SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
1 (157) 2009

MICHAŁ PAJĄK*

The modification of the amount of operational potential during the exploitation phase of a complex technical object

Key words

Exploitation, Maintenance management, Operational potential.

Słowa kluczowe

Eksploatacja, zarządzanie eksploatacją, potencjał użytkowy.

Summary

An operational potential is the measure of a usability of a technical object. The operating and service processes carried out during an exploitation phase change the quantity of the operational potential enclosed in the object. The operating processes decrease and the service processes increase this potential. Therefore, during the exploitation phase, the usability of the machine changes. Describing a process of changes in the operational potential as a time function, it is possible to determine a moment of time at which the operation process should be stopped and the service process should be started to avoid disability of the object. This issue is especially important in the case of a complex, crucial, technical object, because, for such an object, the moment to start the service process has to be determined several months in advance. In the paper, a function of the amount of the operational potential enclosed in the object is described. Next, the

* Radom University of Technology, Faculty of Mechanical Engineering, Department of Thermal Technology, 26-600 Radom, ul. Krasickiego 54, Poland, tel. (48) 48 361 71 49, e-mail: m.pajak@pr.radom.pl

course of the function during the operating and service processes is defined. On the basis of the described function, the idea of the service activity start time determination is also presented.

1. Introduction

Exploitation can be defined as a sequence of random events, which expresses changes in an operation point of objects. Therefore, it can be also treated as a controlled random process of the object's operational resource consumption – ZU in range [1, 2]

$$ZU_P \geq ZU \geq ZU_K \tag{1}$$

where: ZU – operational resource of the object,
ZU_P – initial value of the object operational resource,
ZU_K – final value of the object operational resource.

In the above definition, operational resource means the ability to do useful work according to the design of the system [1]. Therefore, it is a measure of the system's operational ability. Such interpretation is closely linked to the operational potential definition [3]. So, the operational resource can be treated as equivalent to the operational potential.

The definition of the exploitation also stated that the system's state changes during the technical object exploitation phase. According to [4], an action is defined as a modification or transformation of a state. So, it can be assumed that during the exploitation phase, some activities on technical objects are carried out. Two types of the most important sets of activities carried out on the machines during their exploitation phase are servicing and operating [5, 6, 7, 8]. An activity is a purposeful, conscious and voluntary human behaviour [9]. Therefore, the basic purpose of activities performed on a technical object has to be defined. The main purpose of operating a technical object is the realisation of the tasks for which the technical object has been created. The purpose of the technical object servicing is to support or restore the object ability state [10].

As previously stated, during operating and service processes, the amount of operational potential enclosed in the object changes. Therefore, it is necessary to estimate the moment t, when the operation of the object should be stopped and the object should be moved to renovation in order to avoid operational failure.

If we take into consideration a complex, crucial exploitation system, which is of strategic importance for the national economy, then the system operating process interruption should be coordinated throughout the country. Simultaneously, losses caused by stopping the devices due to an emergency that are components of such a system are much higher than the value of lost operational effect [11]. Unscheduled stoppage of the system can bring large economic, human and social wastes or the risk of those wastes [12]. The characteristics of the considered class of the technical objects are dangerous and expansive consequences of damages. The system failure can result in life and health hazards of site personnel, damage to the system elements or environmental pollution [13].

The elements of the examined system are characterised by very high unitary costs. They belong to a group of exploitation materials, which, according to V. Pareto model [14], are very small in terms of quantity (about 10%) and very large in terms of value (about 70%) [15]. Therefore, times of storage of these elements, which are necessary for service activities, should be as short as possible.

Because of the above features of the considered class of exploitation systems, the starting of the service processes has to be determined several months in advance, and this estimation should be very accurate. According to studies that have been the carried out, this moment can be determined on the basis of amount of an operational potential enclosed in the technical object.

2. Modification of the quantity of the operational potential during operating processes

During the operating processes, the operational potential of an object is transformed due to the effects of the exploitation system operation. Simultaneously, the influence of wear factors decreases the amount of the operational potential of the object [16]. If the considered operating process is performed in Δt_u period of time, where t_1 is a start time of a process and t_2 is its end time, then a change of the amount of operational potential included in the object can be expressed according to the following formula:

$$Pu(t_1) = Pu(t_2) + \Delta Pu(c_z^1(\Delta t_u), c_z^2(\Delta t_u), \ldots, c_z^i(\Delta t_u), c_{nz}^1(\Delta t_u), c_{nz}^2(\Delta t_u), \ldots, c_{nz}^j(\Delta t_u)) \tag{2}$$

where: $Pu(t_1)$ – amount of the operational potential for time t_1,
$Pu(t_2)$ – amount of the operational potential for time t_2,
ΔPu – change of the amount of operational potential,
$c_z^i(\Delta t_u)$ – time function of a wear factor no i dependent on the object operation in a time period Δt_u,
$c_{nz}^j(\Delta t_u)$ – time function of a wear factor no i independent on the object operation in a time period Δt_u.

