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The space of a feature of a complex technical system

Key words

Exploitation, maintenance management, complex technical systems, state of a system.

Słowa kluczowe

Sterowanie eksploatacją, złożone systemy techniczne, stan systemu.

Summary

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. The main reason for this is a dependence of operating and service activities and the limitation of access to the technical object. To solve the described problem, the operating and service processes have to be managed together. It means that exploitation processes should be executed according to a maintenance strategy, which defines a moment in time when operation processes should be finished and the object should be intended for service. This moment depends on the system state. Simultaneously, the system state is one of the main factors, which determinates a method of operation and service processes. Therefore, the system state is the most important variable in a process of maintenance control. It should be noticed that the system state is determined by values of the system cardinal features. In this paper, a feature's space of a complex exploitation system is defined. Additionally, different types of a feature's space are described. Next, the state of the system is formulated as a point of the defined space. Proposed interpretation is a base for a projection of the system state changes taking place during different exploitation process execution in the space of one common feature. Thanks to this, the implementation of a coherent mathematical method of the maintenance control process description will be possible.

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1. Introduction

System concept is one of the most basic and general concepts used in different domains of science. There are many definitions of this concept, which can be found in different publications, for example, in [1–6]. The most suitable definition for the purpose of these studies is one that describes the system as an ordered triple < E, R, Ø > which consists of a set of E elements, R sequence (a relation on elements from E set), and a set of Ø objectives realised by the system. E is called the set of elements, R – it is a structure, and Ø is the objective function. Despite the differences between the definitions, each of them uses the set of system elements and the relation between them.

The object of presented studies is a complex, hierarchical exploitation system with technical objects as its elements. Technical objects are identified by their features: qualities and properties. The quality of the object is the feature that is specified only based on knowledge of the object. The loss of object qualities means that object is no longer the same but becomes another one [7]. A property of technical object is a relative feature. It is defined based on its relation to the objects of the environment. Due to property, it is possible to distinguish some objects from the others without that property [8]. Based on object features, we can treat it as a part of set of system elements. Technical object features can be divided into two groups: additive and constitutive. Additive features are independent from relations inside the system, but constitutive ones depend on it [9]. System features resulted from additive features of its elements can be defined as a sum of features of particular system elements. Unfortunately, in case of constitutive features of the system, this way of defining is not proper. Therefore, to identify the system itself, it is necessary to determine the unique set of the system features.

2. The state of features and subspace system states

It is possible to distinguish two types of system features -- measurable and non-measurable ones [10]. As far as non-measurable features are concerned, it is not possible to measure their values because of technical difficulties or because of a lack of researcher knowledge [11]. In order to determine the approximate value of non-measurable features, a range of variability can be assigned. The range of variability is divided homogeneously into m parts described by m values. These values correspond to the intensity of the appearance of an approximated feature. Due to the range of variability implementation, it is possible to express the intensity of the feature between 0 and m values.

Independently from a type of a system's feature x_i, the range of its variability X_{iZM} can be defined as a set of values that the feature can have. The range of variability is limited by its minimum value x_{imin} and its maximum value

x_{imax}. Inside the range of feature variability, depending on chosen criteria, we can distinguish boundary minimum and maximum values (x_{igrmin} and x_{igrmax}) which describe the range of acceptable values.

The subset of the acceptable values that is limited by the suboptimal minimum value x_{isomin} and suboptimal maximum value x_{isomax} is called the suboptimal values range. Among the suboptimal values, it is possible to distinguish the optimal value x_{io}. In defining presented values, the following ranges are formulated (1-4) (Fig. 1).

$$X_{iZM} = \left\langle x_{i\min}, x_{i\max} \right\rangle \tag{1}$$

$$X_{iND} = \left\langle x_{i\min}, x_{igr\min} \right) \cup \left(x_{igr\max}, x_{i\max} \right\rangle \tag{2}$$

$$X_{iD} = \left\langle x_{igr\min}, x_{igr\max} \right\rangle \tag{3}$$

$$X_{iSO} = \left\langle x_{iso\min}, x_{iso\max} \right\rangle \tag{4}$$

Where: X_{iZM} – variability range of a system's feature i,

$x_{i\min}, x_{i\max}$ – minimum and maximum value of a system's feature i,

X_{iND} – range of unacceptable values of a system's feature i,

$x_{igr\min}, x_{igr\max}$ – boundary minimum and boundary maximum value of a system's feature i,

X_{iD} – range of acceptable values of a system's feature i,

$x_{iso\min}, x_{iso\max}$ – suboptimal minimum and suboptimal maximum value of a system's feature i,

X_{iSO} – range of suboptimal values of a system's feature i.

