically, it corresponds to the division of a l long particle into d undividable parts, l/d long – the length corresponding to the linear measure of grinding.

1) to be more precise, weighted average values of the result of operation of that operator

7. Energy flow

With an assumption that stresses will propagate at infinite rate, when closing of the shared area of two holes begins, material condensates evenly in each grain until a limit condensation is exceeded and a grain breaks. Then, layers move with respect to one another with the friction force constant for a unit of adjacent surfaces of two layers. Apart from that, there is also some friction of the material against surfaces of the discs where there are no holes in the next disc.

8. Conclusions

Phenomena, processes and relations of the multi-disc grinding, despite their complexity, are relatively easy to describe formally. Determination of process factors (actions and methods), design features (means, devices and systems), operational conditions and their influence on the dynamics and efficiency of the rice grinding process, with a multi-disc grinder used as an example, was possible, with an assumption that quasi-cutting stresses will propagate at an infinite rate, in relation to:

- probability distribution of grain length,
- probability distribution of particles in a stream leaving the machine through a gap between discs.

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PREDICTION METHODOLOGY OF DURABILITY OF LOCOMOTIVES DIESEL ENGINES

METODOLOGIA PROGNOZOWANIA TRWAŁOŚCI SILNIKÓW DIESLA W LOKOMOTYWACH

The article testifies that technical maintenance and repair terms as well as durability can be predicted accordingly to the maintenance parameters of the diesel locomotives. It is determined that fixing fuel consumption and capacity of diesel locomotives and taking in comparison with limit values allows to set a performance date for technical maintenance. Introduced suggested aspects of interrepair resource of the diesels dependent on comparable fuel consumption and evaluating their operating probability without failure for the durability prediction of diesel locomotives. Currently, the most common are three strategies: until failure, scheduled – premonitory and adaptive (diagnostic). When the quantity of necessary technical maintenances is known for the specific kind of diesel locomotives it is possible to determine interrepair resource depending on comparative and required per hour consumption of fuel and predict their durability taking into account probability of operating without failures.

Keywords: *durability, technical maintenance and repairs, locomotive engines, resources, reliability, prediction.*

W artykule wykazano, że częstotliwość przeglądów technicznych i remontów spalinowozów z silnikami diesla można prognozować analizując parametry eksploatacyjne. Obecnie najbardziej rozpowszechnione są trzy strategie: do awarii, planowo-wyprzedzająca i adaptacyjna (diagnostyczna). W konkretnych warunkach zarządzania gospodarczego na pierwsze miejsce wysuwa się specyfika użytkowania spalinowozów, o zaraz po niej – normatywne wymagania techniczne, reglamentujące eksploatację spalinowozów. Ustalono, że poprzez odnotowywanie zużycia paliwa oraz mocy spalinowozów można określić czas eksploatacji, po upływie którego konieczne będzie przeprowadzenie przeglądu technicznego. Przedłożona została teoretyczna zależność okresu międzyremontowego diesli od porównawczego zużycia paliwa, wykorzystywana do oceny prawdopodobieństwa bezawaryjnej pracy oraz zaproponowana metodyka prognozowania trwałości spalinowozów z silnikami diesla. Znając właściwą dla danej marki spalinowozu liczbę przeglądów technicznych, można oszacować okres międzyremontowy w zależności od godzinnego i porównawczego zużycia paliwa oraz uwzględniając ich prawdopodobieństwo bezawaryjnej pracy, w ten sposób prognozując ich trwałość.

Słowa kluczowe: *trwałość, przegląd techniczny i remont, silniki spalinowozów, okres międzyremontowy, niezawodność, prognozowanie.*

1. Introduction

Operating locomotives on the railroad leads to natural obsolescence of the engines as well as other components and details that consequently increases the number of failures. In order to increase operating reliability and durability of locomotive‘s diesel engines it is necessary to monitor their technical condition employing determined system of their technical maintenance and repairs which essence is to rebuilt nominal or approximate values of diesel state parameters while maintaining certain purposeful complex of implements as elimination of failures in operating conditions requires plenty of time and material resources. In that manner resource is rebuilt, high working probability of diesels without failures is retained.

Great influence on reliability and durability while operating diesels rationally plays technical maintenance and repairs operations. Accordingly, an opportunity to thoroughly analyze technical maintenance and repairs system implementation conditions and methods arises while periodically examining condition and equivalence to normative technical basis that regulate those processes particularly when more new enginery has been acquired.

The aim of this work – theoretical validation of technical maintenance and repairs as well as durability prediction of diesel locomotives according to exploitation parameters.

2. Research methodology and results

There exists a normative technical maintenance and repairs system of the locomotives that regulates technical maintenance and repairs of the machines [16, 17, 19]. However, improving enginery and its maintenance and repairs technologies there is

an appreciable necessity to establish a corrected complex of new organizational technical means that, on one hand, settles united principles of technical maintenance and, on the other hand, various standards and regulations for the planning and management of technical services activities of railways locomotive depots.

With no doubt, a weighty influence on the diesel locomotives engines technical state maintenance has strategies of technical maintenance and repair systems. Currently, the most common are three strategies: until failure, scheduled – premonitory and adaptive (diagnostic). Within the given odds and outs [16, 17] all of them have a right to exist, yet a selection or creation of suitable strategy, furthermore, when selecting combinations of their elements, must be weight up well and, of course, reasoned by the appropriate manner. Particularity of the locomotives usage at specific property management conditions comes up in the foreground and only afterwards normative technical requirements that regulates operation of the locomotives [1–6, 10–13].

Certain algorithms with the attaining information about technical state changes as well as special technical state determination methods of the parts, as technical objects and their components are created and presented in the tasks [14–16, 18]. System of actions pointed to the management of diesel locomotives reliability and durability must base reliable and full information upon certain time limit. Being aware of the operating conditions, normative legal fundamentals, initial state (at the beginning of operating or after repair), chosen technical maintenance and repair system, material conditions of technical supplies allows to determine state of the object fairly precise. Logic says that maximum of information helps in choosing optimal unit of technical means and actions on certain manufacture conditions.

It is a pity that there is no settled constitutional attitude on the support of locomotives technical state. Diagnostics that should determine technical state of separate details and assemblies has a limited application possibility and cannot include a huge amount of factors that influence common technical state.

Guaranteed terms of necessary to perform tasks and moment when it is required to maintain correction actions of the technical state cannot be held if we follow planned – premonitory repair system of technical maintenance whereas applying adaptive strategy is possible only if we obtain very reliable information about technical state of an object. Until failure strategy does not give an opportunity to interpose into the management process.

There have been many trials to forecast resources and system of technical maintenances and repairs [14, 15, 18] taking into account operating rates until now, but this problem hasn't been solved yet.

Effective fuel capacity decreases depending on the technical state of diesel locomotives [7–9]. Evaluation of effective capacity that corresponds to the certain operating regime, according to the operating characteristics of the diesel locomotives it is possible to write expression of the fuel consumption per hour:

$$G_e = N_e \int_0^{P_{\max}} \int_0^{g_{\max}} P(g_e)\,dP\,dg_e \quad , \tag{1}$$

where N_e – effective diesel capacity, kW; $P(g_e)$ – probability function of operation without failure subjected to comparative fuel consumption (it is chosen according to the technical state and graphical interpretation of the diesel; P_{max} – maximal probability value of the diesel operation without failure; g_{max} – maximal comparative fuel consumption that are taken constant during the operating process, g /kW year.

If we trace an amount of used fuel of diesels during every hour while operating and compare those consumption with limit values, then time when we need to perform technical maintenance is expressed in such form:

$$t''^{G}_{M} = \frac{\sum_{i=1}^{n-1} G_{ei} t_i + \sum_{j}^{m} G_{ej}^{\lim} t_j}{\sum_{i=1}^{m} \bar{G}_{ei}} \quad , \quad \begin{matrix} i = 1,2,3...n \\ j = n...m \end{matrix} \tag{2}$$

where $\sum_{i=1}^{m} \bar{G}_{ei}$ – sum of diesel fuel consumption between the limit hours during the interval from j up to m, according to the operating conditions this interval has been chosen by the leadership (investigator) of the depot, with the difference not exceeding at any circumstances 8, kg/h; $\sum_{i=1}^{m} \bar{G}_{ei}$ – sum of average fuel consumption per hour without limited fuel consumption per hour, kg/h; ti – i-th run-in during limited fuel consumption per hour, h; t_j – j-th run-in during limited fuel consumption per hour from the fixed beginning, h.

Using expression (2), when we know values of minimal, maximal and limited fuel consumption per hour, it is possible to show times of technical maintenance performances graphically (Fig. 1).

If we write expression (2) taking into account formula (1), we get dependency of technical maintenance performances to their comparative fuel consumption per hour evaluating possibility of operation without failures:

$$t''^{gP}_{M} = \frac{\sum_{i=1}^{n-1} t_i P_{eV} \int_{\lim}^{P_{\max}} \int_0^{g_{\max}} P(g_{eV})\,dP\,dg_{eV} + \sum_{j}^{m} t_j P_{ej} \int_0^{P_{\lim}} \int_0^{g_{\max}} P(g_{ej}^{g})\,dP\,dg_{ej}}{\sum_{i=1}^{m} \frac{P_{eV}}{m} \int_{\lim}^{P_{\max}} \int_0^{g_{\max}} P(g_{eV})\,dP\,dg_{eV}} \tag{3}$$

Graphical interpretation (3) is given in Fig. 2. There is also necessary to put minimal, maximal and limit values of the comparative fuel consumption per hour.

If we constantly (all the time) obtain information about variation of diesel capacitance during exploitation it is possible to draw graphs of operating probability without failures dependent on the effective capacitance (Fig. 3).

The graph shows that there exists point 2, 3, 5 that correspond to maximal values of probability working without failures during diesels exploitation. Points that are below show decrease of diesels reliability and demand renewal (improvement) of their technical state. As we can see from the graph, transitions from zones with minimal and maximal values of effective capacity can be of several types, i.e. interruption can be sudden in order to improve technical state of diesels, rise the probability of operating without failures or it can be performed

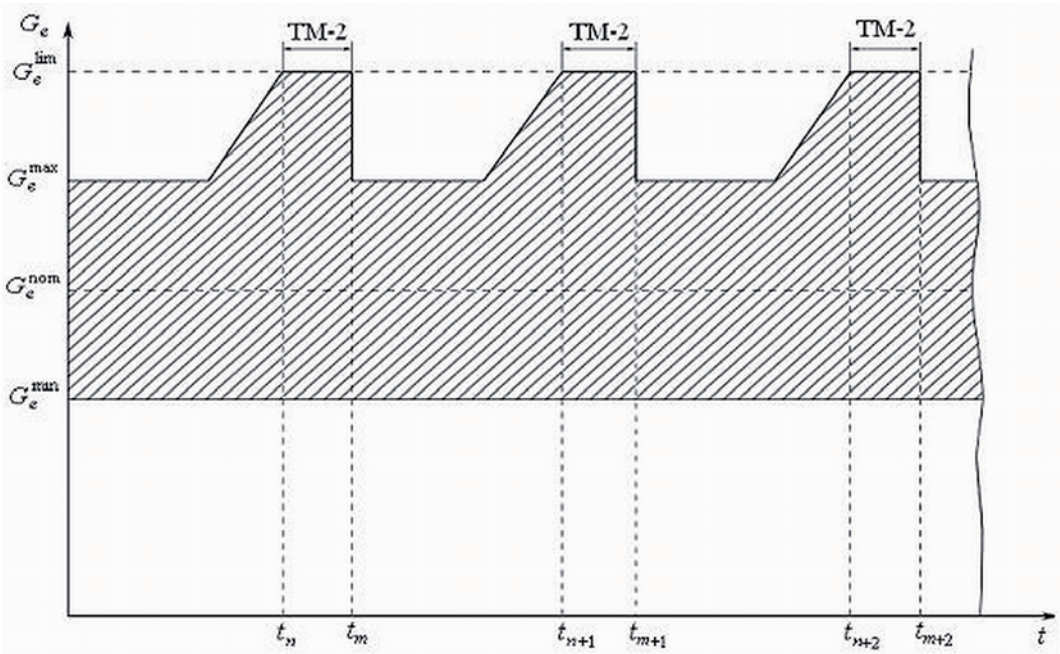

Fig. 1. Technical maintenance performance times according to fuel consumption per hour of the thermo diesels

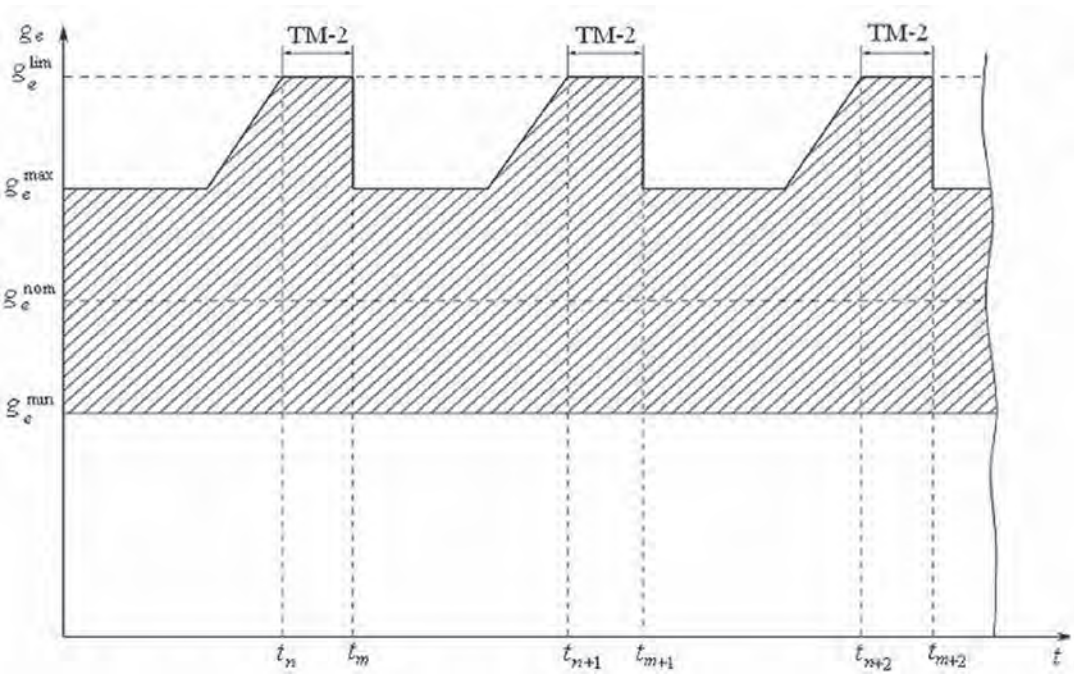

Fig. 2. Technical maintenance performance times according to comparative fuel consumption on the diesel locomotives

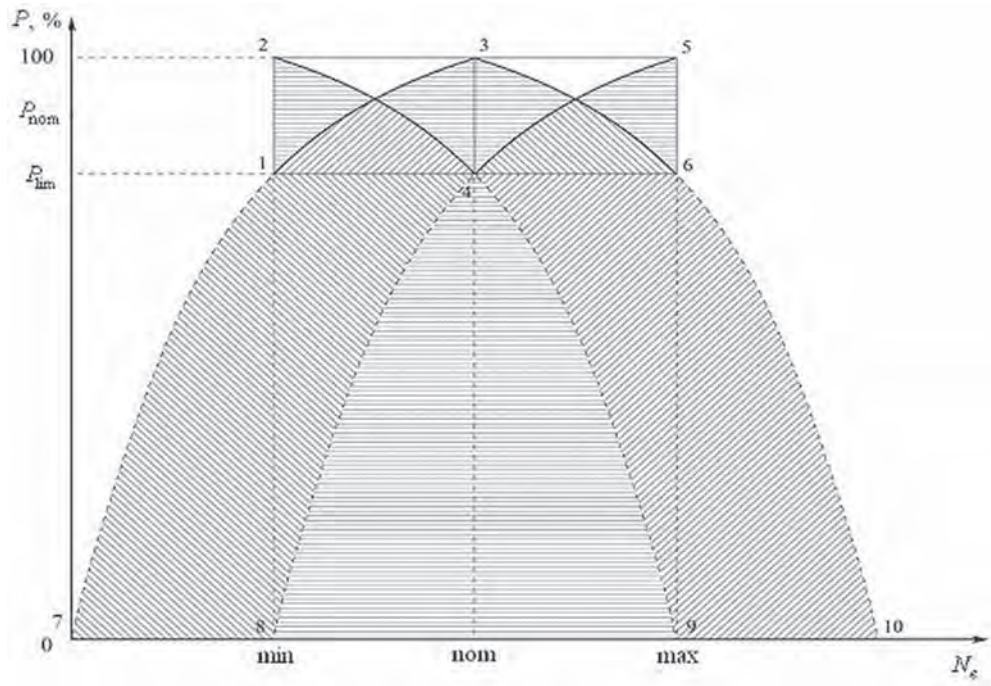

Fig. 3. Dependency of probability working without failures on the effective capacitance of diesel locomotives

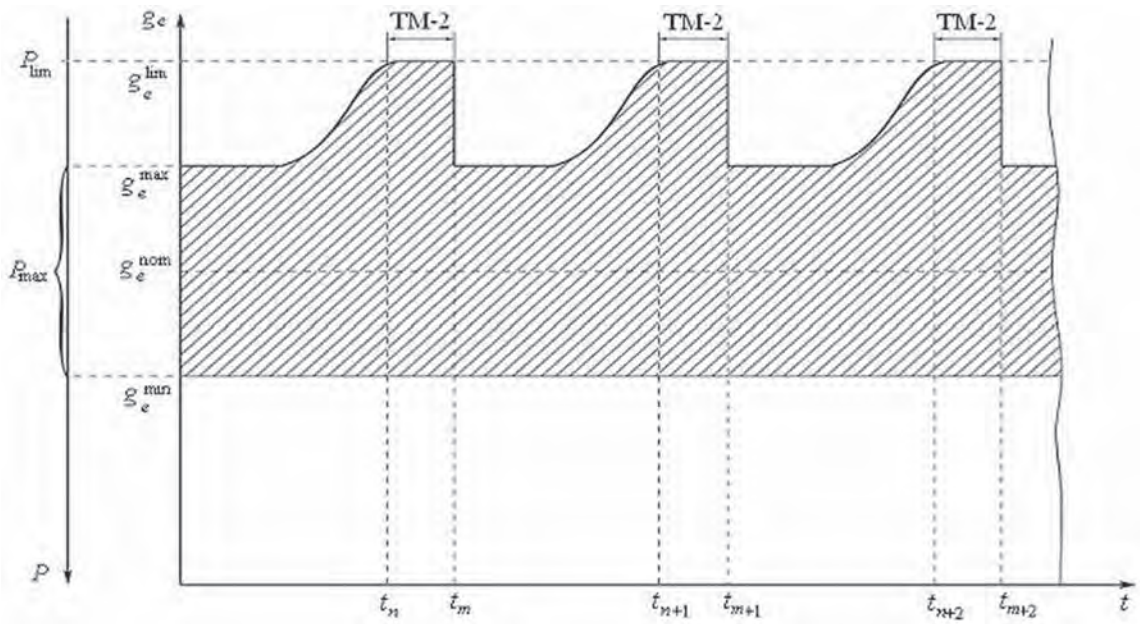

Fig. 4. Dependency of technical maintenance performance dates of diesel locomotives on comparative consumption of fuel and operating without failures probability

during planned technical maintenances that also guarantees high operating probability without failures.

