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CONTROL AND DIAGNOSTIC MODEL OF BRUSHLESS DC MOTOR

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A simulation model of brushless DC motor (BLDC) control and diagnostics is considered. The model has been developed using a freeware complex "Modeling in technical devices". Faults and diagnostic parameters of BLDC are analyzed. A logical-linguistic diagnostic model of BLDC has been developed on basis of fuzzy logic. The calculated rules determine dependence of technical condition on diagnostic parameters, their trends and utilized lifetime of BLDC. Experimental results of BLDC technical condition diagnostics are discussed. It is shown that in the course of BLDC degradation the motor condition change depends on diagnostic parameter values.

K e y w o r d s: brushless DC motor, model, control, diagnostics, fuzzy logic

1 INTRODUCTION

BLDC is a type of electric motors that rapidly gains popularity due to its good performance and the development of microprocessor controls. New PWM switching strategy to minimize the torque ripples in BLDC motor which is based on sensored rotor position control is discussed in the paper [1]. Tuning methodology for the parameters of adaptive current and speed controllers in a permanent-magnet BLDC motor drive system is presented in paper [2]. Two Fault Detection and Diagnosis strategies for detecting Brushless DC Motor faults were considered involving wavelets and state estimation [3]. Bearing faults and stator winding faults, which are responsible for the majority of motor failures, are considered [3]. A novel method using windowed Fourier ridges is proposed in paper [4] for the detection of rotor faults in BLDC motors operating under continuous non-stationarity. The use of quadratic TFRs is presented as a solution for the diagnostics of rotor faults in brushless DC (BLDC) motors operating under constantly changing load and speed conditions [5]. Four time-frequency representations are considered short-time Fourier transform (STFT), Wigner-Ville distribution (WVD), Choi-Williams distribution (CWD), and the Zhao-Atlas marks distribution (ZAM) [5]. Three new algorithms for the detection BLDC motors faults are proposed that can track and detect rotor faults in non-stationary or transient current signals [6]. Park's vector method was used to extract the features and to isolate the BLDC motors faults from the current measured by sensors [7]. Proposed a model of a fault diagnosis expert system with high reliability to compare identical well-functioning BLDC motors [8].

The authors propose to integrate the BLDC control and diagnostic systems. The economic efficiency of diagnostic systems is due to increase in reliability and quality, accident risk and reject rate reduction, decrease of expensive equipment downtime, reduction of maintenance and repair costs and increase of service life. Currently, artificial intelligence technologies are widely used for control and diagnostics of electric motors [9–13].

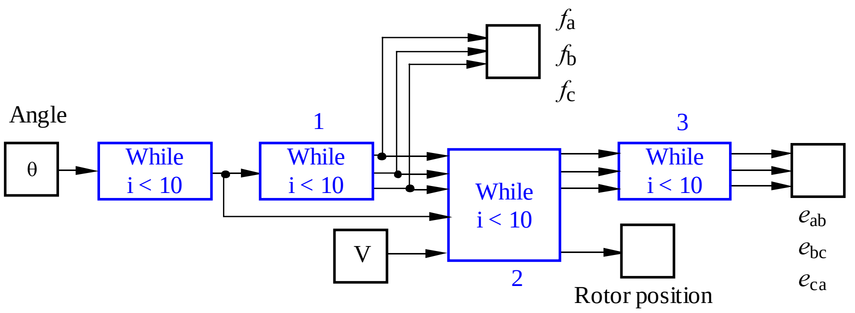

Fig. 1. BLDC Simulation model

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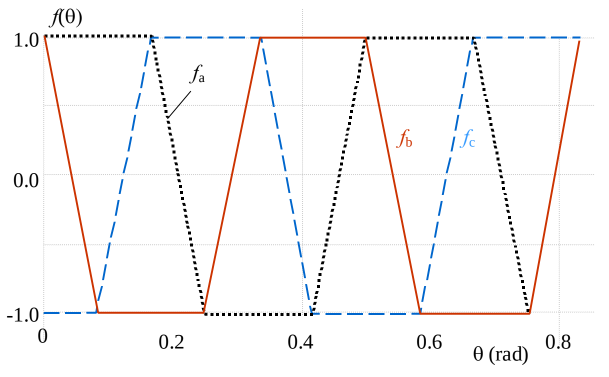

Fig. 2. Relationships between $f_a(\theta)$, $f_b(\theta)$, $f_c(\theta)$ and rotor rotation angle, where 1 – function $f_a(\theta)$, 2 – function $f_b(\theta)$, 3 – function $f_c(\theta)$