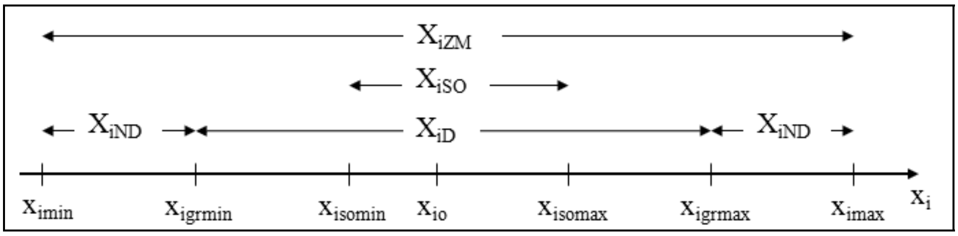

Fig. 1. Variability range of a system's feature
Rys. 1. Przedział zmienności cechy opisującej system

It was stated that the characteristic values of a feature are the values that determine the variability range of the feature and its subsets of unacceptable,

acceptable, and suboptimal values as well as characteristic ranges of the feature, which are the range of variability and unacceptable, acceptable and suboptimal values range of the feature.

If the following set of variables

$$X = \{x_i, i = 1, \cdots, n\} \tag{5}$$

is enough for identifying the system, then the system state is a set of temporary values of *X* variables [12]. The elements of this set are called state variables and their values for a specified moment are called state coordinates [13]. The state variables identify the system, so they are equal to the subset of system features. This subset is defined as a set of cardinal features. Based on the definitions of a state [14], [15], it was defined that a set of cardinal features is the smallest set of the system features which are important for the considered issue. The temporary values of the cardinal features uniquely identify the system state.

The system state, described by vector of cardinal features (state vector)

$$X = [x_1, x_2, \cdots, x_n]^T \tag{6}$$

can be interpreted as a point in an *n*-dimensional space, where *n* is the cardinality of the set of cardinal features. *N*-dimensional space is called the space of features of the system. In Fig. 2, the space of features of a system and a system state point for $n = 2$ is presented.

If we interpret points of the feature's space of the system as the system states, then characteristic ranges of the system features (1 - 4) determine *n*-dimensional subspaces of the system states in a feature's space. The ranges of unacceptable values of the system features determine the subspace of unacceptable system states S_{ND}. The ranges of acceptable values of the system features determine the subspace of acceptable system states S_D; whereas, the ranges of suboptimal values determine the subspace of suboptimal system states S_{SO}. The subspaces of the system states in a feature's space are constructed as the Cartesian product [16], which is an intersection of cylindrical extensions of enumerated ranges of the system features (7, 8).

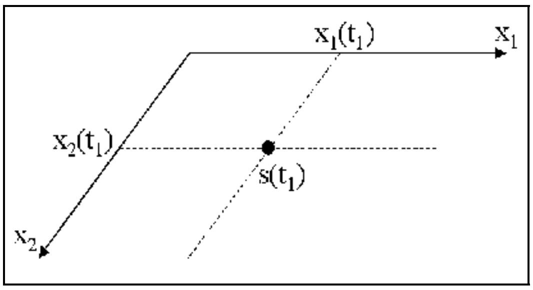

Fig. 2. State of the system in t_1 moment in a space of features [x_1, x_2]
Rys. 2. Stan systemu s dla chwili t_1 w przestrzeni cech systemu [x_1, x_2]

$$\rho\left(\pi_{X_1}(R)\right) = \left\{(x_1, x_2) \in X_1 \times X_2 : x_1 \in \pi_{X_1}(R)\right\} \tag{7}$$

$$\rho\left(\pi_{X_2}(R)\right) = \left\{(x_1, x_2) \in X_1 \times X_2 : x_2 \in \pi_{X_2}(R)\right\} \tag{8}$$

Where: R – relation at X_1 x X_2,

$\pi_{X_n}(R)$ – projection of the relation R on set X_n,

$\rho\left(\pi_{X_n}(R)\right)$ – cylindrical extension of X_n set.