Constant maintenance of diesels high technical state ensures increase in durability of diesel locomotives. Graphical interpretation of obtained formula (3), i.e. dependency of diesels operating probability without failures on effective capacity P (Ne), results in possibility to specify formula (3) and write it in such a form:

$$t_{\text{п}M}^{gP} = \frac{\sum_{i=1}^{n-1} t_i P_{eV} \int_{\lim}^{P_{\max}} \int_{0}^{g_{\max}} P(g_{eV}) dP dg_{eV} + \sum_{j}^{m} t_j P_{ej} \int_{0}^{P_{\lim}} \int_{0}^{g_{\max}} P(g_{ej}^{g}) dP dg_{ej}}{\sum_{i=1}^{m} \frac{P_{eV}}{m} \int_{\lim}^{P_{\max}} \int_{0}^{g_{\max}} P(g_{eV}) dP dg_{eV}} \tag{4}$$

This expression describes terms of technical maintenances with higher probability that can be shown graphically (Fig. 4).

In this case it is necessary to determine limits of the diesels operating without failures probability additionally. Those limits are chosen according to which accurateness technical state diagnosis must be reached. When we know amount of corresponding technical maintenances for the certain kind of diesel locomotives, we can estimate interrepair resource depending on the comparative consumption of fuel evaluating probability of operation without failures:

$$t_{\text{п}M}^{gN_eP} = \frac{\sum_{i=1}^{n-1} t_i \int_{\lim}^{P_{\max}} \int_{0}^{g_{\max}} P(g_{eV}) P(N_{ei}) dP dg_{eV} + \sum_{j}^{m} t_j \int_{0}^{P_{\lim}} \int_{0}^{g_{\max}} P(g_{ej}^{g}) P(N_{ej}) dP dg_{ej}}{\sum_{i=1}^{m} \frac{1}{m} \int_{\lim}^{P_{\max}} \int_{0}^{g_{\max}} P(g_{eV}) P(N_{ei}) dP dg_{eV}} \tag{5}$$

where $A_{\text{TM}-1}$, $A_{\text{TM}-2}$ – amount TM-1 and TM-2 respectively.

In accordance to (2) and (3), durability of diesel locomotives can be expressed as follows.

Dependent on:

– fuel consumption per hour:

$$L^{G} = (A_{\text{TR}} + 1)(A_{\text{TM}-1} + A_{\text{TM}-2}) \frac{\sum_{i=1}^{n-1} G_{ei} t_i + \sum_{j}^{m} G_{ej}^{g} t_j}{\sum_{i=1}^{m} \bar{G}_{ei}} \tag{6}$$

– comparative fuel consumption evaluating probability of diesels operating without failures:

$$L^{gP} = \frac{\sum_{i=1}^{n-1} t_i N_{eV} \int_{g}^{P_{\max}} \int_{0}^{g_{\max}} P(g_{eV}) dP dg_{eV} + \sum_{j}^{m} t_j P_{ej} \int_{0}^{P_g} \int_{0}^{g_{\max}} P(g_{ej}^{g}) dP dg_{ej}}{\sum_{i=1}^{m} \frac{N_{eV}}{m} \int_{g}^{P_{\max}} \int_{0}^{g_{\max}} P(g_{eV}) dP dg_{eV}} \times$$
$$\times (A_{\text{TR}} + 1)(A_{\text{TM}-1} + A_{\text{TM}-2}) \tag{7}$$

where ATR – total amount of overhauls of the diesel locomotives.

Using (5), durability of diesel locomotives can be expressed in such shape:

$$L^{gN_eP} = \frac{\sum_{i=1}^{n-1} t_i \int_{g}^{P_{\max}} \int_{0}^{g_{\max}} P(g_{eV}) P(N_{ei}) dP dg_{eV} + \sum_{j}^{m} t_j \int_{0}^{P_g} \int_{0}^{g_{\max}} P(g_{ej}^{g}) P(N_{ej}) dP dg_{ej}}{\sum_{i=1}^{m} \frac{1}{m} \int_{g}^{P_{\max}} \int_{0}^{g_{\max}} P(g_{eV}) P(N_{ei}) dP dg_{eV}} \times$$
$$\times (A_{\text{TR}} + 1)(A_{\text{TM}-1} + A_{\text{TM}-2}) \tag{8}$$

Prediction of life in economic activities is very important moment, because the object is expensive.

3. Conclusions

Performed theoretical investigations on the durability and dates of technical maintenance and repair performance estimation of diesel locomotives depending on exploitation parameters have shown that:

1. Fuel consumption per hour can be described as graphical interpretation depending on the probability of operating without failures and effective capacity.
2. It is possible to determine necessary date for technical maintenance performance depending on the state of exploitation parameters if we fix fuel consumption of the diesel locomotives during its operating hours and compare them to limit values.
3. When the quantity of necessary technical maintenances is known for the specific kind of diesel locomotives it is possible to determine interrepair resource depending on comparative and required per hour consumption of fuel and predict their durability taking into account probability of operating without failures.

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Zdzisław CHŁOPEK

TESTING OF HAZARDS TO THE ENVIRONMENT CAUSED BY PARTICULATE MATTER DURING USE OF VEHICLES

BADANIA ZAGROŻENIA ŚRODOWISKA CZĄSTKAMI STAŁYMI PODCZAS EKSPLOATACJI POJAZDÓW SAMOCHODOWYCH*

The study presents results of tests on emissions of fractions of PM10, PM2.5 and PM1 dusts. For modeling of emissions of fractions of PM2.5 and PM1 particles, results of empirical tests were used as carried out in air quality supervision stations located in the agglomeration of the city of Brno. The results of modeling of emissions of fractions of PM2.5 and PM1 particles did not make it possible to make unequivocal conclusions, which proves that the discussed problem has to be treated statistically. However, a significant relation between models of emissions of fractions of particulate matter and sources of emissions of dusts and conditions for distribution of the same were observed.

Keywords: *dusts, particulate matter, PM10, PM2.5, PM1, vehicles.*

W pracy przedstawiono wyniki badań imisji frakcji pyłów PM10, PM2.5 i PM1. Do modelowania imisji frakcji cząstek stałych PM2.5 i PM1 wykorzystano wyniki badań empirycznych, przeprowadzonych na stacjach nadzorowania jakości powietrza w aglomeracji czeskiego miasta Brna. Wyniki modelowania imisji frakcji cząstek stałych PM2.5 i PM1 nie umożliwiły sformułowania jednoznacznych wniosków, co dowodzi konieczności statystycznego potraktowania badanego problemu. Stwierdzono jednak istotną zależność modeli imisji frakcji cząstek stałych od źródeł emisji pyłów i warunków ich rozprzestrzenia.

Słowa kluczowe: *pyły, cząstki stałe, PM10, PM2.5, PM1, pojazdy samochodowe.*

1. Introduction

Hazards posed by dusts to the environment are commonly known. The harmful character of dusts for human health has been discussed in a lot of studies relating both to health aspects [1, 10, 16, 18, 28, 31, 34, 35] as well as evaluation of factors affecting emissions of dusts [2, 3, 5–9, 11–15, 17, 19, 21, 22, 24, 27, 29]. Sources of emissions of dusts include natural phenomena and civilization activities. Most significant natural sources of emissions of dusts include volcanic eruptions, deposits, marine aerosols, animal and plant sources as well as forest fires. On a global scale, the natural sources of emissions of dusts are dominant, however, in the areas characterized by particularly intense human activities, anthropogenic sources of dusts have strongest impacts upon contamination of the environment. The anthropogenic sources of dusts include all production processes and fuel combustion processes. Automobile industry plays a significant role in contamination of the environment with dusts, especially in large centers of urban agglomerations.

The harmful character of dusts for human health depends on chemical and mineral composition and physical structure of dusts as well as sizes of dust particles [2, 3, 6, 7, 17, 21, 22, 35]. Depending on conventional sizes of dust particles, the following particles may be distinguished [2, 3, 6, 7, 17, 21, 22, 35]:

- TSP (total suspended particles) – a mixture of small particles of conventional sizes not exceeding 300 μm and suspended in the air (a dispersed phase of the solid body–gas two–phase system),
- PM10 suspended dust – of conventional sizes not exceeding 10 μm,
- PM2.5 fine dust – of conventional sizes not exceeding 2,5 μm,
- PM1 nanoparticles – of conventional sizes not exceeding 1 μm, constituting practically invisible dust [24, 29].

Particulate matter with conventional diameters exceeding 10 μm is mainly arrested in upper respiratory tract, where most of them are exhaled, PM10 particles (with exclusion of PM2.5 particles) even penetrate lungs and, although they do not accumulate in the lungs, they accumulate in the upper respiratory tract. PM2.5 particulate matter penetrates the deepest paths of lungs, where they accumulate. PM1 particulate matter even penetrates the circulatory system. Particularly toxic particulate matter includes dusts containing heavy metal compounds and polycyclic organic compounds, most of which are characterized by carcinogenic properties [31, 35]

Apart from the negative impact of dusts upon human and animal health, dusts also affect plants, soil and water. Combined with sulfur dioxide, carbon oxide and other compounds, dusts contribute to the formation of the London fog. [2, 11]. Dusts also impair the greenhouse effect in the atmosphere [2, 11]. It should also be noted that dusts limit visibility, which affects road traffic safety.

The hazardous character of air pollution is evaluated on the basis of imission of pollution – concentration of pollution dispersed in the air and measured at the height of 1.5 m above the ground level [26]. Exceeded admissible imissions of PM10 par-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

ticulate matter in economically developed countries are most common reasons for authorities to undertake repair activities relating to the environment quality. Since 2009 a reduction of imissions of PM2.5 particulate matter in the European Union has been observed. It is planned to control imissions of PM1 particulate matter in the future.

The evaluation of particular sources of dust emissions as regards their negative impacts upon the environment is very difficult, as tests on the air quality in particular places include influence of all existing sources. Moreover, the quality of air is also affected by conditions of distribution of pollution. Therefore, it is purposeful to conduct comparative tests in places characterized by various shares of sources of pollution emissions and distribution of the same. On the basis of analyses of results of such tests it is possible to draw conclusions concerning impacts of particular sources of pollution emissions upon the air quality. The basic difficulty of such tests involves a relatively scarce network of air quality monitoring stations, which conduct constant measurements of imissions of complete fractions of particulate matter, i.e. PM10, PM2.5 and PM1 according to the present condition. In order to evaluate impacts of particular sources of emissions of dusts upon imission of fractions of particulate matter it is additionally necessary to perform measurements with the frequency enabling identification of dynamic properties of processes, which describe the phenomena causing emission of dusts, e.g. vehicle traffic. It has also been evaluated that, for such purposes, it is necessary to perform measurements with time intervals not exceeding 1 hour. Requirements are also posed to testing time, as it is purposeful to consider variability of the processes determining the anthropogenic emission of dusts connected with a weekly cycle as well as the variability resulting from seasons of the year. Additionally, long–term testing may also contribute effectively to decrease impacts of interferences upon testing results as connected with accidental factors such as weather conditions. As it is known, fluctuations of weather factors have a normal character in a given area and, therefore, their expected values reach zero with lengthening of the observation period. Therefore, it is purposeful that measurements should be conducted for at least one year.

As regards numerous air quality monitoring stations found in Europe, there are such urban agglomerations that include several stations located in places with diversified character of emission sources and distribution of pollution. Additionally, the stations test complete fractions of particulate matter and pollutions such as nitric oxides and carbon oxide, the imission of which is argued as connected with imission of fractions of particulate matter [5–9, 12]. The similar collection of air quality monitoring stations may be found, among others in, the agglomeration of the city of Brno. For the purposes of analysis of imissions of fractions of particulate matter, this study has used results of tests made by three air quality monitoring stations located in Brno.

Brno is a city located in Moravia, the Czech republic. It is located in the south–east flat part of the country at the confluence of the Svratka and Svitava Rivers. Brno has over 400000 inhabitants (2008) and it occupies the area of 230 km^2.

The air quality monitoring stations are owned by the Division of Environmental Protection of the Municipality of Brno. The tests used results of measurements made by the stations located in Svatoplukova, Zvonařka and Lány. The stations differ in the character of the area, in which they are located. Svatoplukova and Zvonařka stations are located at large main roads and Zvonařka station is located directly at the road. Lány station is located far from busy roads. The stations measure imissions of PM10, PM2.5 and PM1 particulate matter as well as nitric oxides and carbon oxide every hour. This study does not use results of tests on imissions of nitric oxides and carbon oxides used for development of behaviorist [4] models of imissions of PM10 particulate matter [6–9], as these could not be contained in this study. However, the selections of stations considered deliberately the possibility of recording of imissions of nitric oxides and carbon oxide, which could facilitate obtaining of complete materials for modeling of imissions of particular fractions of particulate matter.

2. Modeling of imissions of PM2.5 and PM1 particles

Hazards to the environment may be evaluated on the basis of direct measurements of imissions of pollution, however this evaluation only relates to the place and time of measurements and generalization of the test results is not always qualified sufficiently. However, results of long–term tests in places with typical conditions of emission of pollution and distribution of pollution qualify for generalization of conclusions. In such cases, results of tests and modeling of imissions of pollution constitute a basis for evaluation of pollution of the environment. In other cases, hazards to the environment are evaluated on the basis of knowledge of emission of pollution and modeling of distribution of pollution. The knowledge of emission of pollution is possible owing to results of measurements and, in this case, there are the same restrictions as in the case of measurements of imissions. It is completely different in the case of mobile sources of emission such as, for example, vehicles. In this case, it is possible to model pollution only. As modeling of emission of pollution constitutes a basic tool for evaluation of hazards to the environment in most affected places, i.e. in city centers. Traditionally, all types of modeling connected with emission of pollution are referred to as modeling of emission of pollution, although in many cases the modeling applied formally to imissions. This simplification is justified in the possibility of concise formulation of opinions, although, formally it is inaccurate.

Modeling of emissions of PM10 particulate matter does not constitute the subject of this study, however, it is inherently connected with modeling of imission of PM2.5 and PM1 particles. Modeling of emission of PM10 particles has been described extensively in literature [6–9, 12–15, 21, 22, 27]. The following two testing methods are used:

- modeling of emission of PM10 particles on the basis of knowledge of traffic and properties of vehicles and roads – models created on the basis of structural similarity [4],
- modeling of imission of PM10 particles on the basis of imission of nitric oxides and carbon oxide – models created on the basis of functional similarity (behaviorist models) [4].
- models created on the basis of structural similarity consider the following sources of emission of PM10 particulate matter [6, 7, 13–15, 27]:
- vehicles,
- surface of the road,

- solid contamination found on roads – in the form of excitation of dusts.
- sources of dusts emitted by vehicles include [2, 3, 5–9, 13–15, 27]:
- a combustion engine – particulate matter contained in the exhaust gas[11, 23, 29],
- friction pairs – found mostly in the braking system [2, 3] and coupling,
- tires,
- other parts of vehicles that are subject to wear and tear.