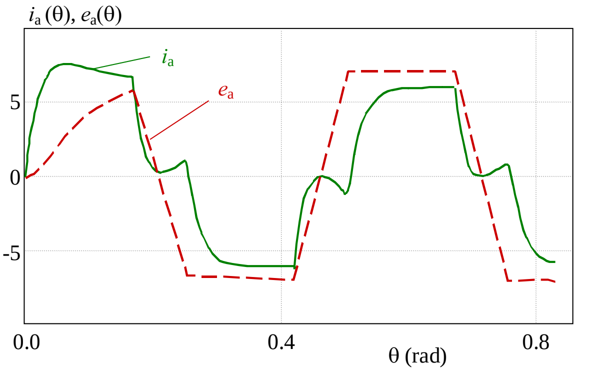

Fig. 3. The relationship between the phase a current i_a (function 1 on the graph) and the rotor rotation angle and the relationship between the back electromotive force e_a (function 2 on the graph) and the rotor rotation angle

2 THEORY

2.1 Simulation model of Brushless DC motor

To investigate BLDC control, a simulation model in natural (phase) coordinates has been created using "Modeling in Technical Devices" (MITD) software developed in Bauman Moscow State Technical University [14] (Fig. 1). MITD is a good alternative to such software packages as SIMULINK, VisSim, MATRIXx, *etc.*

Rotor speed and angle were used as inputs of BLDC simulation model. Relationships between electrical and mechanical parameters and the angle have been determined. The resulting functions $f_a(\theta)$, $f_b(\theta)$, $f_c(\theta)$ are shown in Fig. 2.

The relationship between the phase a current i_a (function 1 on the graph) and the rotor rotation angle and the relationship between the back electromotive force e_a (function 2 on the graph) and the rotor rotation angle are shown in Fig. 3.

Simulation model of BLDC control allows to determine the relationships for phase currents and back electromotive force of perfect BLDC which can be used as diagnostic parameters. To improve diagnostics accuracy, the analysis of faults and other BLDC diagnostic parameters is required.

2.2 BLDC faults and diagnostic parameters

For the purpose of BLDC diagnostics the BLDC faults have been grouped into two classes — of electrical and mechanical faults. BLDC faults are shown in Tab. 1.

Selected diagnostic parameters (current, vibration and temperature) are shown in Tab. 2.

Processing of diagnostic parameter measurements is required to make decision regarding the BLDC technical condition. Fuzzy logic is the most suitable mathematical tool for diagnostic model construction.

Table 1. BLDC faults

Electrical faults
conductor break in the winding; short circuit between the winding turns; unacceptable reduction of the insulation resistance due to insulation ageing or excessive moisture; poor contacts and connections
Mechanical faults
degradation processes in the bearings; destruction of bearing cage, balls and rollers; poor heat transfer due to foul or dusty coils; rotor shaft deformation

Table 2. BLDC diagnostic parameters

Diagnostic parameter	Cause of diagnostic parameter change
Current	overload; winding break or short circuit; mains voltage change
Vibration	shaft misalignment; bearing faults
Temperature	overload; winding short circuit; ambient temperature change

2.3 Logical-linguistic diagnostic model of BLDC

Logical-linguistic diagnostic model of BLDC based on fuzzy logic may be represented by the following system of equations

$$
\begin{aligned}
x(t) &= F(x1(t), x2(t), x3(t)) \,, \\
D(t) &= G(x(t), t) \,, \\
Z(t) &= H(x(t), D(t), t) \,,
\end{aligned}
\tag{1}
$$

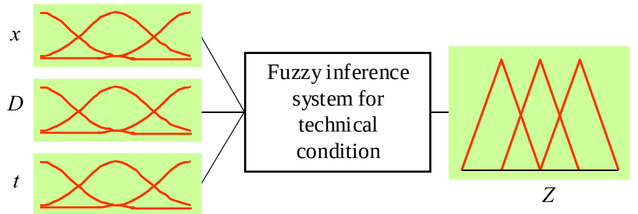

Fig. 4. Diagram of a fuzzy inference system for technical condition assessment with three input variables: x, D and t

