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RULES IN THE GENESIS OF MACHINES STATE

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Abstract

The study concerns the problem of indication of the procedures employed in the machines state genesis which are the foundation for the compilation of the rules of inference for determination of the reasons behind the state of machine incapacity.

Keywords: *genesis the condition of machine, the algorithmization of procedures, the rules of inference.*

1. Problem characteristics

Implementation of the genesis of the vehicles state methods in the exploitation process, what is the base of automation of state identification process, requires, among others, optimization of the diagnostic parameters and genesis methods.

The solution to those problems depends on many factors connected with their degree of dependence on the complexity of the machines, the use of multi-symptom observations, the quality of the exploitation process and utilization process.

Genesis of vehicles state is the process which should enable the forecast of the machine state in the past tense based on the incomplete history of the diagnostic tests results. It allows for machine state estimation or machine breakdown reason finding in examination moment.

The question of the choice, which seems to be especially important in the genesis of the state process, are:

a) the set of diagnostic parameters dependent on the machine working time, examination frequency and the average quantity of the optimal set of diagnostic parameters
b) the genesis method dependent on the machine horizon, the minimal number of the time chain elements necessary for the genesis start-up and the machine working time.

The study of the problems introduced above, the dynamics of their construction, high users expectations as well as the current legal regulations concerning the users safety and environmental protection are the sufficient urge to search new diagnosis methods as well as to determine new measurements and tools to describe the current diagnostic states in their exploitation process. All of above is presented below, as suitable procedures, algorithms and rules flow of them.

2. Procedure concerning optimization of the set of diagnostic parameters

The set of diagnostic parameters stands out of the set of initial parameters. On the base of the already conducted tests, the aim of which was to confirm some suggestions included in the literature concerning diagnostic information reduction in forecasting process, it is assumed that the following problems need to be taken into account while determination of the set of diagnostic parameters in the prognosis and genesis of the machine state [1,2,3,4,11]:

a) the ability of machine state modeling during its exploitation,

b) the amount of information concerning machine state,

c) the proper variability of the diagnostic parameters values during machine exploitation.

Thus the proper algorithms, with taking to account above, are introduced below as the following methods:

1. Correlation method of the diagnostic parameters and machine state which is testing the correlation of diagnostic parameters and machine state $r_j = r(W, y_j)$ (alternatively with exploitation time ($r_j = r((\Theta, y_j))$. In case of lack of data from the W collection these are replaced with machine exploitation time, on the assumption that indication of machine state diagnostic procedures is realized in the period of normal utilization time. Then $r_j = r(\Theta, y_j)$; j=1,..., m; k=1,...,K (r_j – correlation factor between $\Theta_k \in (\Theta_1, \Theta_b)$ (Θ_k – machine exploitation time) and y_j).

2. Maximum information capacity of the diagnostic parameter method.

The aim of this method is to choose the parameter which provides the largest number of information concerning machine state. The importance of the diagnostic parameter rises according to its correlation with the machine state and correlation decreasing with other diagnostic parameters. This correlation is shown in the shape of indicator of diagnostic parameter capacity h_j, which is modification of the indicator concerning the set of variables explaining econometric model.

The advantage of the methods introduced above is the fact that they let choose from the set of initial parameters both one-element as well as multi-element set of diagnostic parameters. One-element set concerns the case when machine is decomposed into the units and it is necessary to choose only one diagnostic parameter. Multi-element set is received when more lenient limits have been employed in the introduced procedures. By more lenient one should understand the situation when parameters of bigger or smaller indicating value have been classified in the set of diagnostic parameters, for which indicators value are higher (lower) in comparison to accepted for high (low) numbers method.

The algorithm for indicating the optimal set of diagnostic parameters values is the following:

1. Data acquisition:

a) the set of diagnostic parameters values in the function of the machine time exploitation $\{y_j(\Theta_k)\}$, gathered during the realization of passive-active experiment, where $\Theta_k \in (\Theta_1, \Theta_b)$;
b) the set of diagnostic parameters: $\{y_j(\Theta_1)\}$ - nominal values, ,$\{y_{jg}\}$ - boundary values, j=1, ..., m
c) the set of machine states $\{\Theta_k: \{s_i\}$, k=1, …, K; i=1,…, I}, achieved during the realization of passive-active experiment, where $\Theta_k \in (\Theta_1, \Theta_b)$;
d) the cost of diagnostic parameters $c(y_j)$ = const.