During operating processes, the amount of the operational potential is decreased. This can be expressed as a compound time function, where inner functions are defined as time functions of the wear factors. The term "compound time function" means that the function can be expressed in the form f(u) where u = ϕ(t). The considered function can be presented in the form of the diagram (Fig. 1) where time is an argument of the function and an amount of operational potential enclosed in the technical object is a value of the function.

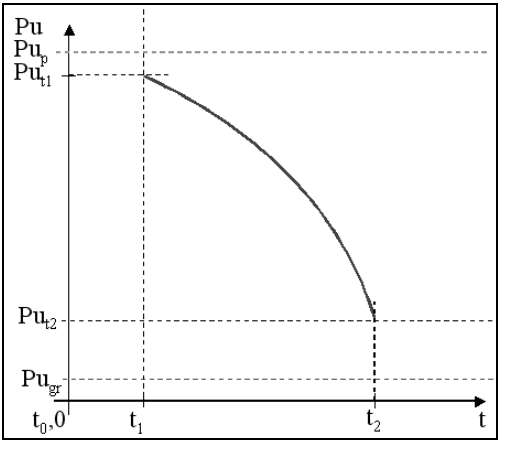

Fig. 1. The course of the function of the operational potential consumption during an operation process
Rys. 1. Przebieg funkcji ubytku potencjału użytkowego w czasie procesu użytkowania

Designations on the diagram are the same as in the Formula 2. Additionally, the amount of the operational potential enclosed in an object at a starting moment of an exploitation phase is marked as Pu_p and a critical amount of the potential is marked as Pu_{gr}. Later in the paper, the value Pu_p will be named as an initial value of the operational potential. The critical amount of the operational potential is equivalent to a lower limit of the availability of an object, so it is the lowest value for which the system operates safely [17]. The course of the function of the operational potential consumption is presented on the diagram in a pictorial way, because, in the case of real industrial processes, the considered function can be of a different shape. Despite the pictorial character of the diagram (Fig. 1), it presents the most important limitations of the function course. The function has to be strictly monotonic and the value of derivative should increase with time.

The wearing processes of the machines can be reduced to an adequate form of energy dissipated internally in a construction of a machine [18]. If we assume that the operational potential is equivalent to a potential of internal dissipation of energy then, according to the idea, which treats a machine as a processor of energy [19], the function of the operational potential consumption has to be not ascending and must satisfy the following condition:

$$\forall x, x' \in D \wedge x > x' \Rightarrow f(x) \leq f(x') \tag{3}$$

where: D – f(x) function domain.

Additionally, according to an analytical differential equation, which describes the evolution of power dissipated externally by a processor of energy [20]:

$$V(\theta) = V_0 (1 - \frac{\theta}{\theta_b})^{-1} \tag{4}$$

where: $V(\theta)$ – the power externally dissipated,
θ – the time,
θ_b – the machine time of life,
V_0 – the initial value of the power externally dissipated.

near the end of the time of life of the machine, almost all power given on input is dissipated. Assuming equivalence of the operational potential and the potential of internal dissipation, a violent increase in the value of the operational potential function gradient described by the formula $\frac{\partial Pu}{\partial t}$ is obtained.

3. Modification of the amount of operational potential during service processes

During service processes, necessary exploitation properties of a machine are restored. The desired effect of service tasks execution is an ability state of a technical object [3]. The ability state is defined as a state in which a technical object is able to meet all defined requirements [21]. The change of an operation point of the object relates to the modification of the amount of operational potential enclosed in it.

The diagram (Fig. 2) presents the changes in the amount of operational potential during operating and service processes. The operation process is performed in a period of time between start time t_1 and end time t_2. In the case of the considered class of technical objects, the service process starts at the end moment of the operating process and go on until t_3 time, which is the end time of the process. The service processes can be realised as regeneration, replacement, or modernisation [22]. On the diagram (Fig. 2) at t_2 moment of time, a replacement of an element takes place. Because of that, at this moment, the amount of the operational potential violently decreases below its critical value Pu_{gr}. Next, the operational potential is restored in the process of the element installation. It should be noticed that, if the service process is realised by the replacement, then the amount of the operational potential included in the object at the end moment of the operation processes (Pu_{t2}) is lost [23].