3. Types of spaces of features of a system

Characteristic values of the system feature i can be dependent or independent from the values of others features of the system. Independent system features are the features that have independent characteristic values; consequently, dependent system features have dependent characteristic values.

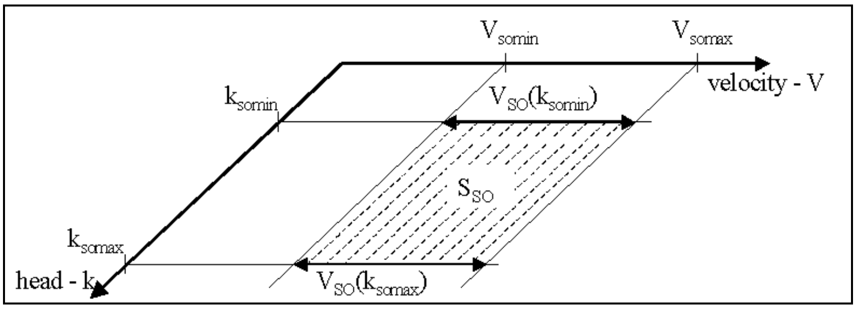

Fig. 3. Subspace of suboptimal system states in a space of two independent features
Rys. 3. Obszar stanów suboptymalnych systemu w przestrzeni dwóch cech niezależnych

As an example of independent features, we can consider velocity and head of a motor-driven vessel. These two features describe the state of an exploitation system of the vessel. Zero and the maxim value of vessel speed limit the range of variability of the „velocity" feature. Inside the range of variability, the minimum boundary value can be distinguished which is equal to its manoeuvring speed, and the maxim boundary speed can be defined. This is a highest speed of the vessel allowed by legal regulations [17]. This is also possible to indicate the maximum and minimum suboptimal values, which are equivalent to the minimum and maximum value of the highest engine efficiency. Omitting waves, sea currents, and wind force influence, the characteristic values of „velocity" feature are independent from the vessel head. For this example, subspace of suboptimal system states is a rectangle in a two-dimensional feature's space (Fig. 3).

The example of dependent features is temperature and the absolute humidity of air, which define a state of a working medium of a ventilation system in a building [18]. The range of variability for the temperature is limited by the minimum value and maximum value decreased by 5ºC [19] defined for external air for a specific climatic zone [20]. Inside the variability range the minimum boundary value is equal to temperature of the anti-freezing program of heating installation and it is equal to 6ºC [21]. The maximum boundary value is equal to the maximum value of variability range. The purpose of ventilation in a room is keeping the heat comfort conditions, which are described by temperature and air absolute humidity [22]. Consequently, the minimum and maximum suboptimal values of feature „temperature" in the presented example are equal to boundary values in the range of the heat comfort area. According to standards [23], these values depend on an absolute humidity of air.

It means that, depending on the value of the „absolute humidity" feature, the boundaries of suboptimal values of the „temperature" feature change [24]. For this example, the subspace of suboptimal states of the system in the two-dimensional space of a feature is presented below (Fig. 4).