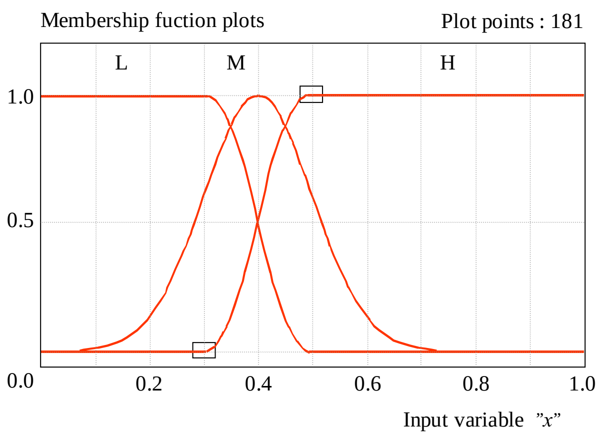

Fig. 5. Examples of membership functions of L, M and H terms of input and output variables

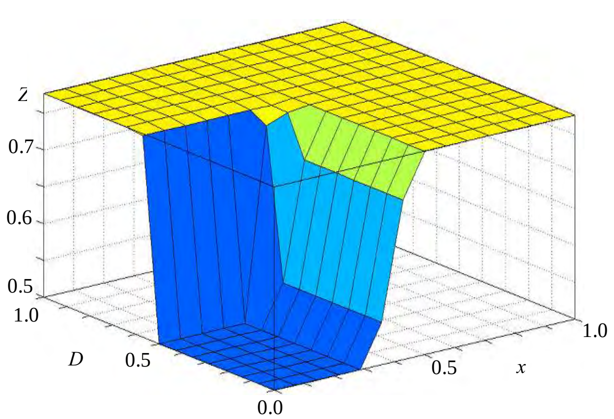

Fig. 6. Response surface of a fuzzy inference system used for technical condition assessment

where $x(t) = F(x1(t), x2(t), x3(t))$ is the equation of diagnostic parameters, $x(t)$ – the vector of diagnostic parameters, $x1(t), x2(t), x3(t)$ – a set of diagnostic parameter measurements, $D(t) = G\big(x(t), t\big)$ – the equation to calculate the trend vector of diagnostic parameters, t – utilized lifetime, $Z(t) = H\big(x(t), D(t), t\big)$ – the equation to evaluate the technical condition.

Logical-linguistic diagnostic model of BLDC is implemented using Fuzzy Logic Toolbox in MatLab. Fuzzy inference system for technical condition assessment is based on Mamdani type fuzzy knowledge database with three input variables x, D and t. Diagram of the fuzzy inference system is shown in Fig. 4.

Gaussian function has been chosen as a membership function of the M term of linguistic variable, as it is rather simple, differentiable and is defined by just 2 parameters which reduces the computational cost of the algorithm. z and s functions have been chosen as membership functions of L and H terms of linguistic variable.

Mamdani fuzzy inference has been chosen with maximum as a t-norm. Defuzzyfication was carried out using center of gravity method which ensures high accuracy and rapid adjustment of fuzzy knowledge base, [8]. Weighted rules and coordinates, corresponding to maxima of membership functions of the M term of linguistic variable, have been used as adjustable parameters.

Examples of membership functions of L, M and H terms of input and output variables are shown in Fig. 5.

Using three linguistic variables having three terms and combining AND and OR logical operations, we obtained 7 rules reflecting relationships between technical condition and the values of diagnostic parameters, their trends and utilized lifetime, as shown below

If (x is L) and (d is L) and (t is L) then (z is L)
If (x is M) and (d is L) and (t is L) then (z is M)
If (x is L) and (d is M) and (t is L) then (z is M)
If (x is L) and (d is L) and (t is M) then ($z$is M)
If (x is H) then (z is H)
If (d is H) then (z is H)
If (t is H) then (z is H)

Response surface of the fuzzy inference system used for evaluation of BLDC technical condition is shown in Fig. 6. The drawing shows change of BLDC technical condition (output variable z) depending on the input variables x and D.

As can be seen from Fig. 6, BLDC is in serviceable condition at low values of x integral diagnostic parameter and minor trend of diagnostic parameter.

Figures 7 and 8 are visualization examples of the rule base of fuzzy inference system used for assessment of BLDC technical condition.

2.4 Simulation model of BLDC diagnostic system

The model of diagnostic system (Fig. 9) is based on the mathematical apparatus of fuzzy logic. The model allows to determine the BLDC condition from diagnostic parameters (current, vibration and temperature). The simulation model of BLDC diagnostics system has been designed in MITD software.

Figure 9 shows the simulation model of the diagnostic system used for assessment of BLDC condition.