The real course of changes in the amount of operational potential in a period of time $<t_2, t_3>$ is a function that depends on several factors, e.g. the amount of manpower, funds, flows and sufficiency of materials and spare parts, constructional limitations, legal regulations, the range of service activities, and assumed work consumption of service activities [24, 25, 26].

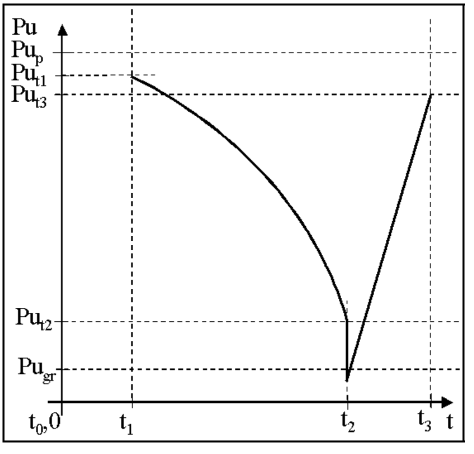

Fig. 2. The changes in the amount of operational potential during operating and service processes
Rys. 2. Zmiany ilości potencjału użytkowego w czasie procesu użytkowania i procesu zapewniania zdatności realizowanego poprzez wymianę

The exact course of the function can be determined on the basis of a detailed schedule of service activities. The creation of the schedule of service activities is a complicated optimisation issue [27]. The shape of the function is related to the solution of the issue. It can be vary depending on the technical object, type of service activity and the exploitation system. The only characteristic that should be noticed is that contrary to the $<t_1, t_2>$ period of time in which the function of the amount of operational potential is not ascending; however, in $<t_2, t_3>$ period of time, this function can be descending (disassembly of elements), ascending (installation or repair) or constant (preparation of service activities). Simultaneously, in the case of the considered class of technical objects, it is not possible to interrupt the service process at a specified moment from the range $<t_2, t_3)$ and start its operation [28]. Therefore, changes in the

amount of the operational potential enclosed in the object during the service process were approximated by a linear function. In spite of the introduced approximation, the diagram (Fig. 2) presents an important feature of the function of the operational potential consumption, which considers a proportion between values Pu_{t1} and Pu_{t3}. According to the theory of incomplete renovation [29], the reliability after a renovation can be described by Formula 5 [30].

$$R_3(x) = [R_2(x)]^{\alpha} \left[\frac{R_2(t+x)}{R_2(t)} \right]^{1-\alpha} \tag{5}$$

where: $R_2(x), R_3(x)$ – the function of the object reliability before and after renovation,
α – the object renovation degree.

This means that, after renovation, the value of the reliability function is lower than their initial value defined for time t_1 and larger than the value defined for time t_2. The difference of the reliability function value comes from the change in the technical status of the object. Therefore, the results of the described phenomena can be shown as a diagram of the function of the amount of operational potential enclosed in the object ($Pu_{t1} > Pu_{t3}$).

4. Identification of an optimal starting time of the service processes

During the exploitation phase, the operating and service processes take place on one technical object. They can be performed at the same time or in sequence. Therefore, in an exploitation system there is an exploitation conflict between people who are responsible for the operation of the object and the servicing of the object [31]. This is a situational conflict [32]. The main reason for it is the dependence of operating and service activities and limited access to the technical object. To solve the described problem, the operating and service processes have to be managed together. Total maintenance management is very important not only because of exploitation conflict. It is also important because of increasing pressure concerning the effectiveness of the use of technical resources. Therefore, the total maintenance management is one of the most important steps to fulfil strategic goals of the exploitation system [33].

Both operating and service processes are described in the paper by the changes in the amount of the operational potential enclosed in the technical object. Therefore, the total maintenance management can be performed analysing the course of the function of the amount of operational potential during the exploitation phase.

At the starting moment of the service process, the amount of the operational potential enclosed in the object is equal to the value Pu_{t2} that is different than Pu_{gr} (Fig. 2). If this difference is lower than zero, it means that the object reached the critical state before starting moment of the service process. Such a situation is unacceptable in the case of the considered class of the technical objects. Otherwise, if this difference is higher than zero, it should be regarded as the amount of the operational potential not transformed into the effect of the exploitation system operation. This value decreases the quality of performed exploitation processes. Therefore, in order to estimate an optimal start time of service processes, it is necessary to determine the course of the time function of the amount of operational potential. Thanks to the determined course of the function, the start time of the service processes can be defined as a time for which the difference $Pu_{t2} - Pu_{gr}$ is as low as possible and positive (6):

$$\min\left(Pu_{t2} - Pu_{gr}\right) > 0 \tag{6}$$

where: Pu_{t2} – the value of the amount of operational potential at the beginning of service process,
Pu_{gr} – the critical value of the amount of operational potential.