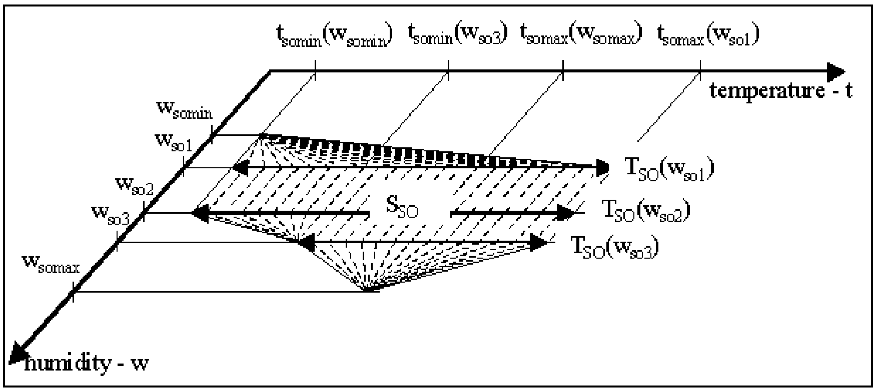

Fig. 4. Subspace of suboptimal system states in a space of two dependent features
Rys. 4. Obszar stanów suboptymalnych systemu w przestrzeni dwóch cech zależnych

Subspaces of a system states defined above in two-dimensional space of features, in case of n-dimensional space are expressed as hyperspaces R^n (9)

$$H(R^n) = \{(x_1, x_2, \cdots, x_n) \in R^n : a_1 \le x_1 \le b_1 \wedge a_2 \le x_2 \le b_2 \wedge \cdots \wedge a_n \le x_n \le b_n\} \quad (9)$$

where: $H(R^n)$ – hyperspace R^n,
a_n, b_n – boundary values in dimension no. n,
$x_1, x_2, \ldots, x_n$ – coordinates of points in R^n space.

If boundary values of hyperspaces in particular dimensions fulfil the conditions (10, 11), then the features of the system are independent ones and hyperspaces R^n become to be hypercubes R^n [25].

$$\begin{bmatrix} \frac{\partial a_1}{\partial x_1} & \frac{\partial a_1}{\partial x_2} & \cdots & \frac{\partial a_1}{\partial x_n} \\ \frac{\partial a_2}{\partial x_1} & \frac{\partial a_2}{\partial x_2} & \cdots & \frac{\partial a_2}{\partial x_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial a_n}{\partial x_1} & \frac{\partial a_n}{\partial x_2} & \cdots & \frac{\partial a_n}{\partial x_n} \end{bmatrix} = 0 \tag{10}$$

$$\begin{bmatrix} \frac{\partial b_1}{\partial x_1} & \frac{\partial b_1}{\partial x_2} & \cdots & \frac{\partial b_1}{\partial x_n} \\ \frac{\partial b_2}{\partial x_1} & \frac{\partial b_2}{\partial x_2} & \cdots & \frac{\partial b_2}{\partial x_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial b_n}{\partial x_1} & \frac{\partial b_n}{\partial x_2} & \cdots & \frac{\partial b_n}{\partial x_n} \end{bmatrix} = 0 \tag{11}$$

If conditions (10, 11) are not fulfilled, then features creating the space of features R^n of the system are dependent ones. Their characteristic values are changing concurrently with the values of correlated features. It implies the creation the hyperspaces of the system states in R^n space, which are more complicated in shape than hypercubes R^n.

The hypercubes R^2 for two independent features are presented in Figure (Fig. 5). The optimal state of the system s_O and real state of the system s_R are also presented.

Based on the definition of cardinal set of features, we can state that it consists of different elements depending on the analysed problem. A different set of cardinal features implies a different space of system features. Consequently, the system state treated as a point in a space of features can belong to different subspaces of system states depending on the space of features in which the state is described.