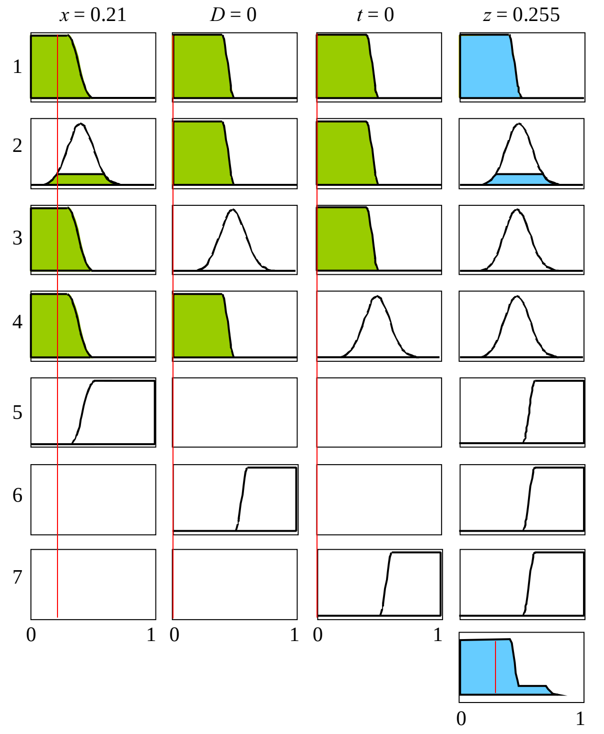

Fig. 7. Visualization of the rule base of fuzzy inference system used for assessment of BLDC technical condition ($x = 0.21$, $D = 0$, $t = 0$, $Z = 0.255$) — BLDC is in good technical condition

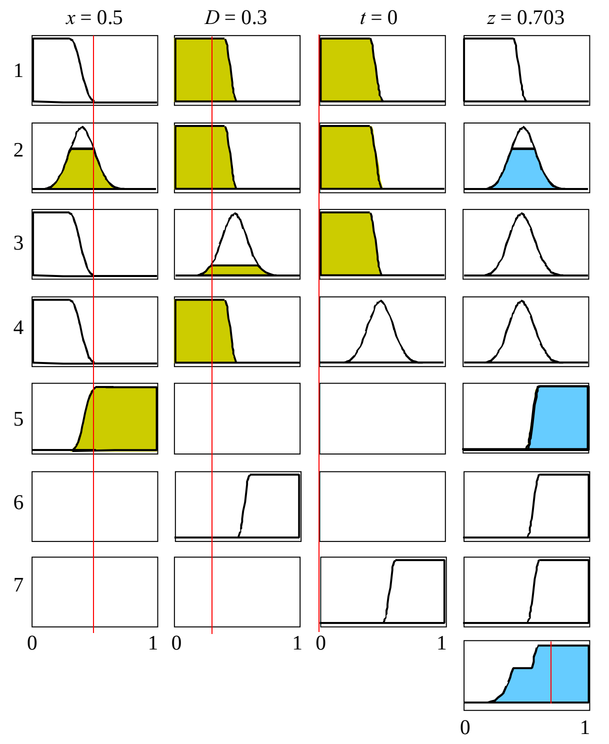

Fig. 8. Visualization of the rule base of fuzzy inference system used for assessment of BLDC technical condition ($x = 0.5$, $D = 0.3$, $t = 0$, $Z = 0.703$ — BLDC is faulty