The changes in the amount of operational potential enclosed in the object depend on the intensity of the operating processes. Therefore, the above issue can be solved by implementation of a universal, mathematical model of the object operation process. Currently developed analytical models, which describe the relation between the wearing processes of the elements of machines and the time functions of wearing factors are employed in the case of technical systems composed of the elements of similar construction where the influence of the wearing factors can be described by simple analytical functions. Thus, these models can not be implemented in the case of compound technical objects. To obtain acceptable accuracy in the estimation of the operation process dynamic, it is necessary to implement the model explicating the Formula 2, because the formula describes in a universal way the functional projection, which determines the change of the amount of operational potential enclosed in the object on the basis of the time functions of wearing factors.

Actually, the studies are carried out to solve the problem of specifying the optimal service processes start time using the model of the control of the operational potential consumption of complex technical systems.

Conclusions

On the basis of the considerations presented in the paper, the following conclusions were formulated:

- During the operating and service processes, the amount of the operational potential enclosed in the object changes, so it is necessary to determine the moment of time at which the operating processes should be stopped and the service processes should be started in order to avoid the damage of the object.
- The starting moment of the service processes can be determined analysing the amount of the operational potential enclosed in the object.
- In a time period in which the operating processes are carried out, the time function of the amount of the operational potential is strictly monotonically not ascending and is characterised by an increase in the value of the derivative along a time axis.
- In a time period in which the service processes are carried out, the time function of the amount of the operational potential can be descending (disassembly of elements), ascending (installation or repair) or constant (preparation of service activities).
- In order to estimate an optimal start time of service processes, it is necessary to determine the course of the time function of the amount of operational potential and then the starting time of service processes should be estimated as a time for which the difference between the amount of an operational potential enclosed in the object and its critical value is as low as possible and positive.
- Because the changes in the amount of operational potential enclosed in the object depend on the intensity of the operating processes, the total maintenance management issue should be solved by the implementation of a universal, mathematical model of the object operation process.

References

[1] Powierża L.: Zarys inżynierii systemów bioagrotechnicznych, ITeE, Radom – Płock 1997.

[2] Oziemski S.: Człowiek w maszynie, ITeE, Radom 2004.

[3] Dąbrowski T.: Diagnozowanie systemów antropotechnicznych w ujęciu potencjałowo--efektowym, Habilitation thesis, WAT, Warsaw 2001.

[4] Konieczny J.: Inżynieria systemów działania, WNT, Warsaw 1983.

[5] Hebda M., Mazur T.: Podstawy eksploatacji pojazdów samochodowych, WKŁ, Warsaw 1980.

[6] Pająk M.: Fuzzy estimation of the maintenance management operation quality, w ZEM 4/2006, ITeE – PIB, Radom 2006.

[7] Będkowski L., Dąbrowski T.: Koncepcja komputerowego systemu wspomagania operatora obsługi, EXPO-SHIP 99, Międzyzdroje – Kopenhaga – Szczecin 1999.

[8] Będkowski L., Dąbrowski T.: Struktura systemu bezpieczeństwa i kryteria bezpieczności systemu antropotechnicznego, Proceedings of KONBiN 2001, Szczyrk, 2001.

[9] Mała encyklopedia prakseologii i teorii organizacji, Ossolineum, Wrocław 1978.

[10] Woropay M., Muślewski Ł.: Jakość w ujęciu systemowym, ITeE, Radom 2005.

[11] Gładyś H., Matla R.: Praca elektrowni w systemie elektroenergetycznym, WNT, Warsaw 1999.

[12] Cempel Cz.: Diagnostyka wibroakustyczna maszyn – historia, stan obecny, perspektywy rozwoju, Problemy Eksploatacji 3/2005, ITeE, Radom, 2005.

[13] Borgoń J., Jaźwiński J., Klimaszewski S., Żmudziński Z., Żurek J.: Symulacyjne metody badania bezpieczeństwa lotów, ASKON, Warsaw 1998.

[14] Pareto V.: Selected works. Introduction and editorial matter., S.E.Finer.Translation, Basil Blackwell, Pall Mall Press Ltd., 1966.