Behaviorist models do not openly consider sources of emission of particulate matter, including those connected with automobiles and other particles. The behaviorist models use a significant statistical relation of imission of particulate matter and imission of other pollution and the theory and practice of automobile technology at least partly justifies such a relation, e.g. simultaneous increase of emission of particulate matter from combustion engines and other vehicle sources and emission of carbon oxide and nitric oxides with an increase of the vehicle velocity and, consequently, engine load.

The behaviorist models usually argue for a linear relation between imission of particulate matter and other contamination.

Generally, results of the analysis of models constructed on the basis of structural similarity cannot be compared to results of the analysis of models constructed on the basis of functional similarity, as structural models do not openly consider dust emission sources other than those connected with vehicle traffic. In reality, a wide scale of discretion of adoption of structural model coefficients, which are usually difficult to identify, causes it to become a significant reason for incomparability of results of the analysis of structural and functional models.

The fraction of PM2.5 particles may be treated as a subset of PM10 fractions. Therefore, a linear relation between imission of PM2,5 particles– $I_{PM2,5}$ and imission of PM10 particles– I_{PM10} is postulated:

$$I_{PM\,2,5} = k_{PM\,2.5\text{–}10} \cdot I_{PM10} \tag{1}$$

where: $k_{PM2.5\text{–}10}$ – coefficient of the model of emission of PM2.5 particulate matter; $k_{PM\,2.5\text{–}10} \in \langle 0;1 \rangle$

Similarly to the modeling of imission of PM2.5 particles, PM1 particles may be treated as a subset of PM10 particles and PM2.5 particles. Thus, imission of PM1 particles – IPM1 may be modeled in a linear relation to imission of PM10 particles:

$$I_{PM1} = k_{PM1\text{–}10} \cdot I_{PM10} \tag{2}$$

where: $k_{PM1\text{–}10}$ – coefficient of the model of emission of PM1 particulate matter; $k_{PM1\text{–}10} \in \langle 0;1 \rangle$

and in a linear relation to imission of PM2.5 particulate matter:

$$I_{PM1} = k_{PM1\text{–}2.5} \cdot I_{PM\,2.5} \tag{3}$$

where: $k_{PM1\text{–}2.5}$ – coefficient of the model of emission of PM1 particulate matter; $k_{PM1\text{–}2.5} \in \langle 0;1 \rangle$.

Identification of models of imission of PM2.5 particles (1) and imission of PM1 particles (2 and 3) involves determination of coefficients of $k_{PM2.5\text{–}10}$, $k_{PM1\text{–}10}$ and $k_{PM1\text{–}2.5}$ models on the basis of results of empirical tests on imission of fraction of PM10, PM2.5 and PM1 particles. Identification results generally depend on conditions of emission of pollution and distribution of pollution as well as the period of measurements.

3. Testing of imission of PM10, PM2.5 and PM1 particles in selected air quality monitoring stations

As used in this study, testing in air quality monitoring stations in Brno was conducted in the period from 1 January to 31 December 2010 with a sampling interval of 1 h. Fig. 1–3 present courses of imission of fraction of particulate matter for averaged values within the period of 1 week for time t as marked with day numbers – d and month numbers – m.

The course of imission of fraction of particulate matter indicates a strong relation between the imission and seasons of the year: imission increases considerably in winter months. One may also observe a relation between imission of fractions and weekdays, which indicated a strong influence of civilization factors upon the imission. The mutual relationship between imissions of particular fractions is especially visible, which justifies adoption of linear models (1–3).

Fig. 4–6 present statistical characteristics of the testes sets of imission of fractions of particulate matter[1] : minimum value, maximum value, average value, standard deviation and span.

There are considerable differences in extreme values of imission of particular fractions of particulate matter. The least values: maximum, minimum and average values of imission of particular fractions were recorded for Lány station (apart from the average value of imission of PM1 particles and minimum value of imission of PM10 particles that are very similar to the values recorded for Zvonařka station). It is interesting that the greatest maximum and average values of imission of all fractions were recorded in Svatoplukowa station located in the area with less intense road traffic than in the case of Zvonařka station.

A strong correlation between imission of fraction of particulate matter results from the same. This is confirmed in the analysis of the correlations. The analysis was carried out with the use of Pearson's theory of linear correlation [30] and non–parametrical methods [33]: Spearmann rang correlation [32], Kendall tau correlation [20] and Kruskal gamma correlation [25]. Fig. 7–9 present coefficients of Pearson r, Spearmann R, Kendall tau and Kruskal gamma correlations between the tested sets.

The probability that the hypothesis assuming absence of correlation between the tested sets will not be rejected does not exceed 1·10–6 in all cases. Results of the analysis of correlation of sets of imission of size fractions of particulate matter fully qualify for formulation of an opinion on a strong correlation between the tested sets. The values of Pearson correlation coefficient for particular sets and the probability that the hypothesis assuming absence of Pearson correlation between the tested sets

1 In statistics and, in particular, in commercial applications, barely formal nomenclature is used, which does not always comply with the formalized mathematics. Therefore, terms such as "maximum value" should be treated as "the greatest value" and "minimum value" as "the least value", as there are not extreme values within the meaning of terms applied in a mathematical analysis. However, due to the fact that such terms are common and make it possible to provide concise statements, this study uses them in descriptions.

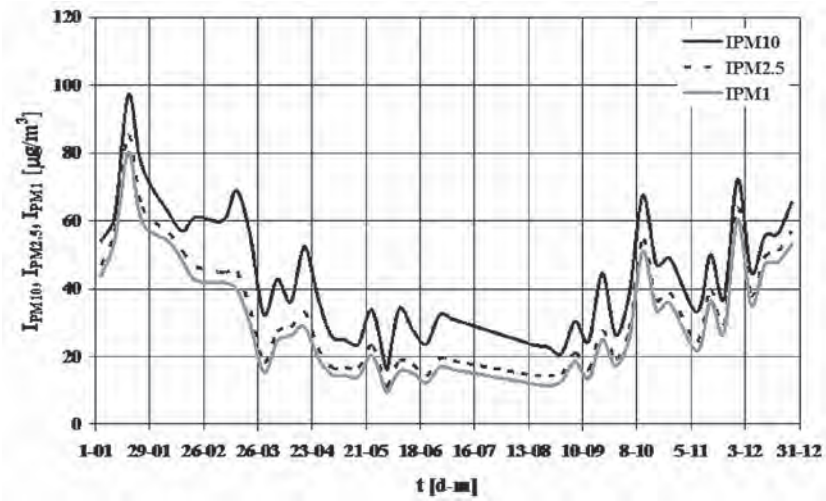

Fig. 1. The process of imission I of PM10, PM2.5 and PM1 particles in Brno–Svatoplukova air quality monitoring station

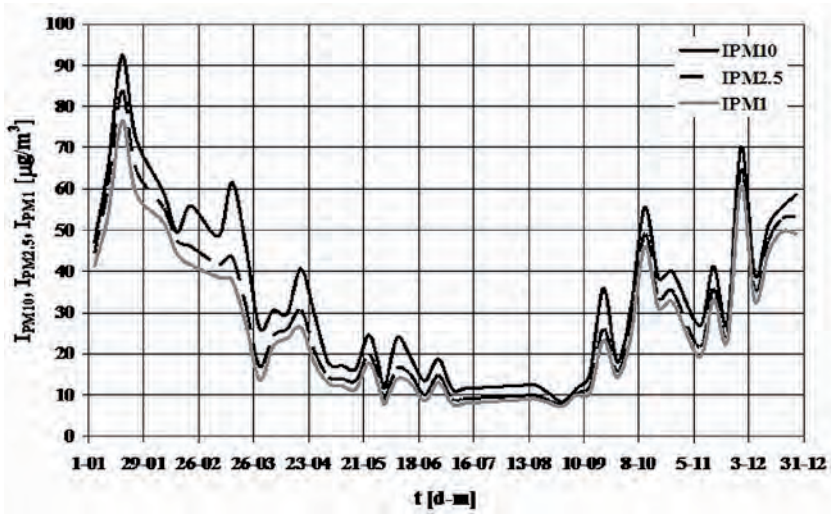

Fig. 2. The process of imission I of PM10, PM2.5 and PM1 particles in Brno–Zvonařka quality air monitoring station

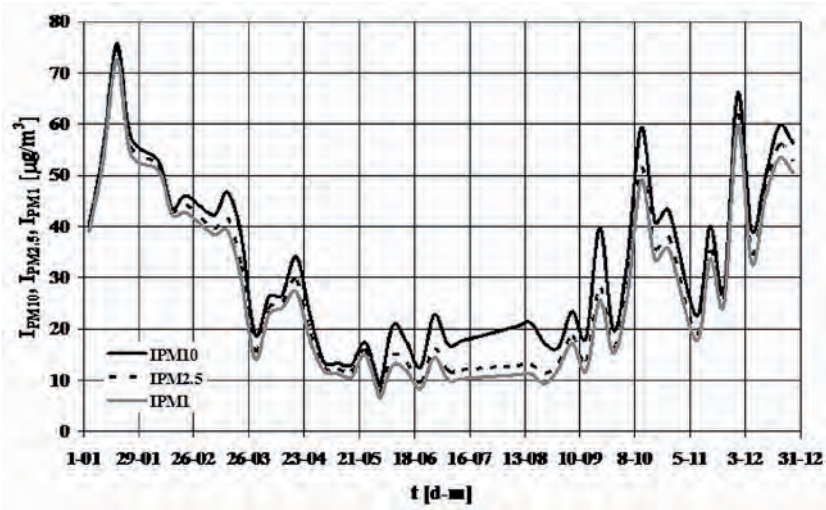

Fig. 3. The process of imission I of PM10, PM2.5 and PM1 particles in Brno–Lány air quality monitoring station

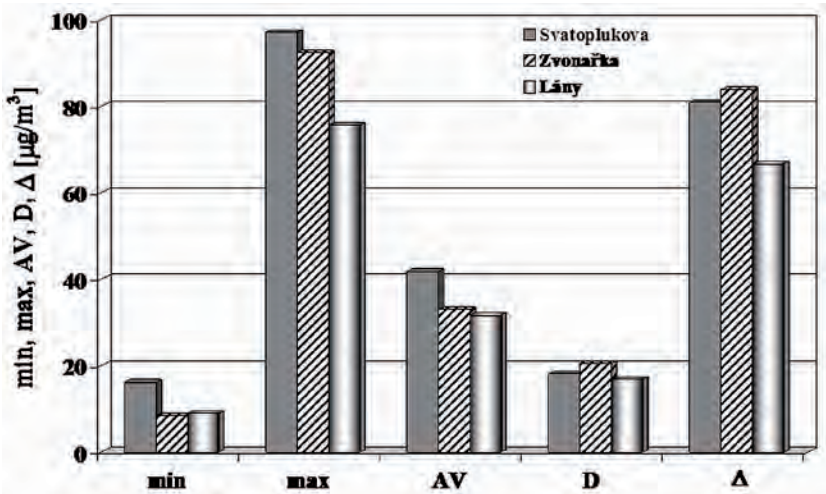

Fig. 4. Statistical characteristics of concentration of PM10: min – minimum value, max – maximum value, AV – average value; D – standard deviation, Δ – span

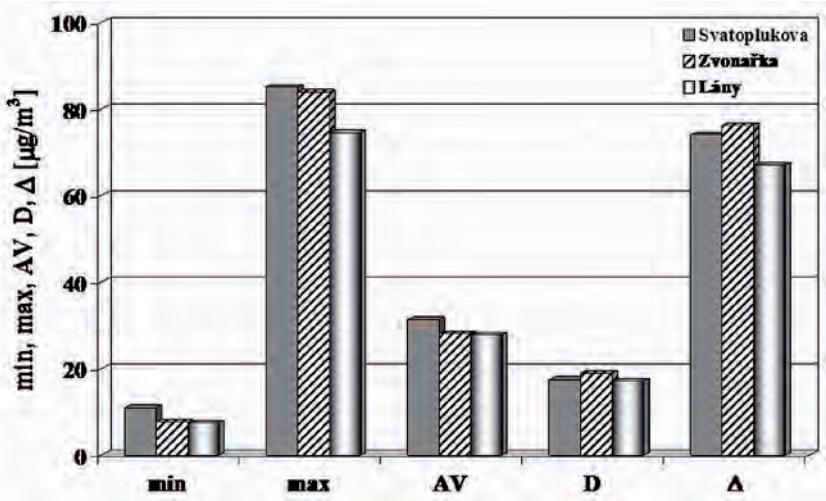

Fig. 5. Statistical characteristics of concentration of PM2.5 particles: min – minimum value, max – maximum value, AV – average value; D – standard deviation, Δ – span

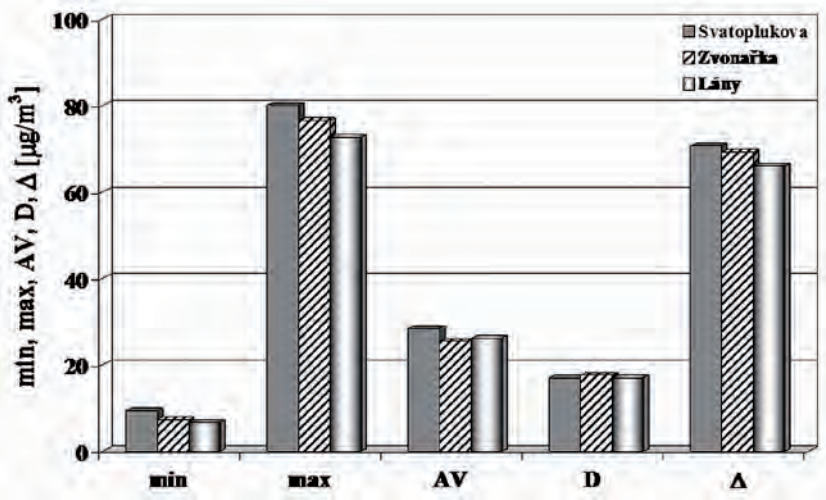

Fig. 6. Statistical characteristics of concentration of PM1 particulate matter: min – minimum value, max – maximum value, AV – average value; D – standard deviation, Δ – span

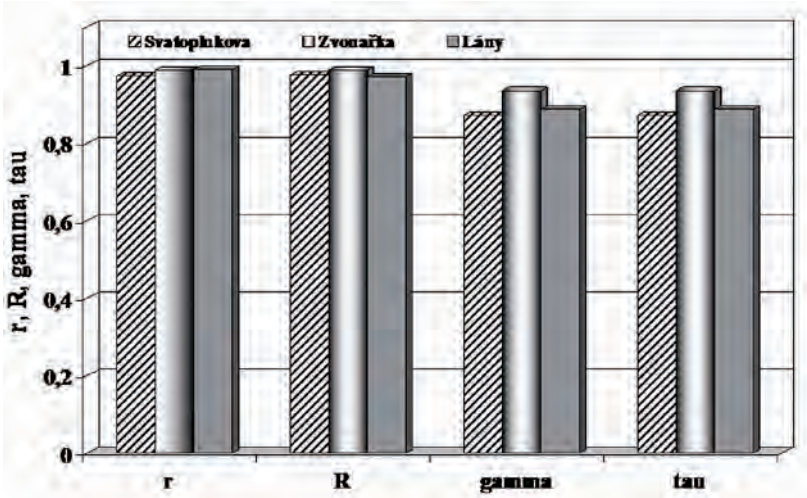

Fig. 7. Coefficients of Pearson r, Spearmann R, Kendall tau and Kruskal gamma correlations between sets of imission of PM10 and PM2.5 particles

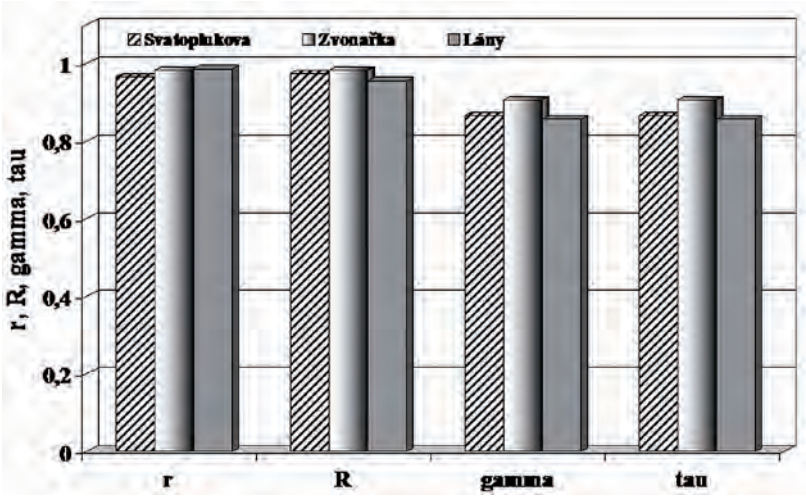

Fig. 8. Coefficients of Pearson r, Spearmann R, Kendall tau and Kruskal gamma correlations between sets of imission of PM10 and PM1 particles