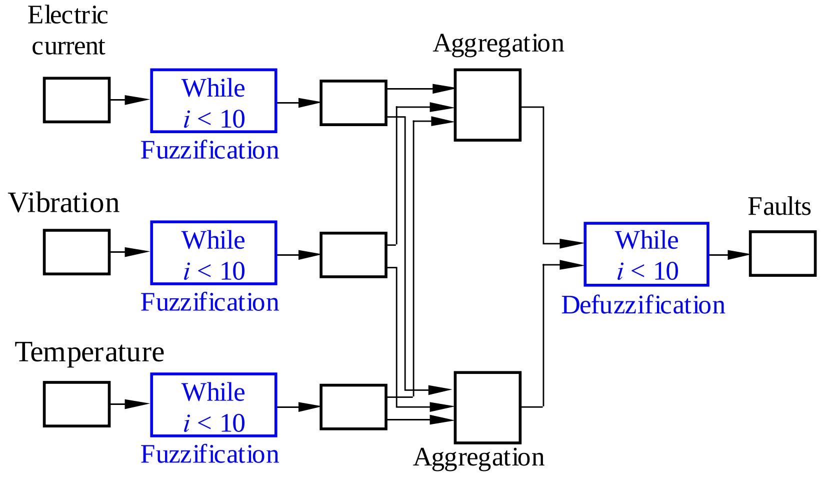

Fig. 9. Simulation model of BLDC diagnostic system

3 EXPERIMENTAL

Figure 10 shows simulation results of the temporal changes (in relative units) of input signals (current, vibration and temperature) caused by BLDC fault. Behavior of the output variable, characterizing the degree of BLDC defect growth, is shown in Fig. 11.

4 DISCUSSION

The resulting curve implies that on the interval 0 … 20 s BLDC is in operational condition. Development of BLDC degradation processes occurs on the interval 30 … 80 s. On the interval 90 … 100 s BLDC is in alarm condition. Dynamics of degradation processes can be judged by the nature of the curve: change of the motor condition from operational to alarm does not happen immediately; it takes place with the increase of diagnostic parameters.

In this way, by analyzing BLDC diagnostic parameters, trend and operating time we can foresee the emergency situation, minimize accident risk and timely schedule the BLDC maintenance and repair works. Experiments were carried out with diagnostic parameters being within and beyond the tolerable limits. The both exper-

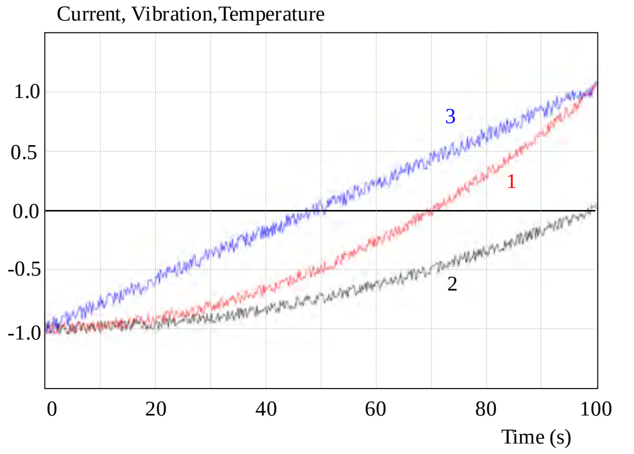

Fig. 10. Simulation results of the temporal changes of input signals (current, vibration and temperature) caused by BLDC fault (in relative units)

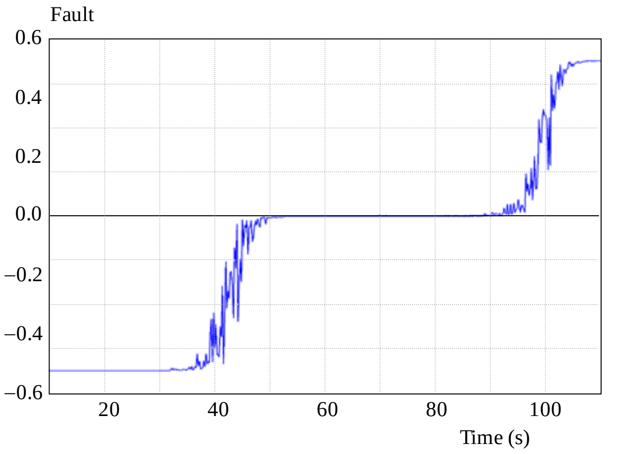

Fig. 11. Condition of BLDC in the course of degradation depending on diagnostic parameters

iments were performed at the same supply voltage and load torque. The simulation model of BLDC control and diagnostic system may be used to study the influence of diagnostic parameters on BLDC performance.

5 CONCLUSIONS

It follows from the paper that a simulation model of diagnostic system built using MITD software developed in Bauman Moscow State Technical University can be efficiently used for BLDC diagnostics. The model is based on mathematical apparatus of fuzzy logic. It allows to determine the BLDC motor condition from diagnostic parameters (current, vibration and temperature).

As a result of BLDC simulation, relationships of phase currents have been obtained which provide basis for selecting diagnostic parameters used in BLDC physical models.

The diagnostic parameters were analyzed by means of original software used for implementation of fuzzy inference system in MatLab. Distinctive feature of the system is the use of integral diagnostic parameter which combines information of diagnostic parameters and their derivatives.

The BLDC model is adjusted by entering parameters of certain BLDC.