2. Optimization of the set of diagnostic parameters values (only in the case of a large quantifity of Y set, e.g. m>10). The set of diagnostic parameters is determined by means of:

a) correlation method of diagnostic parameters values and machine state (with exploitation period, $r_j = r(W, y_j)$, ($r_j = r((\Theta, y_j))$:

$$r_j = \frac{\sum_{k=1}^{K}(\Theta_k - \overline{\Theta})(y_{j,k} - \overline{y_j})}{\sqrt{\sum_{k=1}^{K}(\Theta_k - \overline{\Theta})^2 \sum_{k=1}^{K}(y_{j,k} - \overline{y_j})^2}} \tag{1}$$

$$\overline{\Theta} = \frac{1}{K}\sum_{k=1}^{K}\Theta_k\ , \quad \overline{y_j} = \frac{1}{K}\sum_{k=1}^{K} y_{j,k} \tag{2}$$

b) the method concerning the amount of information of diagnostic parameters about the machine state:

$$h_j = \frac{r_j^2}{1 + \sum\limits_{j,n=1,\, j\neq n}^{m} \left| r_{j,n} \right|} \tag{3}$$

$$r_{j,n} = \frac{\sum\limits_{k=1}^{K}(y_{j,k} - \overline{y_j})(y_{n,k} - \overline{y_n})}{\sqrt{\sum\limits_{k=1}^{K}(y_{j,k} - \overline{y_j})^2 \sum\limits_{k=1}^{K}(y_{n,k} - \overline{y_n})^2}} \tag{4}$$

$$\overline{y_j} = \frac{1}{K}\sum_{k=1}^{K} y_{j,k}\ ; \quad \overline{y_n} = \frac{1}{K}\sum_{k=1}^{K} y_{n,k} \tag{5}$$

where: $r_j = r(W, y_j)$; j=1,..., m - the factor of correlation between W (machine state) and y_j variables.

In case of lack of data from the W collection these are replaced with machine exploitation time, on the assumption that the indication of the machine state procedures is realized in the period of normal utilization time. Then $r_j = r(\Theta, y_j)$; j=1,..., m; k=1,...,K (r_j – correlation factor between $\Theta_k \in (\Theta_1, \Theta_b)$ (Θ_k – machine exploitation time) and y_j variables).
In order to choose the set of diagnostic parameters the weight values are used

a) computable weight :

$$w_{1j} = \frac{1}{d_j}, \quad d_j = \sqrt{(1 - r_j^*)^2 + (1 - h_j^*)^2} \tag{6}$$

$$r_j^* = \frac{r_j}{\max r_j}, \quad h_j^* = \frac{h_j}{\max h_j} \tag{7}$$

b) the criterion of diagnostic parameter(s) choice here is maximum of the weight values w_{1j} and the choice of diagnostic parameters according to the described criterion.
c) in order to match the users preferences it is possible to introduce weights w_2 (standard values) from the (0,1) section and to choose diagnostic parameters according to the described criterion.

3. Genesis of the machine state procedure

While discussing the problem of the machine state genesis, some genesis methods should not be considered better than others. It all depends on the subject of the study and the aim of the machine state genesis. While employing some criteria concerning [5,6,7,8,12]:

a) the character of the genesis (the value of the symptom genesis, the estimated machine state in the past, the value of the past work or a different character of the machine state genesis),
b) the influence of the change of the machine exploitation conditions and the operational activities on the machine exploitation attributes, which need to be considered while choosing the genesis method,

c) genesis methods likely to be used (e.g. quality methods, modified trend extrapolation methods and modified adaptation methods),

Algorithm of the machine state genesis method according to the estimation of the diagnostic parameters value scheme includes the following elements:

1.The set of diagnostic parameters genesis $\{y_j^*\}$:

a) with help of diagnostics parameter y_j^* value approximation methods in time range (Θ_1,Θ_b) with approximation tolerance radius r_a for "tolerance channel";
b) by means of diagnostic parameter y_j^* interpolation in the time range $(\Theta_1,\Theta_{b)}$ with approximation tolerance radius r_a for "tolerance channel" using glued functions method 1, 2, 3 equation;
c) the choice of method according to nominal or maximal value of tolerance radius for approximation or interpolation (machine tolerance e_G).