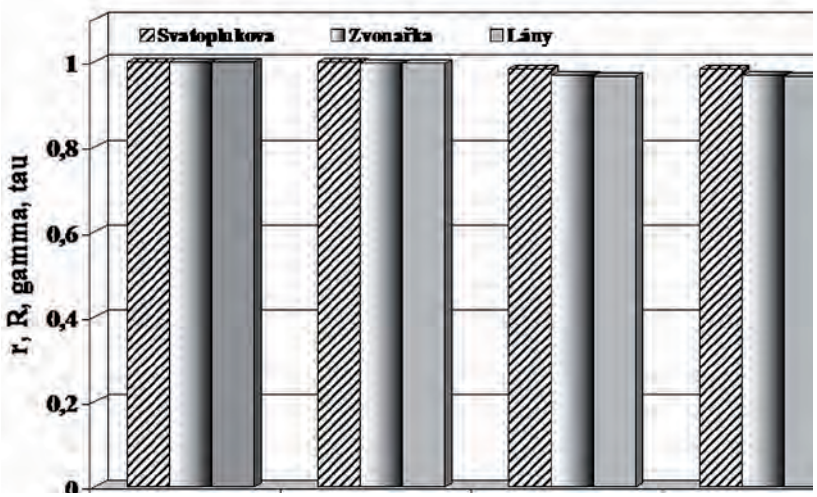

Fig. 9. Coefficients of Pearson r, Spearmann R, Kendall tau and Kruskal gamma correlations between sets of imission of PM1 and PM2.5 particles

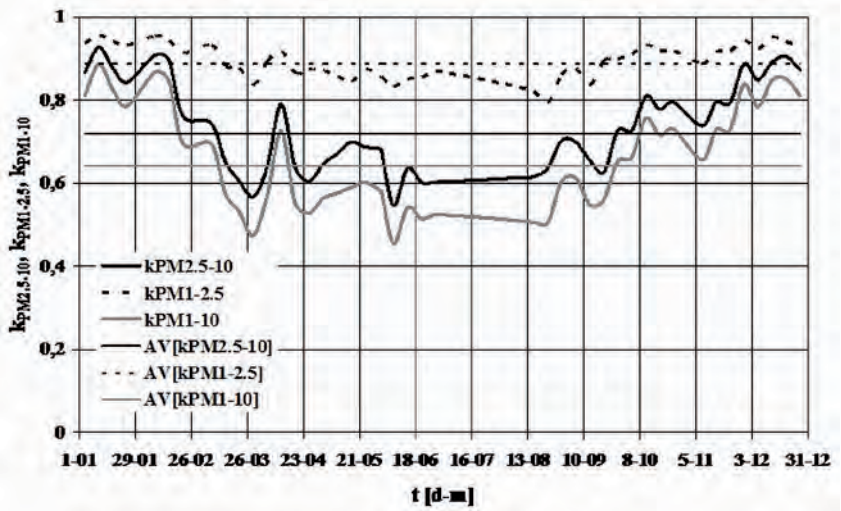

Fig. 10. The process and AV average value of k coefficients of imission models of PM2.5 and PM1 particles in Brno–Svatoplukova air quality monitoring station

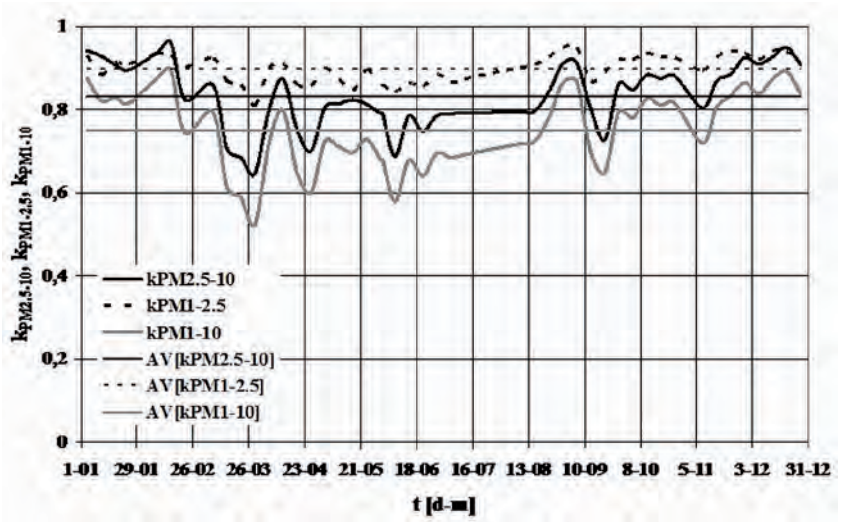

Fig. 11. The process and AV average value of k coefficients of imission models of PM2.5 and PM1 particles in Brno–Zvonařka air quality monitoring station

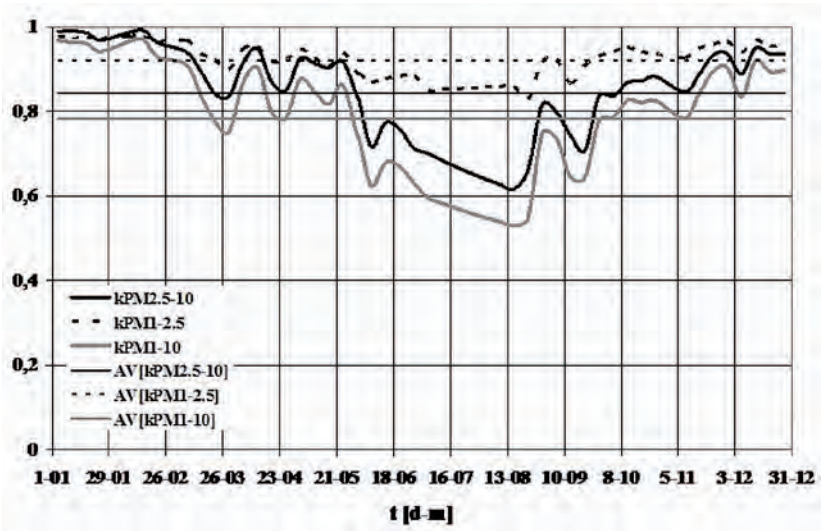

Fig. 12. The process and AV average value of k coefficients of imission models of PM2.5 and PM1 particles in Brno–Lány air quality monitoring station

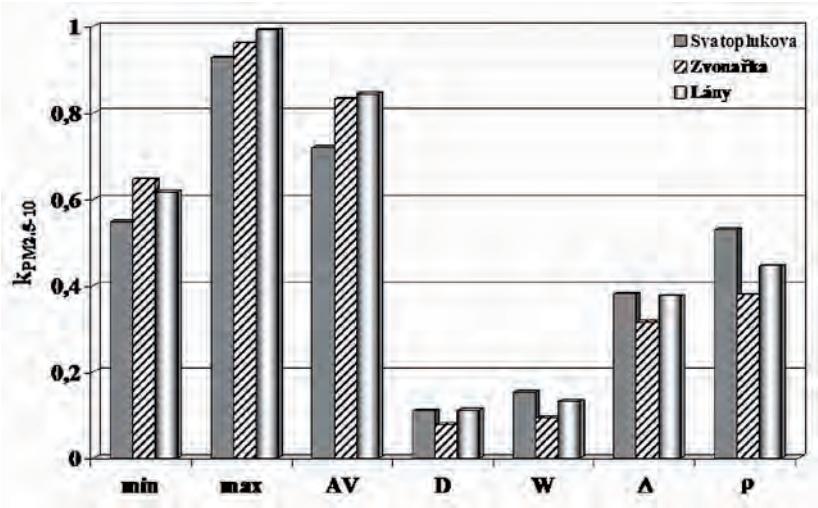

Fig. 13. Statistical characteristics of coefficients of imission model of PM2.5 particles: min – minimum value, max – maximum value, AV – average value; D – standard deviation, W – variability coefficient; Δ – span; ρ – relation between the span and average value

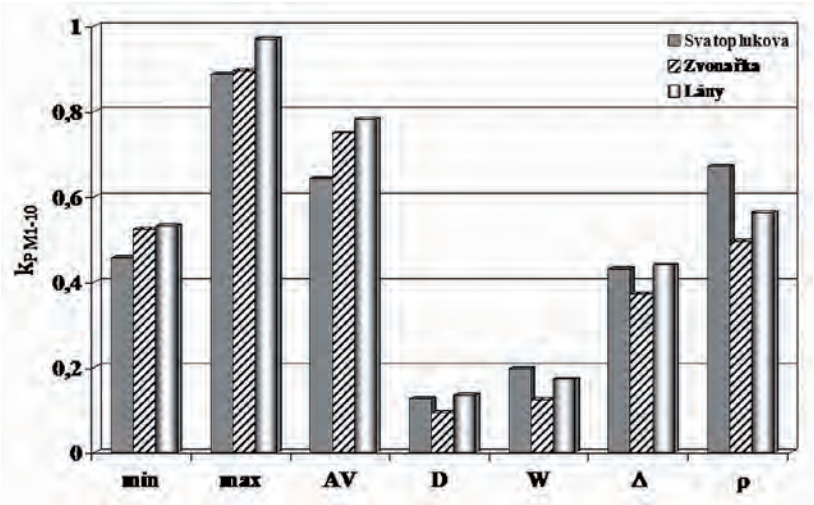

Fig. 14. Statistical characteristics of coefficients of imission model (2) of PM1 particles: min – minimum value, max – maximum value, AV – average value; D – standard deviation, W – variability coefficient Δ – span; ρ – relation between the span and average value

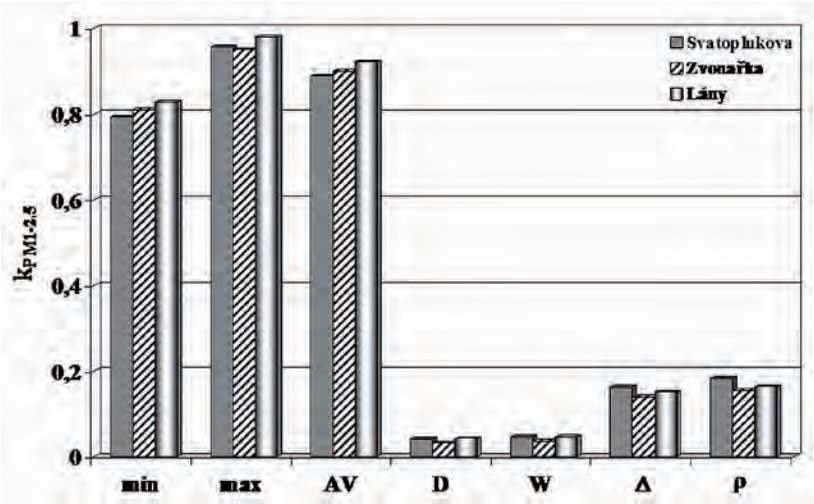

Fig. 15. Statistical characteristics of coefficients of imission model (3) of PM1 particles: min – minimum value, max – maximum value, AV – average value; D – standard deviation, W – variability coefficient Δ – span; ρ – relation between the span and average value

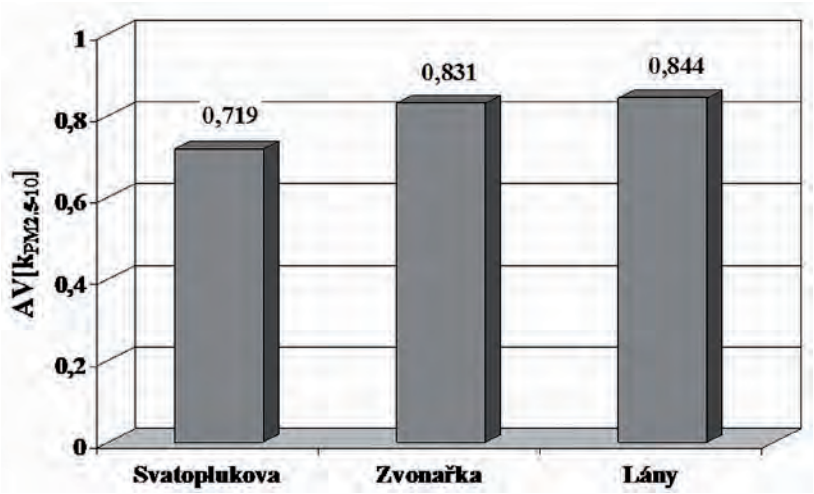

Fig. 16. AV average value of k coefficients of the model of emission of PM2.5 particles

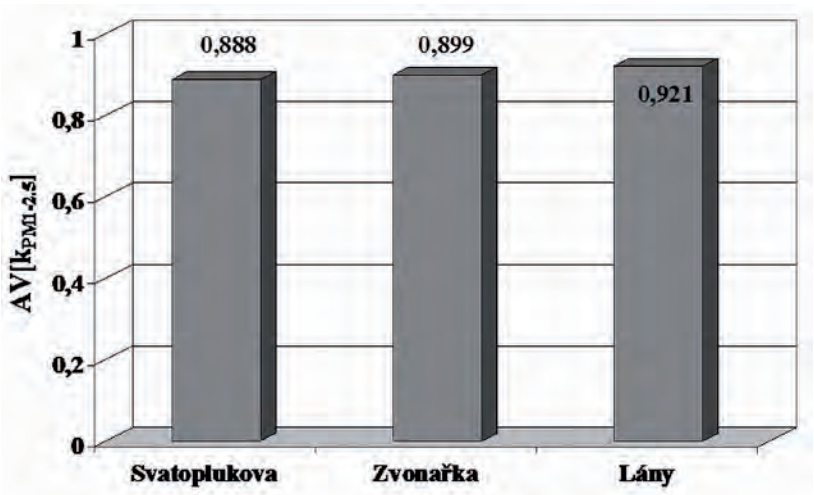

Fig. 17. AV average value of k coefficients of the model (2) of emission of PM1 particles

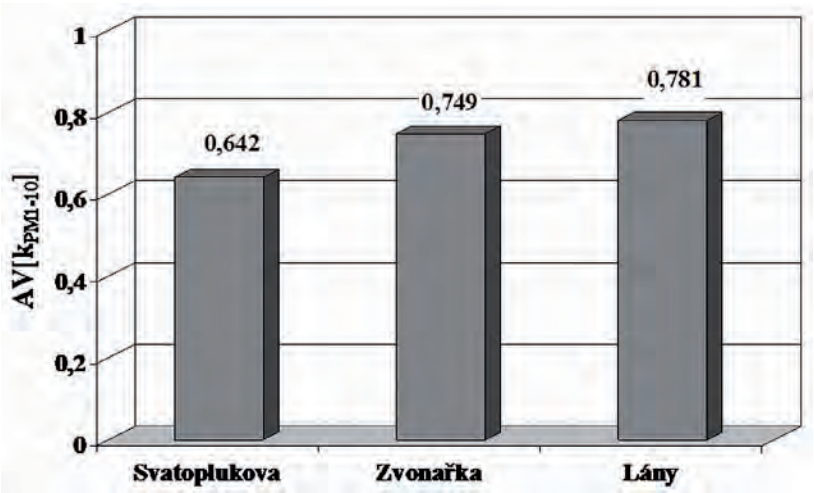

Fig. 18. AV average value of k coefficients of the model (3) of emission of PM1 particles

justify adoption of linear models of imission of PM2.5 and PM1 particles.

On the basis of empirical tests, parameters of imission models of PM2.5 and PM1 particles were identified.

Fig. 10–12 present courses of the coefficient of imission models of PM2.5 and PM1 particles and the average value of those coefficients during tests. There is a visible regularity involving that in cold months coefficients of imission models of fractions of PM2.5 and PM1 particles are greater than in warm months, which means a greater share of fine particles in cold months.

Fig. 13–15 present statistical characteristics of parameters of imission models of fractions of particulate matter. The variability coefficient and relation between the span and average value for coefficients of the models is considerably smaller than in the case of imission sets. The variability coefficient for coefficients of the models is (5 ÷ 20)%.

Average values of imission models of fractions of particulate matter were compared in Fig. 16–18. The determined average values of coefficients of imission models of PM2.5 and PM1 particles are within normal limits found in literature [21, 22]. The results of identification of imission models of PM2.5 and PM1 particles cannot be interpreted unambiguously and one may even say that they are puzzling. The values of coefficients of models for Zvonařka and Lány stations are similar, especially for models of imission of PM2.5 particles and model (3) of imission of PM1 particles. In the case of the model (2) of imission of PM1 particles, the difference of the model coefficient for Lány and Svatoplukova stations is even greater than for Zvonařka and Lány stations. One should expect similar values of model coefficients for Zvonařka and Svatoplukova stations or Svatoplukova and Lány stations, which results from conditions of location of the stations and, in particular, from traffic in the roads found in the vicinity of the stations.

4. Conclusions

Dusts constitute one of most severe hazards for the environment, especially in centers of large urban agglomerations. Evaluation of imission of particular fraction uses results of empirical tests carried out in air quality monitoring stations as well as results of modeling of imission of pollution. Testing of imission of particular fractions of dusts use emission models of PM10 particles that are constructed on the basis of structural similarity and models of distribution of pollution as well as imission models of PM2.5 and PM1 particles constructed on the basis of functional similarity.

