# INFERENCE RULES IN MACHINE STATE FORECASTING

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**Summary.** The article presents problems of determination of machine state forecasting algorithms as the basis for inference rules study.

Key words: machine state forecasting, algorithmization of procedures, inference rules.

#### INTRODUCTION

The use of vehicle state forecasting methods in the process of exploitation, being the basis of automation of the process, requires an optimization of diagnostic parameters collection and forecasting methods. The solution of these tasks depends on many factors connected with machine complexity, application of poly-symptom observations, quality of the process of exploitation and wear.

Vehicle state forecasting is a process which should make it possible to predict the future machine state on the basis of an incomplete history of the results of diagnostic investigations. It makes it possible to estimate the time of unfailing use of a given machine or the value of its future work.

The following problems seem to be particularly important in the choice of state forecasting methods:

- a) the set of diagnostic parameters depending on the working time of a machine, the value of temporary step and the number of the optimum set of diagnostic parameters;
- b) the method of forecast depending on the horizon of forecast, the minimum number of the temporary row units indispensable to start the forecasting and the time of the machine work;

The investigation of the above-mentioned problems in the process of vehicle or working machine state recognition, the investigation of the dynamics of their construction, high requirements imposed by users as well as the valid legal regulations concerning user safety and environmental protection, encourage the search for new diagnostic methods and determination of new measures and tools describing their current diagnostic states in the process of their exploitation, presented below as proper procedures, algorithms and inference rules.

## PROCEDURE OF DIAGNOSTIC PARAMETERS SET OPTIMIZATION

A set of diagnostic parameters can be clearly distinguished from the set of original parameters. On the basis of the conducted investigations, aiming at the confirmation of some proposals in works on the reduction of diagnostic information in the process of forecasting, it can be stated that during determination of the set of diagnostic parameters in the process of forecasting and generating machine state the following should be taken into account:

a) an ability to simulate machine condition changes during exploitation;

b) amount of information on machine state;

c) proper changeability of diagnostic parameters value during machine exploitation.

That is why suitable algorithms taking these postulates into account were presented below as methods. Here they are:

1. Method of correlation of diagnostic parameters value with machine state.

It consists in the investigation of correlation of diagnostic parameters value with 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 set W, it is replaced with machine expoloitation time, provided that machine state recognition procedures are determined in the range of normal wear. Then  $r_j = r(\Theta, y_j)$ ; j = 1,..., m; k = 1,..., K ( $r_j$  – coefficient of correlation between variables  $\Theta_k \in (\Theta_1, \Theta_b)$  ( $\Theta_k$  – machine exploitation time) and  $y_j$ ).

2. Method of the maximum informative capacity of a diagnostic parameter.

This method consists in the choice of a parameter providing the greatest amount of information on machine state. The stronger the correlation between a diagnostic parameter and machine state, and at the same time the weaker the correlation between the parameter and the other ones, the greater its significance in machine state change determination. This dependence is presented as the coefficient of diagnostic parameter capacity  $h_{j_{,j}}$  which is a modification of the coefficient applying to a set of variables illustrating an econometric model.

The advantage of the presented methods is, that they allow to select both mono-element and poly-element diagnostic parameters sets from the original parameter set. A mono-element set concerns the case, when the machine is decomposed into aggregates and the choice of one diagnostic parameter is necessary. A poly-element set is obtained, when in the presented procedures a less rigid approach is applied and also these parameters are accepted to the set of diagnostic parameters whose values of coefficients are higher (lower) than the selected, correspondingly to the method, small (large) positive numbers.