2. Analysis of the cause of $s_i(T_{LU})$ state:

a) the set $\{s_i\ (\Theta_k),\ i=1,\ldots,1;\ k=1,\ \ldots,\ K\}$ presentation.
b) determination of the common point of the „tolerance channel" indicated by the tolerance radius $r^*{}_j=\max\ (r_{ja},\ r_{ji})$ and the diagnostic parameter y_j^* boundary value at the moment $\Theta_S\in(\Theta_1,\Theta_b)$ moment, which means that the reason for the localized state s_i was the temporary appearance of that state in the time (Θ_1,Θ_b);
c) defining more number of the common points of the "tolerance channel" indicated by the tolerance radius $r=\max\ (r_a,\ r_i)$ and the diagnostic parameter y_j^* boundary values in the moments $\Theta_s\in(\Theta_1,\Theta_b)$ means that the cause of the localized state s_i was the rising development of that state in the time (Θ_1,Θ_b);
d) in case of lack of common points defining the minimal length of the "tolerance channel" from the boundary value in the moment $\Theta_S\in(\Theta_1,\Theta_b)$, which means that the cause of the localized state s_i was probably temporary incomplete appearance of that state in the (Θ_1,Θ_b) time;
e) analysis of identity of the set of states $\{s_i\ (\Theta_k),\ k=1,\ \ldots,\ K\}$ and the localized by T_{LU} of s_i state for the determination of its appearance in the context of alternative common points or minimal length of approaches.

4. The rules of making conclusion in the defining of the causes of machine incapacity

The analysis of the task demands in relation to state forecasting and next maintenance time defining, occurred, that in the data base, beside sets of boundary, values, nominal values and diagnostic parameters values registered during exploitation, rules for diagnostic conclusions are necessary.

Analysis of the results of the research into methodology of machine state forecasting [11,12,13] allows for formulation of the rules for conclusion of type "IF-THEN" or "IF-THEN-ELSE" in the field of

a) optimization of diagnostic parameters;
b) machine state genesis.

For example for 6203 car bearing and for the internal combustion engines in Star 11422 cars generated rules are as below:

1. Conclusion rules for 6203 bearing:

a) for diagnostics parameters Y^o set optimization:
   - if $w_{1j}\geq 0{,}02$ to $y_j\in Y^o$,
   - or if $w_{1j}=\ w_{1jmax}$ to $y_j\in Y^o$;

b) for the state genesis:
   - if the set of probable bearing damage occurs, defining of the state of incapacity according

to the level of occurrence probability follows the $p(s_i) \geq 0{,}5$ to $s_i \in S$ rule,

- if there is no probable damage to bearing, defining the states of incapacity according to the measure of exploitation: if $\Theta_i \geq \Theta_l$ to s_i $(\Theta_l) \in S$,
- if the mistake of the second degree approximation for the set $Y^o \leq$ mistakes genesis interpolation method of the first degree for the set Y^o then the genesis method for the set of values in the Y^o set is the first degree interpolation method, or else the second degree interpolation method,
- if the genesied diagnostic parameter distance $y_j \in Y^o$ with genesis mistake from boundary parameter $y_j \in Y^o$ values is: $d(y_{jg}$ – value $(y_{jG} + r_G)$ for $y_{jG} > y_{jG})$, d(value $(y_{jg} - (y_{jG} - r_G)$ for $y_{jG} < y_{jG})$ than minimum value d(•) is the minimum distance d_{min},
- if $d_{min} = 0$, than there is one common point with boundary value (number of $[d_{min}] = 1$), if $d_{min} < 0$, than there is more than one common point for boundary value (number $[d_{min}] > 1$), if $d_{min} > 0$, than there is no common points with boundary values,
- if $d_{min} = d_{min}(\Theta(s_i))$, than minimum value of $d^s_{min} = d_{min}$ occurred in state in $\Theta_S \in (\Theta_1,\Theta_b)$ time, what means, that the reason of located state during s_i T_{LU} test was the temporary appearance of s_i state during (Θ_1,Θ_b), in other case, d_{min} # $d_{min}(\Theta(s_i))$, what means, that the reason of s_i state ocured during T_{LU} test, is impossible to explain,
- if the number $[d^s_{min}] > 1$, it means that reason of located state s_i was caused by increasing development in $\Theta_S \in (\Theta_1,\Theta_b)$ time of s_i occurrence conditions (defined during T_{LU} test),
- if $d_{min} > 0$ and there is no common point with boundary value, it means that most feasible reason of located s_i state (defined during T_{LU} test) was temporary, un full occurance of that state in (Θ_1,Θ_b) time;

2. The rules of meaking conclusions for Star 11422 car combustion engine:
   a) for diagnostic parameters Y^o set optimization:
      - if $w_{1j} \geq 0{,}07$ then $y_j \in Y^o$,
      - or if $w_{1j} = w_{1jmax}$ to $y_j \in Y^o$;