Identification of functional imission models of PM2.5 and PM1 particles (as carried out on the basis of results of measurements of imissions of fractions of PM10, PM2.5 and PM1 particles in 2010 in three air quality monitoring stations in Brno as characterized by diversified sources of emission of pollution and distribution of pollution) made it possible to draw the following conclusions:

1. A strong correlation may be noticed between sets of imissions of particular fractions of particulate matter in all stations.
2. There is a strong relation between imission of fractions of particulate matter and seasons of the year: imission is much greater in cold seasons of the year.
3. There are also relations between imission of fractions of particulate matter and days of the week, which indicates a strong impact of civilization factors upon the imission.
4. There is a visible mutual relation between imission of particular fractions, which justifies adoption of linear models of imission of PM2.5 and PM1 particles.
5. There are great differences in extreme values of imissions of particular fractions, which is confirmed by great values of the variability coefficient and relation between the span and average value.
6. The determined average values of coefficients of imission models of PM2.5 and PM1 particles are within normal limits found in literature [21, 22].
7. There is a visible regularity involving that in cold months coefficients of imission models of fractions of PM2.5 and PM1 particles are greater than in warm months, which denotes a greater share of fine particles in cold months.
8. The results of identification of imission models of PM2.5 and PM1 particles cannot be interpreted unambiguously. No results were obtained indicating an impact of road traffic upon composition of size fractions of particulate matter.

The ambiguousness of results of identification of imission models of PM2.5 and PM1 particles indicates that it is necessary to treat this issue in a more comprehensive way. One may justify the expectation that on the basis of a larger set of result of empirical tests, which also include results from the stations located in other areas, it is possible to draw more unambiguous and general conclusions. Despite the partly critical evaluation of results of testing of imission models of PM2.5 and PM1 particles it may be stated that modeling of size fractions of particulate matter in accordance with the criterion of functional similarity is the only effective method of testing of hazards to the environment caused by dusts.

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Henryk KOMANDER
Ryszard BŁAŻEJ
Leszek JURDZIAK

METHOD OF PREDICTING THE FATIGUE STRENGTH IN MULTIPLIES SPLICES OF BELT CONVEYORS

METODA PROGNOZOWANIA TRWAŁOŚCI ZMĘCZENIOWEJ ZŁĄCZY WIELOPRZEKŁADKOWYCH TAŚM PRZENOŚNIKOWYCH*

Method of testing the stress distribution in overlap adhesive joints of multiply conveyor belts is presented The impact of strength properties of belts and adhesive rubber on the stress scale and fatigue life of splices were defined. The relations enabling to calculate the strength magnitude and predicting the durability of conveyor's belts splices were given.

Keywords: *belt conveyors, conveyor belts, conveyor's belt splices.*

Przedstawiono metodę badań rozkładu naprężeń w spoinie klejowej zakładkowych złączy taśm przenośnikowych wieloprzekładkowych. Określono wpływ właściwości wytrzymałościowych taśm i gumy klejowej na wielkość naprężeń i na trwałość zmęczeniową złączy. Podano zależności pozwalające na obliczenie wielkości naprężeń i prognozowanie trwałości złączy taśm przenośnikowych.

Słowa kluczowe: *przenośniki taśmowe, taśma przenośnikowa, złącza taśm przenośnikowych.*

1. Introduction

Multiplies conveyor belts manufactured in parts of certain length are connected into longer sections or loops according to the pattern showed on figure 1.

The specificity of splice construction is that in cross-sections of plies' contacts is one ply less than in belts being connected. Loss of belt strength in the splice area is inversely proportional to the number of belt plies.

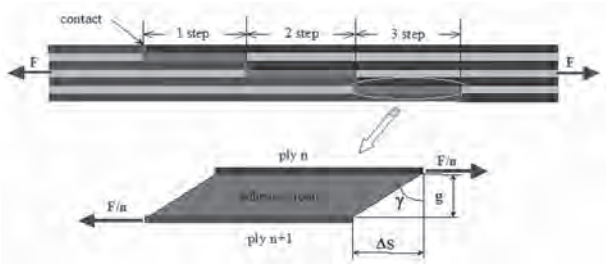

Fig. 1 Dimensional diagram of a 4-plies conveyor belt splice

Test results of static strength of splices indicate that loss of strength is bigger than the one resulting from the loss of one ply. This is caused by shearing stresses in the adhesive joint, which are the biggest on the ply connections and strengthen th e function of notch at that point of splice. During the test of static tension of properly manufactured splice it is destroyed due to breakage of plies on the joint of the first or the last notch. Often in practical use the connections of splice are unstuck, what is the beginning of its destruction. It results from the fact that under the fatigue loads the adhesive joint is damaged [1,2,3].

Problems related with establishing what properties of conveyor belts and vulcanization materials have the essential impact on the stresses in the adhesive joint and its fatigue life, were the subject of studies carried out in Laboratory of Belt Transportation of Mining Laboratory at Wroclaw University of Technology [4,5]. The results are presented in the paper.

2. Tests of stresses in adhesive joint of conveyor belt splice.

The size of stresses in adhesive joint of splice was tested by measuring the angle of non-dilatational strain of γ joint. γ angle is defined as ratio of absolute ΔS non-dilatational strain and the distance between relocating edges of the joint under the F stretch force (fig.1).

$$tg\gamma = \frac{\Delta S}{g} \tag{1}$$

In view of properties of fabric plies and the rubber of adhesive joint, the angle of γ non-dilatational strain is not the same at the whole length of separate notch of the slice. (fig.2), thus

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

its measurement must be made at many points along the length of the splice.

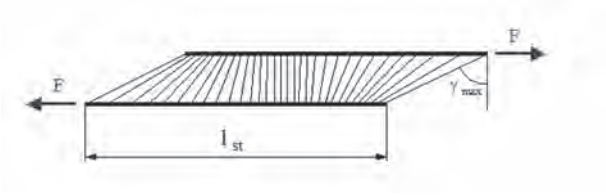

Fig. 2 Strain diagram of the adhesive joint along the length of the 1st step of a belt splice

The measurements of γ angles were made on the full-scale splices of four-ply belts. To render the test results independent from the impact of possible production defects, the splices were made in the special manner. Individual notches were obtained through cutting the belt plies at certain places equal the notch length.

50 mm wide samples for tests were cut out along the belt axis and then were loaded by the force giving the stress accounting for 15% of belt strength. Basing on measured γ angles, the chart of the $\gamma=f(l_x)$ relation where l_x is a distance between the measuring point and the place of contact of cut plies was plotted. Example results of γ measurements after the approximation by the trend line are presented on figure 3.

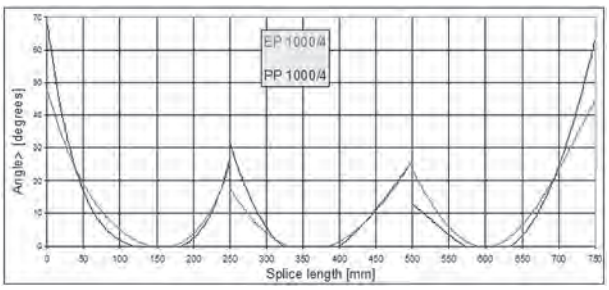

Fig. 3 Distribution of non-dilatational strain angles γ in adhesive joint along the length of EP1000/4 and PP1000/4 belt splices

The charts of $\gamma=f(l_x)$ relations were approximated by trend lines and the relative elongations of ε joint were calculated using the formula (2):

$$\varepsilon = \frac{1-\cos\gamma-\varepsilon_t\cdot\nu}{\cos\gamma+\nu\cdot\sin\gamma} \tag{2}$$

where:

ε_t – relative elongation of belt at the stress of 15 % of belt strength,

ν - Poisson's ratio of adhesive rubber.

The foregoing relation was determined investigating the schema of adhesive joint deformation presented on figure 4, assuming that relative elongation of the joint is $\varepsilon=(g_1-g)/g$ and taking into consideration the impact of belt elongation as well as Poisson's ratio of adhesive rubber.

The calculations gave the charts of distribution of adhesive joint elongations along the splice length i.e. $\varepsilon=f(l_x)$. In order to obtain the picture of stresses distribution in the adhesive joint

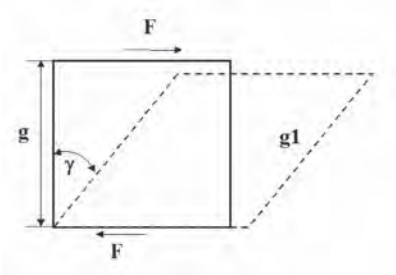

Fig. 4 Dimensional deformations diagram of adhesive joint component of a belt splice

along the splice, the tests of adhesive rubber were carried out to get the $\tau=f(\varepsilon)$ relation, what in turn helped to recalculate the results into the $\tau=f(l_x)$ relation. Example results of calculations of stress distribution in the joint of EP1000/4 and PP1000/4 belt splices were showed on figure 5.

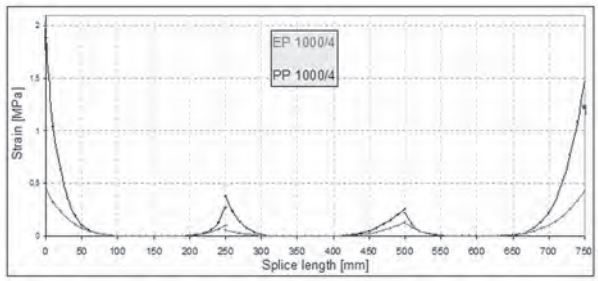

Fig. 5 Stress distribution in the adhesive joint along the length of EP1000/4 and PP1000/4 belt splices

The results of measurements of basic properties of spliced belts, properties of the adhesive rubber as well as results of tests on stresses magnitude at outside connections of splices are presented in Table 1. Stretch resistance of belts (Rt) and elongations (ε_t) were determined according to EN ISO 283:2008 standard, modulus of elasticity of belt Mt according to EN ISO 9856:2005 standard, stretch strength of adhesive rubber according to ISO 252:2007 standard, modulus of adhesive rubber according to ISO 252:2007 standard at elongation of 100% reached after 3 hour of loading the samples with constant force.

In the tests both γ angles of adhesive joint and modules of joint rubber were determined after three hours after their stress because of big impact of creeping effect of those materials on their elongation during the initial period of stretching forces application.

The results of tests presented in table 1 were analyzed to present the relation of τ stresses versus M_t/R_t and M_g variables. The following form of this relation was assumed (3):

$$\tau = C\left(\frac{M_t}{R_t}\right)^x M_g{}^y \tag{3}$$

where: C – constant,

x, y – exponents in demand.

This function was brought to the linear by taking a logarithm of both sides of the equation and thus the linear regression could be applied. The C, x and y values in demand were determined using STATGRAPHICS Centurion XV (v.15.2.06,

Table 1. Results of strength properties tests of belts and stresses in adhesive joint of splice

Item	Properties of connected belts				Properties of adhesive rubber		Maximum stress in adhesive joint τ [MPa]
	Type of material - plies	Stretch strength R_t [kN/m]	Modulus of belt elasticity M_t [kN/m]	Relative elongation at 15% Rt ε_t [%]	Stretch strength TS [MPa]	Modulus of rubber M_g [MPa]	
1	PP	1356	4639	6.28	6.2	1.3	1.70
2	PP	1258	4375	5.45	10.9	1.7	1.65
3	EP	1050	12665	1.11	12.4	0.8	0.43
4	EP	997	14717	1.07	15.2	1.2	0.79
5	PP	2359	11030	4.27	7.0	1.4	1.95
6	EP	1771	26577	1.13	6.2	1.3	0.74
7	EP	1942	18683	1.97	7.2	0.8	0.62
8	PP	1752	8697	6.17	9.6	0.9	1.00

edition Professional) software of StatPoint Inc. The academic license of it is possessed by the Institute of Mining Engineering at Wroclaw University of Technology. As a result of multiple linear regression with logarithmic transformation, the following form of demanded relationship was chosen:

$$\tau = 2,434\left(\frac{R_t}{M_t}\right)^{0,525} M_g^{\,0.99} \qquad (4)$$

Correlation coefficient of this function in relations with the test results was R2=90.6%, while its corrected value was 86.9%. Since the obtained P value in the table of variance analyze ANOVA was lower than 0.05 (P-value=0.0027), the statistical dependence between the variables at the 95.0% level of confidence was identified.

The chart of function (4) is presented on figure 6.

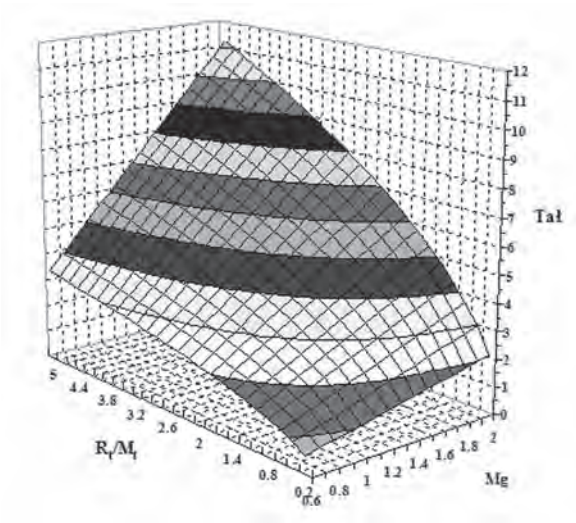

Fig. 6. The relationship of the dependent variable τ from independent variables Mt/Rt and Mg (4)

The tests showed that the strength properties of belts being connected and the adhesive rubber have the essential impact on the magnitude of stresses in the adhesive joint. Maximal stresses occurring on the outside contacts of the splice plies may differ even several times depending on the elasticity modulus of the belt and modulus of the rubber, as it is showed on the example charts for splices of EP100/4 i PP1000/4 belts on figure 5,

The approximate value of maximal stresses in the adhesive joint may be evaluated using the formula (5):

$$\tau = 2,4\sqrt{\frac{R_t}{M_t}}M_g \qquad (5)$$

3. Tests of fatigue life of splices

In the adhesive joint of splice subjected the cyclic fatigue loads, the heat is accumulated and therefore its temperature increases. The increase of temperature depends on the size and frequency of loads as well as on the type of the joint rubber and properties of the belt textile plies. Even at the same load conditions the temperature difference between individual splices may be up to tens of degrees. In such case comparing the test results for different types of splices is not possible. During the fatigue test it was assumed that the temperature of adhesive joint of splices being tested cannot exceed the range of 23°C±2°C. It was experimentally established that the above range of temperatures is possible to obtain under the following test conditions:

- Range of load form 5% to 20% of the belt strength
- Frequency of loads – 0.3 Hz
- Sinusoidal characteristics of loads
- Ambient temperature – 18°C

Temperature of joint was controlled using the pyrometer. The tested samples had a shape of small scull which was 50mm wide in the tested part and 100 mm wide in holding part. The total length of samples was 1150mm. After the analyze of test results of stress magnitude in the adhesive joints, the central notches of splices were shorten to 150mm. Outside notches had the standard length. The experiments were performed on the machine for dynamic tests of HC-25type, produced by Zwick-Amster. As a criterion for evaluation the fatigue life of splices number of fatigue cycles causing the splice delamination equal 3mm. Basic parameters of tested splices and numbers of fatigue cycles obtained during the tests are showed in table 2. The total of 12 samples of splices were tested. The number of

Table 2. Results of fatigue tests of splices

Item	Material type of plies	Tensile strength belt R_t [kN/m]	Elasticity modulus of belt M_t [kN/m]	Adhesive strength of joint T [N/mm]	Number of fatigue cycles after which the splice is delaminated LC
1	PP	1356	4639	6.3	440
2	EP	1050	12665	11.4	212 000
3	EP	997	14717	14.6	359 000
4	EP	1771	26577	9.2	145 000
5	EP	1942	18683	7.5	8600
6	PP	1752	8697	12.1	1900

fatigue tests showed in the table is the average for two tested samples. Table 2 contains also the properties of splices, which according to the previous analyze, had the essential impact on their fatigue life. The T adhesive strength between connected plies was determined according to ENISO 252:2008 standard.

Results of fatigue tests listed in table 2, were analyzed to present the relationships between number of cycles and R_t, M_t, M_g and T variables.

It was assumed that number of cycles may depend on 3 variables i.e. R_t/M_t, Mg and T and in STATGRAPHICS software the procedure of multiple regression model selection was used for them. It turned out that the best, from the point of corrected value of R^2, is the model based on two variables R_t/M_t, and T (R^2=95.04%, and its corrected value is 91.74%). As a result of non-linear multiple regression analyze, the following relations for number of cycles LC was obtained:

$$LC = 12,3362(\frac{M_t}{R_t})^{1,90881}T^{1.92878} \quad (6)$$

The correlation coefficients received for the relationship (6) are: R^2=94.7% and the corrected value is 91.2%. Figure 7 presents the relationship described by the equation (6).

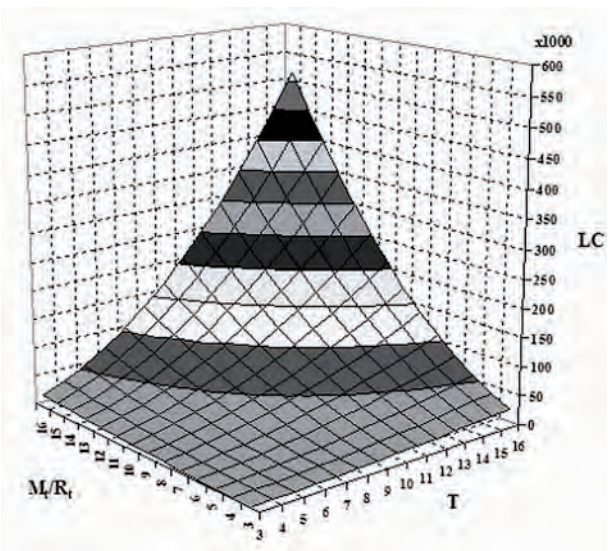

Fig. 7 Dependence of the number of cycles LC of the independent variables Mt/Rt and T (6)

For practical purposes relationship (6) may be simplified to the form (7):

$$LC = 8,05(\frac{M_t}{R_t})^2 T^2 \quad (7)$$

The correlation coefficients received for relationship (7) are: R^2=94.6% and its corrected value is 94.6%.