Algorithm of methodology of the determination of the optimum diagnostic parameters set involves the following stages:

1. Acquisition of data:

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

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

a) the method of the correlation of diagnostic parameters values with machine state (with exploitation time,  $r_i = r(In, y_i)$ ,  $(r_i = r((\Theta, y_i))$ :

$$\mathbf{r}_{j} = \frac{\sum_{k=1}^{K} (\Theta_{k} - \overline{\Theta})(y_{j,k} - \overline{y_{j}})}{\sqrt{\sum_{k=1}^{K} (\Theta_{k} - \overline{\Theta})^{2} \sum_{k=1}^{K} (y_{j,k} - \overline{y_{j}})^{2}}}$$
(1)

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

b) the method of the amount of diagnostic parameters information on machine state h.:

$$h_{j} = \frac{r_{j}^{2}}{1 + \sum_{j,n=1,j\neq n}^{m} |r_{j,n}|}$$
(3)

$$\mathbf{r}_{j,n} = -\frac{\sum_{k=1}^{K} (y_{j,k} - \overline{y_j})(y_{n,k} - \overline{y_n})}{\sqrt{\sum_{k=1}^{K} (y_{j,k} - \overline{y_j})^2 \sum_{k=1}^{K} (y_{n,k} - \overline{y_n})^2}}$$
(4)

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

where:  $r_j = r(W_n, y_j); j = 1,..., m$  - the coefficient of correlation between variables W (machine state) and  $y_j$ ,  $r_{jn} = r(y_j, y_n); j, n = 1,..., m; j \neq n$  - the coefficient of correlation between variables  $y_j$  and  $y_n$ .

In case of lack of data from the set W it is replaced with machine expoloitation time, provided that machine state recognition procedures are determined in the range of normal wear. Then  $r_j = r(\Theta, y_j)$ ; j = 1,..., m; k = 1,..., K ( $r_j$  – the coefficient of correlation between variables  $\Theta_k \in (\Theta_1, \Theta_b)$  ( $\Theta_k$  – machine exploitation time) and  $y_j$ ).

In order to select the set of diagnostic parameters, the values of weights are used: a) Computational weights  $w_{ij}$ :

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

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

- b) the maximization of weight values  $w_{1j}$  and selection of diagnostic parameters according to the above-mentioned criterion were accepted as the method of the diagnostic parameter (diagnostic parameters) choice.
- c) in order to satisfy a user's preference there is a possibility to introduce weights  $w_2$  (standard values) from the range (0,1) and to select diagnostic parameters according to the above-mentioned criterion.

## PROCEDURE OF MACHINE STATE FORECASTING

Algorithm of machine state forecasting involves the following stages:

- 1. Forecast of the value of the diagnostic parameter y<sub>i</sub><sup>\*</sup>:
- a) by the adaptive method of Brown-Mayer of the row 1 (B-M1) with the coefficient  $\alpha = (0, 5 0, 8)$  and for the forecast horizon  $\tau = (1 3)\Delta\Theta$  determined for the time range  $(\Theta_1, \Theta_n)$ ,
- b) by the adaptive method of Holt with the coefficient  $\alpha_1 = (0, 6 0, 8)$  and  $\alpha_2 = (0, 4 0, 8)$  for the forecast horizon  $\tau = (1 3)\Delta\Theta$  determined for the time range  $(\Theta_1, \Theta_2)$ ,
- c) by analytic methods (linear, exponential, power method of the first, second and third row) for the forecast horizon of  $\tau = (1 3)\Delta\Theta$  determined for the time range  $(\Theta_1, \Theta_2)$ ,
- 2. Setting the deadline for the next servicing and diagnosing of the machine  $\Theta_d$ :
- a)  $\Theta_{d1}$  by the method of levelling the forecasting error for the ray of the forecasting error  $r_{\sigma}$  (for the level of significance  $\beta = 0.05$ ) according to the dependence:

for 
$$y_j(\Theta_b) > y_{jg}$$
:  $\Theta_{jd1} = \Theta_{jb} + \frac{\tau [y_j(\Theta_b) - y_{jg} - r_\sigma]}{y_j(\Theta_b) - y_{j,p}(\Theta_b + \tau)}$  (8)

for 
$$y_j(\Theta_b) < y_{jg}$$
:  $\Theta_{jd1} = \Theta_{jb} + \frac{\tau \left[ y_{jg} - y_j(\Theta_b) - r_\sigma \right]}{y_{j,p}(\Theta_b + \tau) - y_j(\Theta_b)}$  (9)

where:  $r_{\sigma}$  – ray of forecasting error range (counted a posteriori respectively for every method of the forecast value determination  $y_{i,n}(\Theta_{b} + \tau)$ );