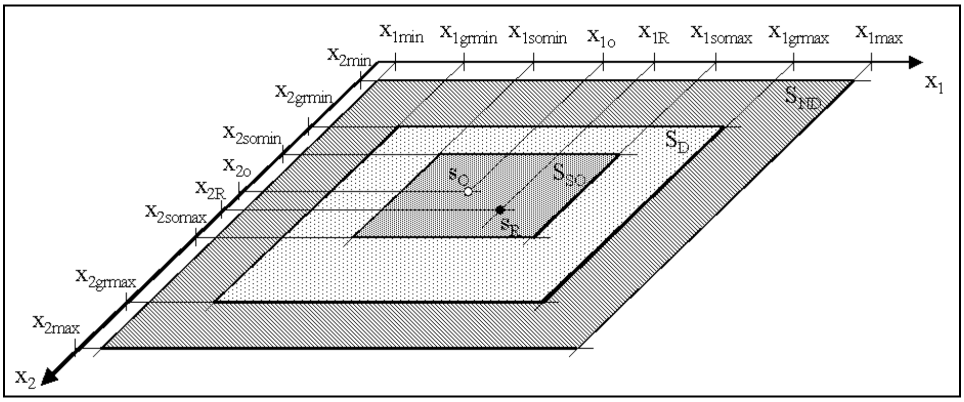

Fig. 5. Subspaces of system states presented in the independent space of features R^2
Rys. 5. Obszary stanów systemu przedstawione w przestrzeni R^2 cech niezależnych

Due to the system state interpretation as a point in a space of features, it is possible to express the changes of system state during the exploitation phase as a trajectory of a system state point in its space of features. Additionally, defining subspaces of ability states, inability states, and limited ability states of the system, it is possible to estimate a risk of inability state appearance by analysis of the distance between points in n-dimensional space. It can be the basis of the mathematical methods implementation in the area of the management of maintenance processes in complex technical systems.

5. Conclusions

Based on the considerations presented in the paper, the following conclusions were formulated:

- Characteristic values of feature are defined as values that determine the feature variability range and subsets of its unacceptable, acceptable, and suboptimal values.
- Characteristic ranges of the feature are the following: variability range, unacceptable value range, acceptable value range, and suboptimal value range.
- The set of cardinal features is the smallest set of the system's features, which are important for the considered issue, and its temporary values uniquely identify the system state.
- System state described by a vector of cardinal features can be interpreted as a point in an n-dimensional space, where n is the cardinality of the set of the cardinal features. N-dimensional space is called the space of features of the system.

– Subspaces of system states in a space of a feature are constructed as Cartesian products, which are the intersections of cylindrical extensions of the ranges of the system's features.
– Independent features of a system are the features that have independent characteristic values; consequently, dependent features of a system have dependent characteristic values.
– The system state treated as a point in a space of features can belong to different subspaces of system states, depending on the space of features in which the state is described.
– The system state interpretation as a point in a space of features can be the basis of the implementation of mathematical methods in the area of the management of maintenance processes in complex technical systems.

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Przestrzeń cech złożonego systemu technicznego

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

W fazie eksploatacji system techniczny występuje zarówno w procesie użytkowania, jak i obsługi zachodzących równocześnie lub po sobie. Powstaje wówczas konflikt wobec zależności działań oraz ograniczoności dostępu do obiektu technicznego. W celu rozwiązania konfliktu eksploatacyjnego procesy użytkowe i procesy zapewnienia zdatności muszą być procesami łącznie organizowanymi. Oznacza to, że w celu prowadzenia eksploatacji obiektu technicznego w sposób racjonalny, koniecznym jest zastosowanie strategii eksploatacyjnej określającej chwilę zakończenia procesów użytkowania i przekazania systemu do obsługi. Chwila ta wyznaczana jest na podstawie stanu systemu. Jednocześnie stan systemu jest również jednym z podstawowych czynników wpływających na sposób przeprowadzania procesów użytkowania i obsługi. Stan systemu jest zatem podstawową zmienną w procesie sterowania eksploatacją. Stan systemu z kolei jest opisany wartościami cech kardynalnych systemu. W opracowaniu zdefiniowano pojęcie przestrzeni cech systemu oraz omówiono rodzaje takich przestrzeni. Następnie przedstawiono stan systemu jako punkt zdefiniowanej przestrzeni. Zaproponowana interpretacja stanu systemu stanowi podstawę do wyrażania zmian stanu systemu zachodzących w trakcie realizacji odmiennych procesów eksploatacyjnych w jednej wspólnej przestrzeni jego cech. Podejście takie umożliwia zastosowanie spójnego aparatu matematycznego do opisu procesu sterowania eksploatacją złożonych systemów technicznych.