4. Summary

The test results presented in the paper showed how the stresses behave in the adhesive joint along each notch of multiply splices of conveyor belts.

It was identified that extreme values of these stresses occurring at splice joints depend mainly on elasticity modulus of the belt being connected, its strength and modulus of the adhesive rubber. Basing on the calculated relationship (4 or 5) producers of conveyor belts and materials used to join them, can select their parameters to have the maximal stresses in the adhesive joint at the level of 0.5 MPa, under the belt load amounting 15 % of its strength.

Fatigue tests of splices demonstrated that the essential impact on its durability has R_t/M_t the unit elasticity modulus of the jointed belts, and T adhesive strength of rubber used to join the plies.

Tests enable to define the relationship (6, 7) which allows to calculate the fatigue life of splice, measured in number of fatigue cycles causing the start of delamination of splice joints under the cyclic loads within the range from 5% to 20% of belt strength.

It was stated that depending on the strength parameters of jointed materials, the boundary number of fatigue cycles may be from several hundred to several thousands, what among other things, explain the reason of ungluing of numerous splices in working practice.

The deduced formulas calculating the number of LC fatigue cycles enable to select very simply, the belts and adhesive materials properties to obtain the high fatigue life of splices and thus their better reliability.

Conducted research has indicated significant parameters affecting the strength and durability of multi-plies conveyor belt splices. It seems advisable to test using developed method more splices having different properties and construction. This will clarify any of the models shown in the article and allow on more accurate prediction of fatigue life of belt splices.

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Henryk WNĘK

MAKE USE OF THE FRICTION COEFFICIENT DURING BRAKING THE VEHICLE

WYKORZYSTANIE PRZYCZEPNOŚCI PODCZAS HAMOWANIA POJAZDU*

In this publication is presented use the tyre-road friction during vehicle braking. Results presented in this publication are based on the road tests of the vehicle equipped in the anti-lock brake system (ABS). Two kinds of tests applied were carried out - the road tests of vehicle making the manoeuvre of braking on the straight section of the road and on the curve of the road. The braking forces and the friction coefficients for the individual wheels of the vehicle were defined on the basis of road tests, including the border values of the friction coefficient.

Keywords: *friction coefficient, vehicle testing, braking vehicle, curvilinear track, slip of wheels, ABS.*

W publikacji przedstawiono zagadnienie wykorzystania przyczepności opony do nawierzchni jezdni podczas hamowania. Wyniki prezentowane w publikacji oparto na badaniach drogowych pojazdu osobowego wyposażonego w układ zapobiegający blokowaniu kół. Przeprowadzono dwa rodzaje prób stosowanych do badania wykorzystania przyczepności - badania pojazdu wykonującego manewr hamowania na prostoliniowym odcinku drogi oraz na łuku drogi. Na podstawie badań określono siły hamowania oraz współczynniki przyczepności dla poszczególnych kół pojazdu, w tym wartości graniczne współczynnika przyczepności.

Słowa kluczowe: *przyczepność, badania pojazdu, hamowanie pojazdu, tor krzywoliniowy, poślizg kół, ABS.*

1. The introduction

The tyres and the road surface condition were accountable for passing on forces from the vehicle to road during the motion of the vehicle. The values of forces transferred on the surface of the road depend on the parameters of vehicle and its motion. They are limited the friction forces on contact area of the tyre - road. The phenomenon of friction occurs on the wheel contact area with the road and encloses all conditions and mechanisms be present during this co-operation. At present, vehicles are equipped in arrangements preventing locking wheels while braking (ABS) what limits the range of the changes to be in operation on the area of limited wheel slip of the braking system. The problem of the co-operation of the wheel with road were introduced in the work while braking the vehicles on the rectilinear road and on the curve of the road, the appointed border values of the friction coefficients and the variation of these coefficients got from road tests.

2. Tyre – road friction

During the motion of the vehicle the mechanism of formation of forces on the contact area of the tyre with the road appear from contiguous and normal intensity of stress in the area of this contact area. Wheel load on the road are different in every place of contact area with the tyre and change both in the longitudinal and lateral direction. While rolling the problem of the assymetry of the trace of the co-operation comes still. Every unit of the tyre, being in the contact area, is responsible for the transfer of longitudinal and lateral forces.

There are two primary mechanisms [1, 2, 3, 4, 5, 6, 10] responsible for formation of the friction forces between tyre and road: hysteresis and adhesion. The adhesion comes into rise on the surface of the adhesion the force in the result of intermolecular bonds between the gum of the tread and the aggregate in the road surface. This influence is reduced with the presence of dirts or water in the area of contact. The mechanism of the bulk hysteresis comes into being in the result of the loss of energy while deforming the gum on agregate in the road. The friction comes into being in the order of this mechanism he is not „so affected" on dirts and the presence of water.

The motion of the vehicle can be divide on compliant with the longitudinal axis of the vehicle and in perpendicular direction to this axis. The tyre-road friction can be describeed using the coefficient of adhesion (the ratio of the tyre-road friction force to the wheel load force) [2]. The coefficient of adhesion is understood, as the relation of maximum contiguous resultant force transfers by wheel to the load force working on this wheel. The temporary coefficients of adhesion were marked during the analysis using relationship:

$$\mu = \frac{W}{F_Z}$$

The tire-road friction forces enclose together force transferred on the surface of the road in longitudinal direction X_K and

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

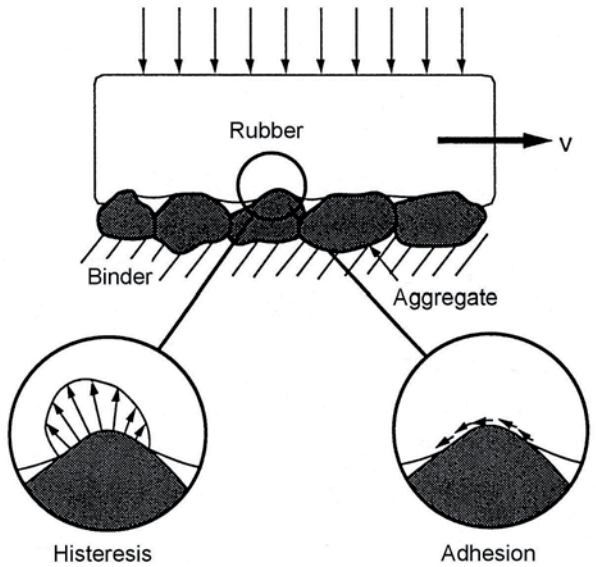

Fig. 1. Mechanisms of tyre-road friction

lateral direction Y_K. The resultant force W is limited the friction force of the wheel to the road surface F_μ.

$$W = \sqrt{X_K^2 + Y_K^2} \text{ and } W \le F_\mu$$

Considering individual wheels separately, we can assign the border values of the friction forces which can be transferred to road surface. The above mentioned relationship will simplify oneself during the vehicle motion on the straight, level section of the road because of the possibility of the omission of transverse forces. The whole wheel-road friction force can be used on braking in such case.

In the case of the vehicle motion on the curvilinear track of the road, the influence of lateralis force is smaller if the radius of turn is larger. In the case, when on wheel acts simultaneously longitudinal and transverse force with a simplify [9] one can record relationship defining the friction coefficient as:

$$\mu = \sqrt{\mu_x^2 + \mu_y^2}$$

where: μ_x - the coefficient of longitudinal friction,
μ_y - the coefficient of transverse friction.

While braking on the curve of the road the possible to use friction force in the longitudinal direction were limited by the centripetal force depend on the drive velocity and radius of turn. From this regard only part of the friction force can be used on braking the vehicle. The analysis the motion of the driving vehicle can mark what part of the friction coefficient can be used on braking on the circular track:

$$\mu_h = \sqrt{\mu_m{}^2 - \left(\frac{v^2}{g \cdot R}\right)}$$

where: μ_h - part of the friction coefficient used on braking the vehicle,
μ_m - friction coefficient (the maximum value of the relative friction force which can be got in given con ditions),
v - drive velocity,
R - radius of the track,
g – acceleration of gravity (9.81 m/s^2).

During the manoeuvres of speeding up or drive with the steady velocity (on the flat road) the whole wheels frictions is used relatively seldom. The full use of friction is more considerably often in cases of the braking manoeuvres on the straight road or on the curve track of the road, particularly during realize manoeuvres on the wet road, covered by snow or icy.

The use of anti-lock brake systems (ABS) limits the wheels slip. This will be result in the limitation of braking forces acting on the individual wheels of the vehicle.

The exploration of use of the friction of the vehicle during braking were introduced below.

3. Exploration of the tyre-road friction of the vehicle.

3.1. The assumption to exploration.

Two kinds of tests applied to the explore of use of the tyre-road friction were carry over - the testing of vehicle making the manoeuvre of braking: on the straight road section and on the curvelinear track.

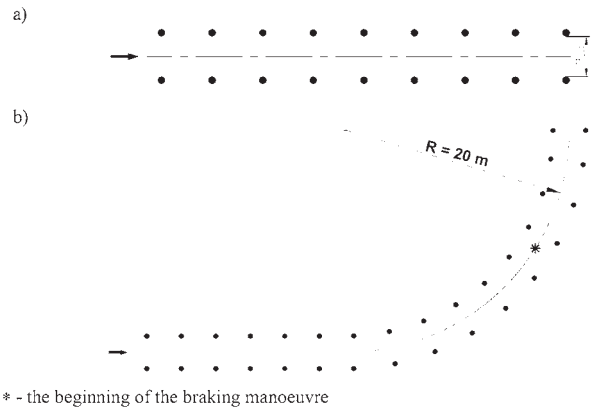

Fig. 2. The tracks of tests: a) braking on the straight section of the road, b) braking on the curve of the road

From the safety considerations the exploration was made on the dry and clean aggregate surface. The sensors were used to exploration thrusts installed in the brake system, head to the measurement of the longitudinal and lateral velocity, the sensor of force on the pedal of the brake, sensors to measure accelerations of the vehicle in directions X and Y, sensors to the measurement of the angular speeds of the motion of the car body and sensors to measurement of the turn angle and moment on the steering wheel [7, 8]. The weight of the vehicle resulted from his own weight, weight of measuring equipment and a driver.

Thus when the vehicle decelerate during braking load is transfered from the rear to the front axle in proportion to acceleration. This results in the change of the border friction forces and in the effect of the use of the anti-lock brake system (ABS), the limitation of the braking force generated through brakes in-

dividually for any wheel. The loads of the vehicle wheels were calculated on the basis of the measurements of the location of the vehicle centre of gravity, and longitudinal and lateral forces resulting from the motion conditions. The change of the location of the centre of gravity resulting from the inclination of the vehicle was not considered to calculate the forces of the load on respective wheels. Braking forces for individual wheels were assigned on the basis of measured pressure in the brake system and the geometrical parameters of brakes. The influence of the wheels inertia was considered on braking forces caused on the change of their rotative velocity.

3.2. Test of braking on the rectilinear section of the road.

First test was carried out on the rectilinear section of the road. The driver keep up for the rectilinear direction of the track. He pressed on the pedal of the brake after the obtainment of the suitable velocity. The force of the pressure on the brake pedal assured to be active the anti-lock brake system (ABS).

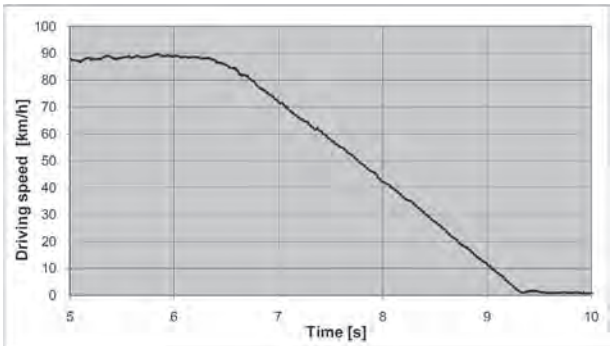

Fig. 3. The process of the driving velocity of vehicle during the test of braking on the rectilinear section of the road

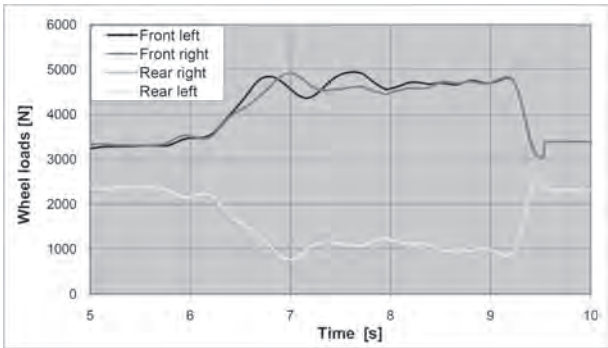

Fig. 4. The process of the loadings of the vehicle wheels during the test of brakeing on the rectilinear section of the road

On graphs were described visible braking load of front wheels and the clear difference of the quantity of braking force at the front and rear axis. Certain translation in operation of the brakes of right and left wheels were result from the inhomogeneity of background and small asymmerty of the loads of the vehicle.

3.3. Test of braking on the curve of the road.

Second test was carried out on the curved section of the road. The driver provided for steering wheel in such way the vehicle drived on the circular track. After conquest about 15 m on the circular track, the driver pressed on the brake pedal.

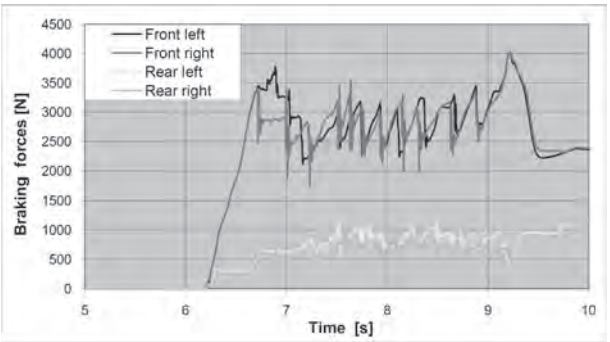

Fig. 5. The process of braking forces acting on the respective wheels of the vehicle

The force of the pressure on the pedal assured the working of the system ABS.

On figure 6 was introduced the track vehicle motion got on the drive test. Below were showed courses of loads changes of wheels (fig. 7), on the next graphs were showed forces acting on respective wheels of vehicle (fig. 8).

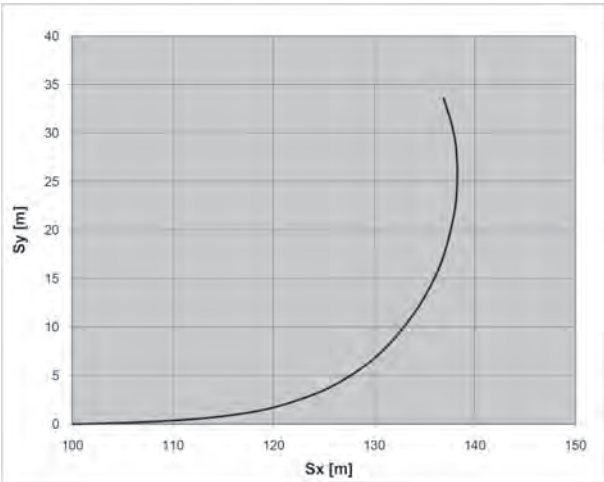

Fig. 6. The track of the vehicle motion during the test of braking on the curvelinear road

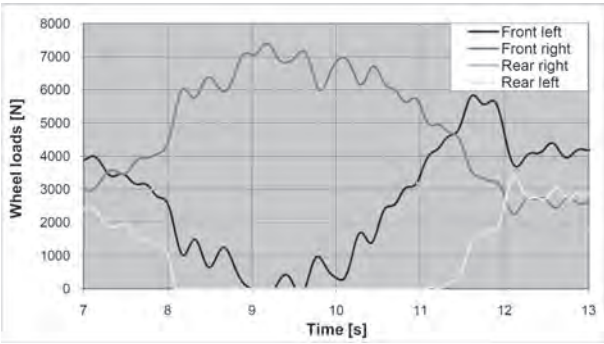

Fig. 7. The process of the wheel loads during the test of braking on the curvelinear road

On the figures were introduced visible changes of the loads on right and left wheels while braking on the curvilinear track. It can see also the clear difference of the quantity of braking forces the front and rear axis, corrected regard of the schedule of wheel loads and centripetal force acting on the vehicle. One can notice that the loads of the rear wheel left is close to the zero what is produce desired results the limitation of the brak-

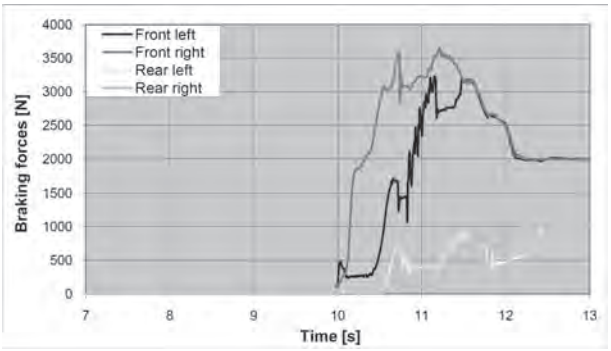

Fig. 8. The process of braking forces acting on the respective wheels of the vehicle

ing pressure by anti lock system in the circuit of the brakes of rear wheels in the initial phaze of braking and the same fall of the braking forces to small values.