   b) for state genesis:
      - if there is set of most feasible combustion engine break down for Star 11422, defining, the set of its out of work states according to initial breakdown probability level rule: if $p(s_i) \geq 0{,}5$ than $s_i \in S$,
      - if there is no set of most feasible Star 11422 combustion engine breakdown, defining the set of its out of work states according to exploitation measure value: if $\Theta_i \geq \Theta_l$ than s_i $(\Theta_l) \in S$,
      - if the genesis approximation ,2 equate, method mistake for set $Y^o \leq$ genesis mistake 1 equate for Y^o set, then interpolation 1 equate is the genesis method for Y^o set, in other case, 2 equate approximation i the genesis method,
      - if the approximation 2 equate genesis mistake for Y^o set $\leq$ genesis method with 1 equate interpolation for Y^o set, than the 1 equate interpolation is the genesis method for Y^o set values, in other case 2 equate approximation is the method,
      - if genesis diagnostic parameter $y_j \in Y^o$ value distance with genesis mistake from parameter y_{jg} boundary value: $(y_{jg}$ – value $(y_{jG} + r_G)$ for $y_{jG} > y_{jG})$, d(value $(y_{jg} - (y_{jG} - r_G)$ for $y_{jG} < y_{jG})$ then the minimal distance d_{min} is the minimum value d(•),
      - if $d_{min} = 0$, than tere is only one common point with boundary value (number of $[d_{min}] = 1$), if $d_{min} < 0$, then there is more then one common point with boundary value (number $[d_{min}] > 1$), if $d_{min} > 0$, than there is no common points with boundary value,
      - if $d_{min} = d_{min}(\Theta(s_i))$ than minimum value $d^s_{min} = d_{min}$ occurred with state during $\Theta_S \in (\Theta_1,\Theta_b)$, what means that temporary s_i state appearance in $\Theta_S \in (\Theta_1,\Theta_b)$ time was the reason of occurred located s_i state T_{LU} test, in other case d_{min} # $d_{min}(\Theta(s_i))$ what means that it is impossible to define reason of s_i state during T_{LU} test,

- quantity $[d^s_{min}]$ >1 mean, that the increasing of s_i occurring conditions development during $\Theta_S \in (\Theta_1,\Theta_b)$ time was the reason of located s_i (defined during T_{LU} test),
- if $d_{min} > 0$ and there is no common point with boundary value means, that temporary, un full s_i located state occurring during (Θ_1,Θ_b) time was the most feasible s_i located state occurring (s_i defined during T_{LU} test).

Presented making conclusion rules in range of machine state genesis, after suitable verifications can be the base for dedicated machine state estimation application in on-line mode for specific system or off-line mode for stationary system.

5. Conclusion

The above presentation of the vehicle state genesis procedure allows for the following conclusions:

1.Presented procedures allow for defining optimal, according to the assumed, criterion:

a) the set of diagnostic parameters;
b) diagnostic parameter values genesis and estimation of the causes of the machine state;

2.Taking the above into consideration, in order to define the set of diagnostic parameters and genesis the presented procedures may constitute the foundation for defining the rules of inference in the fields:

a) defining the optimal set of diagnostic parameters;
b) estimation of diagnostic parameters values in the past and estimation of the cause of the state of the object in the moment of testing.

References

[1] Ameljańczyk, A., *Multiple optimization* (in Polish), WAT, Warszawa 1986.

[2] Batko, W., *Synthesis methods of prediction diagnoses in technical diagnostics* (in Polish), Mechanika, z. 4. Zeszyty Naukowe AGH, Kraków 1984.

[3] Bowerman, B., L., O`Connel, R., T., *Forecasting and Time Series*, Doxbury Press (USA), 1979.

[4] Box, G., Jenkins, G., *Time series analysis, forecasting and control*, London 1970.

[5] Brown, R., G., *Statistical Forecasting for Invertory Control*, Mc Graw-Hill, New York 1959.

[6] Cempel, C., *Evolutionary symptom models in machine diagnostics* (in Polish), Materiały I Kongresu Diagnostyki Technicznej, Gdańsk 1996.

[7] Cholewa W., Kaźmierczak J.: Data processing and reasoning in technical diagnostcs. WNT, Warszawa 1995.

[8] Inman, D., J., Farrar, C., J., Lopes, V., Valder, S., *Damage prognosis for aerospace, civil and mechanical systems*, John Wiley & Sons, Ltd. New York 2005.

[9] Staszewski W.,J., Boller C., Tomlinson G.,R.: Health Monitoring of Aerospace Structures. John Wiley & Sons, Ltd. Munich, Germany 2004.

[10] Theil, H., *Applied economic forecasting*, North-Holland, Amsterdam 1971.

[11] Tylicki, H., *Optimization of the prognosis method of mechanical vehicles technical state* (in Polish), Wydawnictwa uczelniane ATR, Bydgoszcz

[12] Tylicki, H.,: Inference rule in machine state forecasting. Comission of Motorization and Power Industry in Agriculture. Polska Akademia Nauk, Oddział w Lublinie, vol. VIIA, Lublin 2007, pp. 114-120.

[13] Żółtowski, B., *Diagnostic system for the metro train*, ICME, Science Press, pp..337-344, Chengdu, China 2006.