- b)  $\Theta_{d2}$  by the method of levelling the border value of diagnostic parameter
  - $(y_{jg1} = y_{jg}, y_{jg1} = y_{jg} + \gamma(y_{jn} y_{jg}) \text{ for } y_{jn} > y_{jg} \text{ and } y_{jg1} = y_{jg}, y_{jg1} = y_{jg} \gamma (y_{jg} y_{jn}) \text{ for } y_{jg} > y_{jn}), e.g. \text{ for } \gamma = 0,1:$

for 
$$y_j(\Theta_b) > y_{jg}$$
:  $\Theta_{jd2} = \Theta_{jb} + \frac{\tau [y_j(\Theta_b) - y_{jg1}]}{y_j(\Theta_b) - y_{j,p}(\Theta_b + \tau)}$  (10)

for 
$$y_j(\Theta_b) < y_{jg}$$
:  $\Theta_{jd2} = \Theta_{jb} + \frac{\tau \left[ y_{jg1} - y_j(\Theta_b) \right]}{y_{i,p}(\Theta_b + \tau) - y_j(\Theta_b)}$  (11)

c) Setting the deadline for the next servicing and diagnosing of the machine:  $\Theta_d^* =$  the mines  $(\Theta_{d1}, \Theta_{d2})$ .

#### INFERENCE RULES IN SETTING THE TERM OF MACHINE SERVICE

An analysis of activity requirements concerning machine state forecasting and setting the term of machine service shows, that in the database inference rules are necessary as well as the sets of border and nominal values or diagnostic parameter values.

An analysis of results of studies on machine state forecasting allows to create the dedicated inference rules of the type "IF – THEN" or "IF – THEN – ELSE" in the area:

- a) optimization of diagnostic parameters;
- b) state forecasting.

For example for car gear transmission and combustion engine UTD-20 the generated inference rules accept the following shape:

- 1. The inference rules for car gear transmission:
- a) for the optimization of the diagnostic parameters set Y<sup>o</sup>:
- if  $w_{1i} \ge 0,1$  then  $y_i \in Y^o$ ,
- or if  $W_{1i} = W_{1imax}$  then  $y_i \in Y^o$ ;
- b) for state forecasting:
- if  $w_{1i} = w_{1imax}$  and if  $w_{1i} \ge 0.9$  then  $y_i \in Y^o$  and set  $Y^o$  is a one-element set,  $Y^o = Y^{o1}$ ,
- if  $w_{1j}^{ij} = w_{1jmax}^{ijmax}$  and if  $w_{1j}^{ij} < 0.9$  then  $y_j^{ij} \in Y^o$  and set  $Y^o$  is not a one-element set,  $Y^o = Y^{oo}$ ,
- if the forecast error by Holt method (with the suitable values of parameters  $\alpha_1, \alpha_2$ ) for the set Yo1 < the forecast error by Brown - Mayer method (with the suitable value of the parameter  $\alpha$ ) for the set Y<sup>o1</sup> then the proper method of forecasting the set Y<sup>o1</sup> value is the Holt method (with the suitable values of parameters  $\alpha_1$ ,  $\alpha_2$ ), in the opposite case the proper Yol value forecasting method is the Brown-Mayer one (with the suitable value of the parameter  $\alpha$ ).
- if the value of deadline of the next survey of gear transmission  $\Theta_{d1}$  (Y<sup>01</sup>)  $\leq$  the value of deadline of the next survey of gear transmission  $\Theta_{d2}$  (Y<sup>o1</sup>) then the proper method of setting the term of the next survey of gear transmission is the method of levelling the forecasting error value, in the opposite case it is the method of diagnostic parameter border value forecasting.
- if forecast errors for methods: Holt's (with proper values of parameters  $\alpha_1, \alpha_2$ ) or Browna - Mayer's (with a proper value of parameter  $\alpha$ ) for the diagnostic parameters of the set Y<sup>oo</sup> show minimum values, then the above-mentioned methods are adequate for the forecasting of the value of proper diagnostic parameters of the set Yºo.
- if the value of deadline of the next survey of gear transmission  $\Theta_{d1}$  (Y<sup>oo</sup>)  $\leq$  the value of deadline of the next survey of gear transmission  $\Theta_{d2}$  (Y<sup>oo</sup>) then the proper method of setting the term of the next survey of gear transmission (for the investigated diagnostic parameter) is the method of levelling the forecasting error value, in the opposite case it is the method of diagnostic parameter border value forecasting,
- if the value of deadline of the next survey of gear transmission  $\Theta_{a}$  is set for Y<sup>oo</sup>, then this value is the balanced one of  $\Theta_{dw}$ .
- 2. The rules of inference for the combustion engine UTD-20:
- a) for the optimization of the diagnostic parameters set Y<sup>o</sup>:
- if  $w_{1i} \ge 0.05$  then  $y_i \in Y^o$ ,
- or if w<sub>1j</sub> = w<sub>1jmax</sub> then y<sub>j</sub> ∈ Y<sup>o</sup>;
- b) for state forecasting:
- $\begin{array}{ll} \mbox{if } w_{1j} = w_{1jmax} \mbox{ and if } w_{1j} \geq 0.9 \mbox{ then } y_j \in Y^o \mbox{ and set } Y^o \mbox{ is a one-element set, } Y^o = Y^{o1}, \\ \mbox{if } w_{1j} = w_{1jmax} \mbox{ and if } w_{1j} < 0.9 \mbox{ then } y_j \in Y^o \mbox{ and set } Y^o \mbox{ is not a one-element set, } Y^o = Y^{oo}, \\ \mbox{is a one-element set, } Y^o = Y^{oo}, \end{array}$
- if the forecast error by Holt method (with the suitable values of parameters  $\alpha_1, \alpha_2$ ) for the set  $Y^{o1}$  < the forecast error by Brown-Mayer method (with the suitable value of the parameter  $\alpha$ ) for the set Y<sup>o1</sup>, then the proper method of forecasting the set Y<sup>o1</sup> value is the Holt method (with the suitable values of parameters  $\alpha_1$ ,  $\alpha_2$ ), in the opposite case the proper Yo1 value forecasting method is the Brown-Mayer one (with the suitable value of the parameter  $\alpha$ ),