4. Analysis of tests results of the friction forces utilization

Utilization of the friction forces of the vehicle wheels during the road tests of braking on the rectilinear section and on the curve of the road was calculated on the basis introduced above analyses and the results of road tests. On figures 9 and 10 was presented values appointed, the used coefficients of friction and the border values of these coefficients resulting from the conditions of the motion.

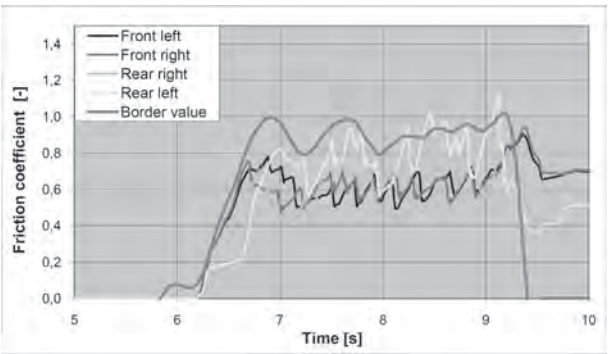

Fig. 9. Coefficients of braking friction on the rectilinear section of the road.

One can notice that in first case the maximum value of the used friction coefficient for front wheels oscillates around value 0.75, and is larger for rear wheels and oscillates around value 0.8.

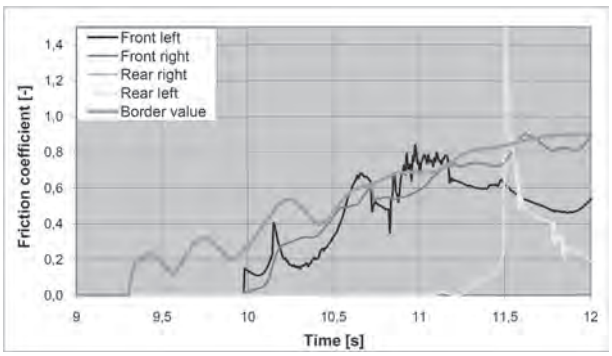

Fig. 10. The friction coefficients while braking on the curvelinear track of the road

In the case of braking on the curvelinear track of the road the level of used friction coefficient grow up from the beginning of braking to the maximum value together with with decrease of the drive velocity. The value of friction coefficient is larger for the front right wheel (with cornering load) than for left wheel. They stabilize the coefficients value after decrease of the velocity of the drive. The friction coefficients of rear wheels are clearly smaller in the initial stage of braking and they grow up to maximum values. Differences between the coefficients values for front wheels, result from the their inaccuracy of estimation caused omission of the inclination influence of the side car and from the considerable difference of the loads of the right and left side of the vehicle.

The exploration of braking the vehicle on the curve of the road allowed to delimitation of border total coefficient of friction (fig. 11) appointed on the basis of the friction ellipse.

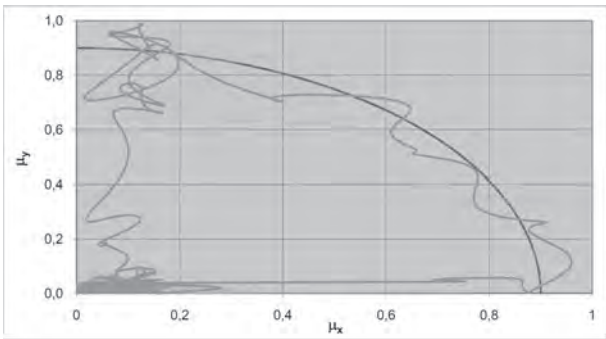

Fig. 11. The border values of friction coefficients got during the test of braking on the curve of the road (the fricrion ellipse was marked the thick line)

5. Recapitulation and conclusions.

The exploration of the friction forces acting between wheels and surface of the road, showed that the friction force (while emergency braking on the rectilinear road) is used in the complete since the initial moment of braking, until to the stop of the vehicle. Uploading of the front axis and unloading of the rear axis produced desired results the clear differentiation of pressure in brake circuits what allows to complete use of the wheels friction forces. Small difference among the individual wheels of one axis, are results depends on the local conditions of friction and is generating by small inequality and dusty surface of road.

In the case of braking on the curve of the road the limitation of longitudinal friction results from the occurrence of centripetal force. The system ABS (preventing locking the wheels while braking) does not allow to achieve large longitudinal force, assure suitable conditions on proceed lateral forces and keep of the stability of the vehicle motion. The correction arise from the motion on the curvelinear track of the road gets smaller together with from the drive velocity is smaller. The clear differentiation of the individual wheels loads, particularly the sides - right and left, it arise from the working of centripetal force. Asymmerty generated by the load the vehicle by the only driver additionally influence on the quantity of individual loads and unreeled forces braking. Similarly as while braking on the straight line section of the road, the considerable differences of pressure be presented in the circuits of brake front and rear wheels.

The friction forces of front wheels is used in the complete, however in the case of the rear wheels full use of friction follows just near the lower velocities of the drive of which the rear left wheel loses the contact with the road temporarily and rear right put under load partly. The clear growth of braking force on rear wheels follows what causes the considerable enlargement of force braking after the crossing of the border speed where switch off the ABS system. This state was showed on drawing 11, on which also is presented the border values of the friction coefficient appointed from the ellipse of friction (got from road testing).

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INFLUENCE OF THERMAL FATIGUE AND AGEING ON THE MICROHARDNESS OF POLYMER-CERAMIC COMPOSITES FOR BIOMEDICAL APPLICATIONS

WPŁYW ZMĘCZENIA CIEPLNEGO ORAZ STARZENIA NA MIKROTWARDOŚĆ KOMPOZYTÓW POLIMEROWO – CERAMICZNYCH DO ZASTOSOWAŃ BIOMEDYCZNYCH*

Studies presented in this paper, concern polymer-ceramic composites applied in the conservative dentistry. The aim of the study was to evaluate a long-term impact of the humid environment and cyclic thermal loads on the microhardness of new silorane-based composites and two methacrylate-based composites. The composite samples were subjected to normal saline environment with cyclically variable temperatures (5°C and 65°C), using a special thermal shock simulator. Microhardness was measured with Vicker's method before the fatigue test and after a series of 4000 thermal cycles. It is known that microhardness of silorane-based composite in opposite to methacrylate-based composites not decrease under the influence of cyclic thermal loads. It was found slight increase of microhardness under conditions of conducted tests. The ageing studies were also conducted consisting in microhardness evaluation of the composite samples in 6 months period. During that time the samples were kept in normal saline. The studies of hardness were carried out after each month of the exposure time. No long-term impact of normal saline environment with constant temperature on the microhardness of the studied materials has been noticed.

Keywords: *thermal fatigue, ageing, microhardness, dental composite fillings.*

Badania prezentowane w niniejszej publikacji dotyczyły kompozytów polimerowo-ceramicznych stosowanych w stomatologii zachowawczej. Celem pracy była porównawcza ocena wpływu długotrwałego oddziaływania wilgotnego środowiska oraz cyklicznych obciążeń cieplnych na mikrotwardość nowego kompozytu bazującego na siloranach oraz dwóch tradycyjnych kompozytów bazujących na związkach metakrylanu. Próbki z kompozytów poddano oddziaływaniu środowiska soli fizjologicznej o cyklicznie zmiennych temperaturach (5°C i 65°C) wykorzystując specjalny symulator szoków termicznych. Wykonywano pomiary mikrotwardości metodą Vickersa przed rozpoczęciem testu zmęczenia cieplnego oraz po serii 4000 cykli termicznych. Wykazano, że w przeciwieństwie do tradycyjnych kompozytów stomatologicznych mikrotwardość kompozytu bazującego na siloranach nie zmniejsza się pod wpływem cyklicznego oddziaływania szoków termicznych odpowiadających warunkom fizjologicznym jamy ustnej. W warunkach przeprowadzonych badań stwierdzono nieznaczny wzrost tej mikrotwardości. Przeprowadzono również badania starzeniowe polegające na ocenie mikrotwardości próbek kompozytów przez okres 6 miesięcy. W tym okresie czasu próbki przechowywano w soli fizjologicznej. Pomiary mikrotwardości wykonywano po każdym miesiącu ekspozycji. Wykazano, że długotrwałe oddziaływanie środowiska soli fizjologicznej w warunkach stałej temperatury nie zmienia mikrotwardości żadnego z badanych materiałów.

Słowa kluczowe: *zmęczenie cieplne, starzenie, mikrotwardość, kompozytowe wypełnienia stomatologiczne.*

1. Introduction

Polymer-ceramic composites are commonly applied as dental fillings materials. They are used due to their aesthetic properties (wide range of colours) and good mechanical properties. Polymer composite materials based on the methacrylate compounds consist of the matrix, which is a light-cured resin (up to 40% of the structure volume) and inorganic micro- or macro-nanofillers in most cases based on the silicon compounds (above 60% of the structure volume) [2,11,17]. Additionally, composite is composed of photo-initiators and pre-adhesive agents. A short characteristic of the polymer composite compounds is given in table 1.

Recently, in dental practice more and more the new silorane-based composite are used. A silorane-based composite has been introduced with distinctive polymerization characteristic to reduced polymerization shrinkage. The silorane matrix is formed by opening-ring during polymerization process. The silorane molecule represents a hybrid built-up of siloxane and oxiran

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

Table. 1. Characteristics of the selected polymer-ceramic composites applied in dentistry.

Indication	Name of the compound	Characteristics
Organic composite phase (polymer)		
Bis-GMA	Bisphenol A-Glycidyl Methacrylate	Bis-GMA monomers have a large molecular weight and they undergo free-radical polymerization creating polymer rich in cross bonds and initiators.
TEGMA	Tetraethyleneglycol Dimethacrylate	These are dissolving monomers, they make composite material less viscous, their kontent influence also the level of polymerization shrinkage.
UDMA	Urethane *Dimethacrylate*	-
PCDMA	polycarbonate *dimethacrylate*	-
Inorganic composite phase		
-	This chase consists of among the others: lithium aluminium silicates, crystalline quartz, barium-aluminium-barium-silicon glass, strontium-barium-aluminium-fluorosilicate glass, silica, silanized lime	Based on ethe smolecules size inorganic phase can be divided into macro – (1 -30 µm) of qartz, glass, ceramic or micro-fillers (0,007 do 0,04 µm) prepared of silicon dioxide or in a different way – pre-polymerized as a result of technological performance (1-200 µm), agglomerated (1-25 µm) or spheroidal (20-30 µm).
Photo-initiator		
CQ	camphorquinone	Fotoinitiators are used to polymerization by the generation of free radicals (in case of light photo-polymerization with wave length of approx. 400-500 nm, blue or violet light

structural moieties [15]. The silorane-based composite opens new vistas in reduction of marginal microleakage phenomenon [5,15,19]. Based on the literature [14] it is known that silorane-based composite has very good mechanical properties: high impact resistance, flexural strength and satisfactory hardness. Whereas the stability question is unknown in conditions log-term influence humidity environment and cyclically thermal fatigue correspond to oral cavity. Therefore, authors undertake a study of comparison the influence of ageing and thermal fatigue on microhardness new silorane-based composite and properties two "traditional" methacrylate-based composites.

Microhardness is a composite property, which is correlated with resistance to wear, also in case of thermal fatigue [3]. Investigations of microhardness allow evaluating mechanical properties of the composite. As it has been demonstrated in [13] there is a strong correlation between composite microhardness and elasticity modulus values, photo-polymerization depth, and the strongest with a polymerization shrinkage degree. In the paper concerning relation between physical-mechanical properties of the polymer composites and their application [9,16] a relationship between composite microhardness and degree of its wear in in vitro simulation conditions has been shown. Additionally, a correlation with the degree of composite filler conversion has been demonstrated [6]. Microhardness studies can be also used to evaluate a local gradient of photo-polymerization, which is a specific homogeneity of composite in the area of impact of the lamp light spectrum [8,18], influence of polymerization time and the type of the lamp's light. It can be also applied as a measure of residual mechanical properties in the ageing and fatigue studies.

Undertaking in vitro thermal fatigue simulation studies of the mechanical tooth-composite filling system, the loads conditions reflecting physiological conditions in the human oral cavity should be ensured. The following parameters should be controlled: temperature of the operating liquid (artificial saliva or normal saline), retention time of the operating liquid in the container with samples, or the studied sample in the container with operating liquid, as well as number of load cycles (thermal shocks).

In the previous studies different assumptions have been made with regards to the experimental parameters. Lower operating liquid temperature applied in the experiments, was between 2 and 24ºC [7], whereas heated liquid temperature was in a range of 45ºC [4] and 60 ºC [20]. Retention time of the liquid in the container with samples was from 15 even up to 180 seconds, while number of cycles varied from 25 to 1 million thermal cycles [1,7]. Currently, most often the following experimental parameters are assumed:

- Cooled operating liquid temperature − 5 ºC,
- Heated operating liquid temperature from 55ºC to 65 ºC,
- Retention time of the operating liquid in the container with samples – 30 seconds,
- Number of thermal cycles – from a few up to a few thousands.

2. Materials and methods

In both conducted tests of thermal fatigue and ageing, the same composites applied in stomatology were considered. The commercial methacrylate-based materials, such as: Ice (SDI), Venus (Heraeus) and new silorane-based Filtek Silorane (3M ESPE) – table 2.

The examples of SEM analysis results are presented in figure 1. There are visible molecules of composite polymer phase (larger), and also molecules of inorganic filler (smaller). The latter ones are the molecules with more regular shape, often close to spherical, with a similar size of grains.

From the selected materials disk shape samples with 14 mm diameter and 1 mm thickness were made. Photo-polymerization

Table 2. List of the studied composites

Material Type	Manufacturer	Resin	Filler content (wt%)	Size of filler molecules
Ice nanohybrid	SDI	multifunctional methacrylic ester	77,5 inorganic filler	0,04 – 1,5 µm
Venus microhybrid	Heraeus-Kulzer	bisphenol-A glycidyl methacrylate (Bis-GMA) trietylen glycol dimethacrylate (TEGMA)	80 barium glass inorganic filler	0,04 -1 µm
Filtek Silorane silorane	3M ESPE	silorane	76 inorganic filler	0,04 – 1,7 µm

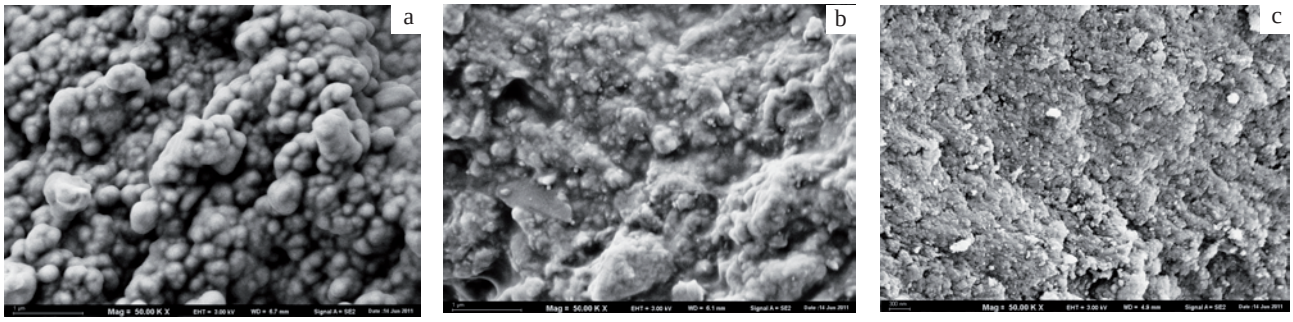

Fig. 1. SEM images of the sections of the studied materials: a) Filtek Silorane, b) Ice, c) Venus

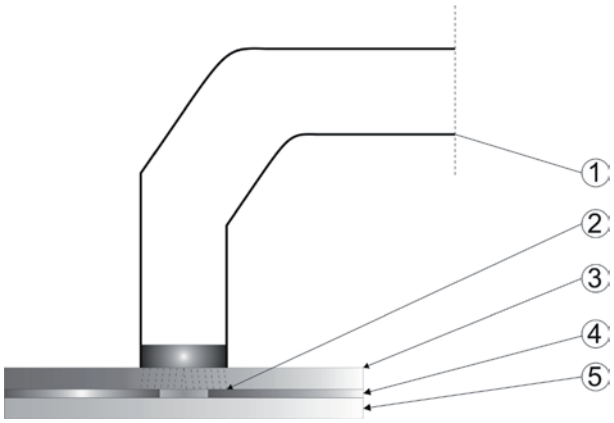

Fig. 2. Production of samples made of light-cured composites: 1 – lamp, 2 – exposed composite sample, 3 and 5 – plexiglass plates, 4 – steel form

process was conducted with the use of halogen lamp as shown in figure 2. The exposure time of the samples was 40 seconds, according to materials manufacturers' recommendations.

In these studies a thermal shocks simulator was applied, designed in order to investigate dental materials. The device was made by the staff of the Mechanical Department of Technical University in Lublin in cooperation with Medical University in Lublin.