Trend of the integral parameter allows to calculate the expected time point when the limit technical condition will be reached and to minimize the risk of premature failure through accident-preventive measures like scheduling of routine maintenance and repair. In case of development of BLDC degradation processes during the mechatronic system operation one can change the control action on the BLDC motor by reduction in current and so switch over to derated operation mode.

The simulation experiments confirmed the efficiency of the proposed diagnostic model and the prospects of its application to diagnostics of mechatronic systems with BLDC.

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References

[1] WAEL, A. S.—DAHAMAN, I.—KHALEEL, J. H.: PWM Switching Strategy for Torque Ripple Minimization in BLDC Motor, Journal of Electrical Engineering **62** No. 3 (2011), 141–146.

[2] MOHAMED, A. A.—EHAB, H. E. B.—HISHAM, M. S.: Adaptive Deadbeat Controllers for Brushless DC Drives using PSO and ANFIS Techniques, Journal of Electrical Engineering **60** No. 1 (2009), 3–11.

[3] DRAŠNAR, P.—KUDLÁČEK, J.—PEPELNJAK, T.—CAR, Z.—PAZDEROVÁ, M.: Zinc-Polytetrafluoroethylene Composite Coating with Exploitable Tribological Properties, Journal of Engineering Technology **30,** No. 1 (2013), 28-34.

[4] RAJAGOPALAN, S.—HABETLER, T. G.—HARLEY, R. G.—ALLER, J. M.—RESTREPO, J. A.: Diagnosis of Rotor Faults in Brushless DC (BLDC) Motors Operating under Non-Stationary Conditions using Windowed Fourier Ridges, Industry Applications Conference, vol. 1, Fourtieth IAS Annual Meeting. Conference Record, 2-6 Oct. 2005, pp. 26–33.

[5] RAJAGOPALAN, S.—RESTREPO, J. A.—ALLER, J. M.—HABETLER, T. G.—HARLEY, R. G.: Selecting Time-Frequency Representations for Detecting Rotor Faults in BLDC Motors Operating under Rapidly Varying Operating Conditions, IECON 2005 31st Annual Conference of IEEE, Industrial Electronics Society.

[6] RAJAGOPALAN, S.: Detection of Rotor and Load Faults in Brushless DC Motors Operating under Stationary and Nonstationary Conditions, Georgia Institute of Technology, https://smartech.gatech.edu/handle/1853/11524?show=full.

[7] BAE, H.—KIM, S.—VACHTSEVANOS, G.: Fault Detection and Diagnosis of Winding Short in BLDC Motors based on Fuzzy Similarity, International Journal of Fuzzy Logic and Intelligent Systems **9** No. 2 (June 2009), 99–104.

[8] BAEK, G.—KIM, Y.—KIM, S.: Fault Diagnosis of Identical Brushless DC Motors under Patterns of State Change, Fuzzy

Systems, 2008. FUZZ-IEEE 2008 (IEEE World Congress on Computational Intelligence), pp. 2083–2088.

[9] NIKITIN, Yu.: Development of Intellectual Mechanotronic Modules with Diagnostic Functions, Mechatronika 2009, Proceedings of 12th International Conference on Mechatronics, Trenčianske Teplice, Slovak Republic, 3–5.6.2009, pp. 133–137.

[10] NIKITIN, Yu.—ABRAMOV, I.: Algorithms for Mechatronic Systems Diagnosing, AIM 2010, Proceeding of 5th International Symposium. Advances in Mechatronics, Dec 7–9 2010, pp. 60–62.

[11] NIKITIN, Yu.—ABRAMOV, I.: Mechatronic Modules Diagnosis by Use of Fuzzy Sets, Mechatronika 2011, Proceedings of 14th International Conference on Mechatronics, Trenčianske Teplice, Slovakia, 2011, pp. 109–111.

[12] NIKITIN, Yu.R.—ABRAMOV, I. V.: CNC Machines Diagnostics, Mechatronika 2010, Proceedings of 13th International Symposium on Mechatronics, June 2-4, 2010, pp. 89–91.

[13] NIKITIN, Yu.R.—ABRAMOV, I. V.: Information Processes Models of Mechatronic Systems Diagnosis, University Review, vol. 5, 2011, pp. 12–16, http://www.tnuni.sk/fileadmin/dokumenty/univerzita/casopisy/university_review/UR_2011_01.pdf.

[14] Site of software package "Simulation in technical devices" http://mvtu.power.bmstu.ru/.

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