- if the value of deadline of the next survey of the engine UTD-20  $\Theta_{d1}$  (Y<sup>o1</sup>)  $\leq$  the value of deadline of the next survey of the engine  $\Theta_{d2}$  (Y<sup>o1</sup>), then the proper method of setting the term of the next survey of gear transmission is the method of levelling the forecasting error value, in the opposite case it is the method of diagnostic parameter border value forecasting,
- if forecast errors for methods: Holt's (with proper values of parameters α<sub>1</sub>, α<sub>2</sub>) or Browna
   – Mayer's (with a proper value of parameter α) for the diagnostic parameters of the set Y<sup>00</sup>
   show minimum values, then the above-mentioned methods are adequate for the forecasting
   of the value of proper diagnostic parameters of the set Y<sup>00</sup>.
- if the value of deadline of the next survey of the engine UTD-20  $\Theta_{d1}(Y^{00}) \leq$  the value of deadline of the next survey of the engine  $\Theta_{d2}(Y^{00})$ , then the proper method of setting the term of the next survey of gear transmission is the method of levelling the forecast error value, in the opposite case it is the method of diagnostic parameter border value forecasting,
- if the value of deadline of the next survey of the engine UTD-20  $\Theta_d$  is set for  $Y^{00}$ , then this value is the balanced one of  $\Theta_{dw}$ .

The presented rules of inference concerning machine state forecasting, after adequate verification can serve as the basis for dedicated machine state recognition software either as an on-line application (for the deck system) or an off-line one (for the stationary system).

## CONCLUSION

The above-presented analysis of procedures for vehicle state forcasting allows to draw the following conclusions:

1. Due to the accepted criterion, the presented procedures allow to determine the optimum:

- a) set of diagnostic parameters;
- b) forecast of the value of diagnostic parameters and estimation of machine service term;
- Consequently, aiming at the determination of the set of diagnostic parameters and forecast, the above-presented procedures can serve as the basis for the creation of inference rules concerning:
- a) determination of the optimum set of diagnostic parameters;
- b) estimation of the value of future diagnostic parameters and setting the next vehicle service term.

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