The thermal shocks simulator (fig. 3) consists of the microprocessor control system and hydraulic system. The device enables creation of thermal shocks in the samples placed in the measuring container located in the simulator. Operation of the device consists of the cyclic pumping in and out of the operating liquid from the measuring container. The container is alternately filled with heated (65°C) or cooled operating liquid (5°C) from two independent temperature conditioning systems [11].

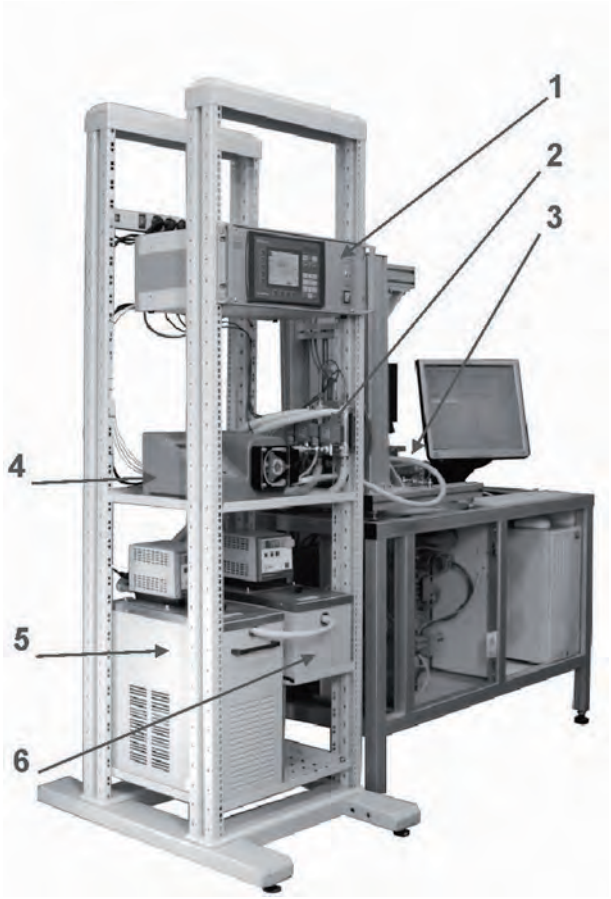

Fig. 3. Experimental stand for durability studies with specific thermal shocks module components: 1 – micro-processor control system, 2 – control valves, 3 – chewing simulator, 4 – peristaltic pomp, 5 – cooling thermostat, 6 – heating ultra-thermostat

Time of the subsequent procedures performance within each thermal shocks cycle was programmed and repeatable. Retention time of the cooled and heated liquid was 30 seconds, time pumping in and out of operating liquid was 10 seconds (fig. 4).

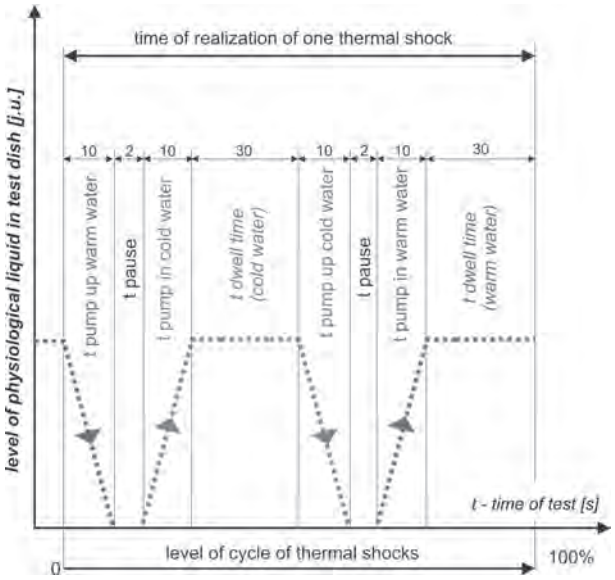

Fig. 4. Thermal shock algorithm with a single pumping of the operating liquid

Microhardness studies were conducted according to Vicker's method using Futertech FM 700 (Future-tech Corp. Japan), with load of 50g. A specified penetration time of the indenter was 15 seconds. The measurements were taken at ten points of the samples' surfaces. Measuring coordinates were determined in order to include possibly a whole sample surface. They were identical for all samples. The studies were conducted both at the exposed (lc) and non-exposed (nlc) samples surface.

Microscopic analyses of the composites structure were carried out in the Laboratory of Electron Microscopy of the Catholic University in Lublin. Microscopic observations were conducted by means scanning electron microscope (SEM) by Zeiss.

Ageing studies were also performed (for 6 months period), based on micro-hardness evaluation of composites as a function of exposure time in saline. One of the objectives of the studies was to obtain a reference sample for the comparison with the results obtained in thermal fatigue test.

3. Studies results

Results of the performed fatigue tests with the use of thermal shocks simulator are shown in fig. 5 and table 3. The results of ageing studies are presented as a box plot in figure 6.

4. Discussion

The effect of the thermal influence on the decrease of microhardness methacrylate-based composites Venus and Ice. The highest drop of microhardness after 4000 thermal cycles (4kTC) for Venus material was noticed, which can be seen in the graph (fig. 5c) and was confirmed by the t-Student test results (tab. 4). T parameter values for this material were the highest in the most comparisons. The influence of the thermal fatigue on the faster weakening of non-exposed surface (nlc) than the exposed one (lc) of Venus material has been demonstrated.

Investigations of Ice material confirmed the influence of thermal shocks on the micro-hardness decrease. It was not as high as in case of Venus material, however it was visible. This relationship was confirmed by t-Student test. The highest values of t parameter were obtained in comparison of the results before and after thermal fatigue test performance.

In case of FSi (Filtek Silorane) material a decline in average microhardness values after 4000 TC cycles was not shown. However, a slight increase was noticed. Statistically significant increase of micro-hardness at the exposed surface was also confirmed by t-Student test results. However, in case of this material impact of 4000 thermal cycles was the least visible and it resulted in different consequences that the observed for the two other materials.

That fact is connected with different phase composition Filtek Silorane, a new silorane-based composite. Similar observation was presented in the literature [14].

Analysing the results of ageing studies it can be concluded that despite a slight micro-hardness fluctuations during the test

Table 3. Results of microhardness. Descriptive statistics. TC – thermal cycles, lc – expose surface, nlc – non-exposed surface

Group	Valid N	Mean	Median	Minimum	Maximum	Std.Dev.	Coef.Var.
Filtek Silorane 0TC lc	40	51,97275	52,20000	48,80000	57,00000	1,791623	3,447235
Filtek Silorane 0TC nlc	40	49,38750	49,71000	42,76000	55,48000	2,742934	5,553903
Filtek Silorane 4kTC lc	40	54,80075	55,24500	47,42000	61,31000	3,102902	5,662153
Filtek Silorane 4kTC nlc	40	50,15750	50,02500	42,09000	56,24000	3,091503	6,163590
Ice 0TC lc	40	51,95350	51,86500	45,53000	57,71000	2,736424	5,267064
Ice 0TC nlc	40	49,96100	49,84000	45,18000	54,28000	2,700346	5,404909
Ice 4kTC lc	40	47,23800	47,22500	41,92000	51,75000	2,737509	5,795141
Ice 4kTC nlc	40	44,58550	44,99500	35,28000	52,56000	4,141693	9,289327
Venus 0TC lc	40	48,60775	48,39500	43,94000	55,73000	2,613053	5,375794
Venus 0TC nlc	40	48,88650	49,11000	42,90000	54,27000	2,974151	6,083787
Venus 4kTC lc	40	37,78125	37,88000	33,82000	41,77000	1,973859	5,224440
Venus 4kTC nlc	40	35,14625	34,96000	30,37000	41,45000	2,322400	6,607817

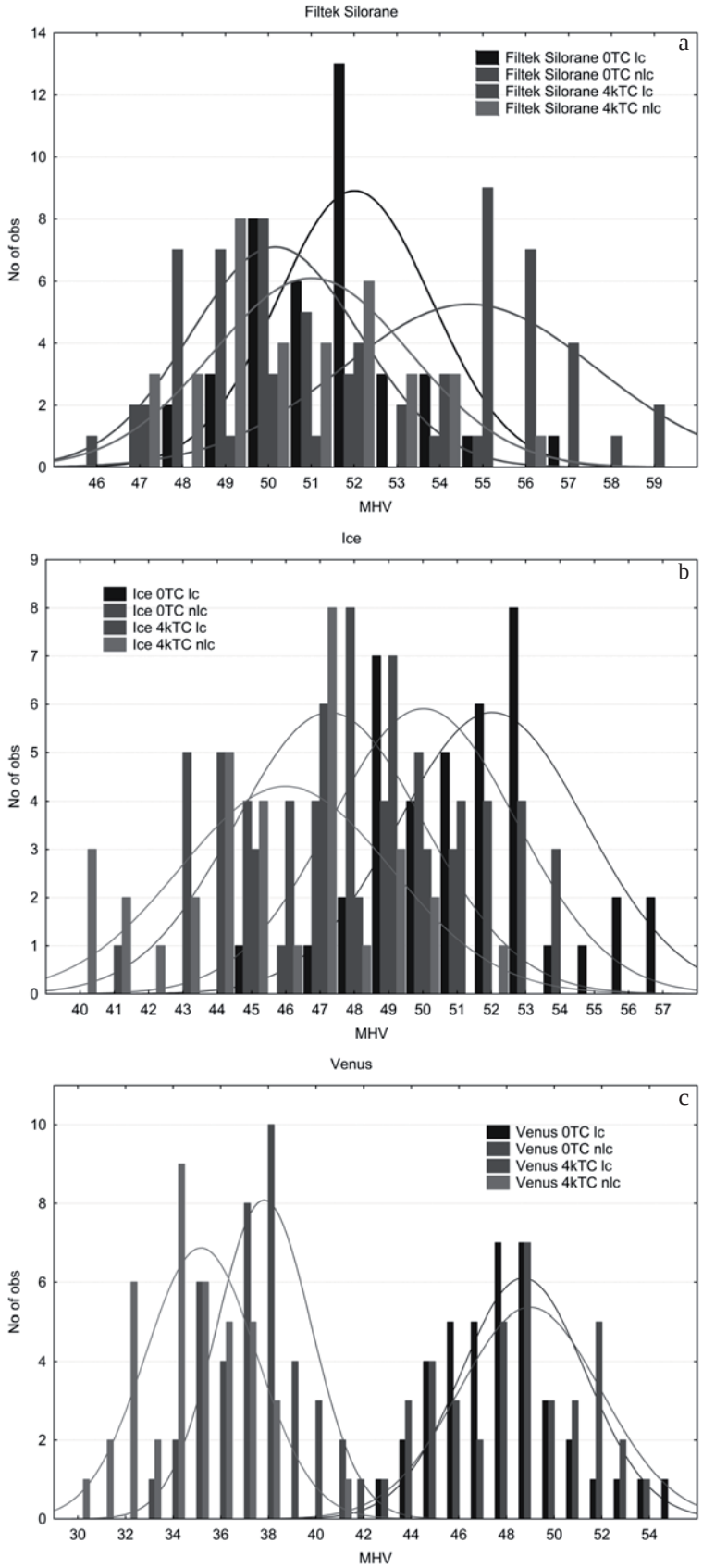

Fig. 5. Stemplot of micro-hardness of the studied materials after fatigue tests: a) Filtek Siloran, b) Ice, c) Venus

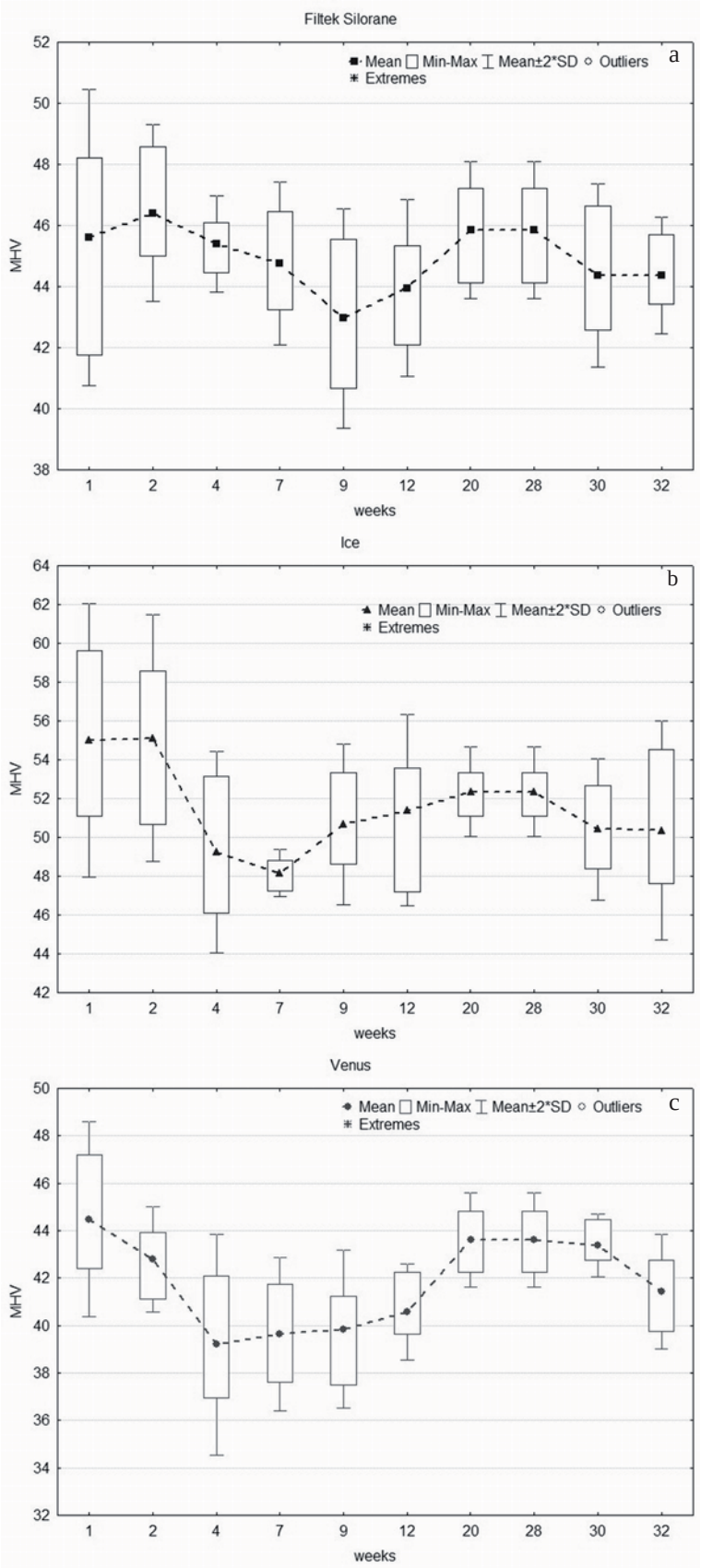

Fig. 6. Relationship of micro-hardness of the studied materials and ageing time in saline: a) Filtek Siloran, b) Ice, c) Venus

Table 4. T-Student test results of microhardness. TC – thermal cycles, lc – exposed surfaces, nlc – non-exposed surfaces

No	Gr. 1 vs Gr. 2	T	df	p
1	FSi 0TC lc vs. Fsi 0TC nlc	4,99	78	0,000004
2	FSi 0TC lc vs. Fsi 4kTC nlc	3,21	78	0,00191
3	FSi 4kTC lc vs. Fsi 0TC lc	4,99	78	0,000004
4	FSi 4kTC lc vs. Fsi 0TC nlc	8,27	78	0
5	FSi 4kTC lc vs. Fsi 4kTC nlc	6,7	78	0
6	FSi 4kTC nlc vs. Fsi 0TC nlc	1,18	78	0,242252
7	Ice 0TC lc vs. Ice 0TC nlc	3,28	78	0,001563
8	Ice 0TC lc vs. Ice 4kTC lc	7,71	78	0
9	Ice 0TC lc vs. Ice 4kTC nlc	9,39	78	0
10	Ice 0TC nlc vs. Ice 4kTC lc	4,48	78	0,000025
11	Ice 0TC nlc vs. Ice 4kTC nlc	6,88	78	0
12	Ice 4kTC lc vs. Ice 4kTC nlc	3,38	78	0,001138
13	Venus 0TC lc vs. Venus 4kTC lc	20,91	78	0
14	Venus 0TC lc vs. Venus 4kTC nlc	24,35	78	0
15	Venus 0TC nlc vs. Venus 0TC lc	0,45	78	0,657331
16	Venus 0TC nlc vs. Venus 4kTC lc	19,68	78	0
17	Venus 0TC nlc vs. Venus 4kTC nlc	23,03	78	0
18	Venus 4kTC lc vs. Venus 4kTC nlc	5,47	78	0,000001

period (fig. 6), an unequivocal impact of the exposure in saline on the changes in micro-hardness have not been demonstrated.

5. Conclusions:

1. Changes of microhardness for FSi (Filtek Silorane) material due to thermal shocks were insignificant.
2. The impact of thermal fatigue on the microhardness decrease of the methacrylate-based composites Venus and Ice has been demonstrated.
3. No impact of ageing in humid environment on the microhardness of the studied materials has been noticed.
4. It has been concluded that the applied method of the studies can be useful for the preliminary qualification of the operational usability of the dental composite materials.

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