[15] Downarowicz O.: System eksploatacji zarządzanie zasobami techniki, ITeE, Gdańsk – Radom 2005.

[16] Pająk M., Woropay M.: Estimation of operational potential consumption on base of exploitation parameters values, Journal of KONES Powertrain and transport vol. 13, No. 3, Warsaw 2006.

[17] Zdoński M., Mcgeough J.A., Szpytko J.: On the use a maintenance developments to improve inherent reliability, w Engineering achievements across the global village, International Journal of INGENIUM, Cracow – Glasgow 2005.

[18] Cempel C.: Diagnostyka wibroakustyczna maszyn, Press of Poznań University of Technology, Poznań 1985.

[19] Cempel C.: Energy Processors in Systems Engineering and Their Evolution, Bulletin PAN, Techn. Sciences., vol. 47, no 4, 1997, pp. 495–511.

[20] Cempel C.: Theory of energy transformation systems and their application in diagnostics of operating systems, Applied Mathematics and Computer Science, vol. 3, No 2, 1993, pp. 533–548.

[21] Birollini A.: Reliability engineering, Theory and Practice, Third Edition, Springer Berlin, 1999.

[22] Socha M.: Procesy odnowy obiektów technicznych. Cele i zasady zarządzania, WNT, Warsaw, 1979.

[23] Pająk M.: The analysis of maintenance management strategies from the operational potential usage point of view, Journal of KONES Powertrain and transport, Warsaw 2008.

[24] Factory norm: Zakładowy normatyw pracochłonności remontu młyna węglowego typ MKM-33, Lublin, WOE, TKK/1/86 1986.

[25] Factory norm: Zakładowy normatyw pracochłonności remontu wygarniacza żużla kotła OP-650, Lublin, WOE, TKK/7/86 1986.

[26] Factory norm: Zakładowy normatyw pracochłonności remontu pyłoprzewodów, palników, skrzyń palnikowych, klap powietrza wtórnego kotła OP-650, Lublin, WOE, TKK/9/86, 1985.

[27] Pająk M., Woropay M., On the possibility of genetic algorithms implementation in the exploitation domain, Journal of KONES Powertrain and transport vol. 13, No. 4, Warsaw 2006.

[28] Polish government regulation: Ustawa o Dozorze Technicznym, Dz. U. 2000 No 122 pos. 1321.

[29] Wang H., Pham H.: Reliability and Optimal Maintenance, Springer, London 2006.

[30] Salamonowicz T., Okulewicz J.: Preventive maintenance with imperfect repairs of vehicles, Journal of KONES Powertrain and transport vol. 14 No. 3, Warsaw 2007.

[31] Systemy eksploatacji – teoria i praktyka, Proceedings of scientific conference „Modern exploitation systems", Wrocław SIMP 1977.

[32] Webber R.A.: Management: Basic elements of managing organizations, R.D. Irwin 1975.

[33] Pietrzyk A., Uhl T.: Wykorzystanie analizy ryzyka w procesie planowania zadań serwisowych, Problemy Eksploatacji 3/2005, ITeE, Radom 2005.

Manuscript received by Editorial Board, May 4th, 2009

Zmiana ilości potencjału użytkowego podczas fazy eksploatacji złożonego obiektu technicznego

S t r e s z c z e n i e

Potencjał użytkowy jest miarą możliwości użytkowych obiektu technicznego. Przeprowadzane w czasie fazy eksploatacji procesy użytkowania i zapewnienia zdatności zmieniają ilość potencjału użytkowego zawartego w obiekcie. Procesy użytkowe zmniejszają, a procesy zapewnienia zdatności zwiększają ilość potencjału użytkowego w obiekcie. W związku z tym w trakcie fazy eksploatacji zmienia się przydatność maszyny do wypełniania stawianych jej zadań. Odwzorowując proces zmian ilości potencjału użytkowego w czasie uzyskuje się możliwość określenia momentu, w którym należy zakończyć proces użytkowania i przekazać obiekt techniczny do odnowy w celu niedopuszczenia do osiągnięcia przez obiekt stanu niezdatności. Zagadnienie to nabiera szczególnego znaczenia w przypadku złożonego krytycznego obiektu technicznego, dla którego moment przekazania do obsługi musi być planowany z wyprzedzeniem wielu miesięcy. W pracy określono przebieg funkcji zmiany ilości potencjału użytkowego w czasie trwania procesów użytkowania i zapewnienia zdatności. Przeprowadzono dyskusję przebiegu zmienności określonej funkcji oraz zaproponowano sposób wyznaczenia momentu przekazania obiektu do odnowy.