Multiparameters Fault Diagnosis of Driven System with a Noise

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Abstract — **The paper presents the application of diagnostics of mechatronics systems with a noise. Three-step DC-engine is the model of the investigation. Fuzzy logic methods are using for building the decision block without a noise. The noise is medley of two source: first source is a white noise; second source is medley of a white noise and noise of the real engine. The wavelet transform is using for de-noising of medley signal-noise.**

I. INTRODUCTION

KNOWN methods of parameters diagnostics of different systems, including mechatronics systems, ensure satisfactory diagnostics results only when results of systems analysis conducted on PC are used as measured signals. We consider fuzzy logic for fault diagnosis in the systems without noise (Chapteer VI, CaseA).On practice measured signals have restricted dynamic range and noise. Methods of diagnostics systems using signals with a noise frequently do not give reliable results. In the paper a diagnostic method of mechatronics system is proposed when measured signals are additive composition of actual signal and a noise (Case B). Signal is detected from composition of actual signal and noise using wavelet transform. When it is done diagnostics of mechatronics system is performed in the same way using Fuzzy logic method as in the case of system without a noise (Case C).

II. TECHNIQUE FOR DIAGNOSTIC SYSTEM CONSTRUCTION

To create diagnostics system a technique presented in [1] can be used. A structural scheme for system diagnostics is described in [1].

The first stage of system diagnostics is to obtain measured data from object.

The second block presents wavelet transform that is used for filtering of noisy data. Wavelet transform is one of new methods used for noise elimination. Its variable time-and-frequency window allows to analyze effectively non-stationary signals.

The third block presents the process of detection of informative components of the signal. After this a decision about possible parameters alteration can be done.

Output signal Y of presented system of diagnostics is a set of parameters of investigated object defined as function of two signals:

$$Y = f(s_n, s_a + \xi) \tag{1}$$

where s_n is a signal obtained during simulation of nominal system, s_a is signal of actual system (parameters.of actual system were changed), ξ is additive noise. Difference between s_n and $s_a+\xi$ is a basis for research

The fourth block presents a diagnostics algorithm used oriented toward to make decision as to possible parameters variation. To construct the forth block a fuzzy logic method is used

III. MODEL OF MECHATRONICS SYSTEM

Electric DC motor with power 2 kW and three-stage starter [1] was used as test example. An equivalent circuit of the motor is shown in fig.1. Electric motor consists of two main parts: stator and rotor.

The model of rotor consists of series connection of the voltage source (constant electromotive force E), three-stage starter block, resistor R_a and inductance L_a. Into the electric circuit of rotor a converter of electric energy into mechanical energy (CEMF-counter electromotive force) is connected.

Electric circuit of stator consists of voltage source (constant electromotive force E_f), inductance L_f and resistor R_f. connected in series.

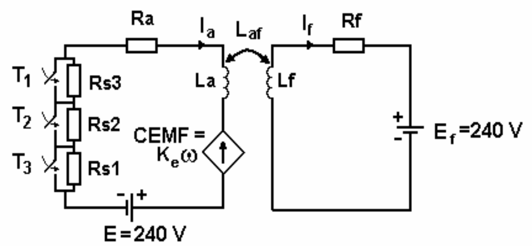

Fig. 1. Equivalent circuit of motor electric part.

Angular velocity ω of rotor is controlled by rotor current I_a. Mechanical part of motor is presented by moment of intertia J, bearing friction coefficient F_r, load torque T_L, and coulomb friction torque T_f.. To make soft start of motor switchers $T1$, $T2$, $T3$ are implemented. Feedback of electric motor with factor B_l is taken into consideration.

Electric part of motor is defined by equation (2), where $\alpha_i(t)$ is Heaviside function (equal to 1 when $t \geq T_i$ and 0 otherwise).

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$$E = I_a(t)(\alpha_1(t)R_{s1} + \alpha_2(t)R_{s2} + \alpha_3(t)R_{s3}) + + I_a(t)R_a + L_a\frac{dI_a(t)}{dt} + K_e\omega + L_{af}\frac{dI_f(t)}{dt} \quad (2)$$

$$E_f = I_f(t)R_f + L_f\frac{dI_f(t)}{dt} + L_{af}\frac{dI_a(t)}{dt}$$

Mechanic part of the motor is defined by the following equation

$$J\frac{d\omega(t)}{dt} + F_r\omega + T_f + B_l\omega = L_{af}I_a(t)I_f(t) \quad (3)$$

All calculations were conducted in MATLAB6 environment using Simulink package.

Instantaneous values of current in rotor winding I_a and number of rotor revolution per minute ω are measured signals.

During the diagnostics procedure an actual signal should be compared with nominal signal which is etalon. Model has 16 parameters, just 6 of them are variable, and others have fixed values. Obtained parameters have the following nominal values: T_1=2.8 s, T_2=4.8 s, T_3=6.8 s, F_r=0 N·m·s, J=1.5 kg·m^2, B_l=0.22. Parameters with fixed values are as follows: $R_{s1}=R_{s2}=R_{s3}$= 0.01 Ω, R_a=6 Ω, L_a=120 mH, R_f=240 Ω, L_f=130 H, L_{af}=1.5 H, initial cyclic frequency ω_0=0 rad/s, i T_f=0 N·m.

Eight specific pieces of information from motor’s response were extracted (block II): switching instances T_1, T_2, T_3, the corresponding maximum currents I_{a1}, I_{a2}, I_{a3}, current value in steady-state I_{ast}, and steady-state radial speed ω_{st}. Differences between nominal and actual values: ΔT_1, ΔT_2, ΔT_3, ΔI_1, ΔI_2, ΔI_3, ΔI_{st}, $\Delta\omega_{st}$, are called the stamps. The meaning of the stamps is explained in [2].

IV. Diagnostic system based on fuzzy logic

When diagnostic system for mechatronics device is developed it is necessary to choose its creation strategy. Widely spread and known techniques (PCA and etc.) have some drawbacks because they do not take into account human experience as to changes of parameters. Diagnostics techniques developed on the basis of fuzzy logic theory are free from mentioned disadvantages[3].

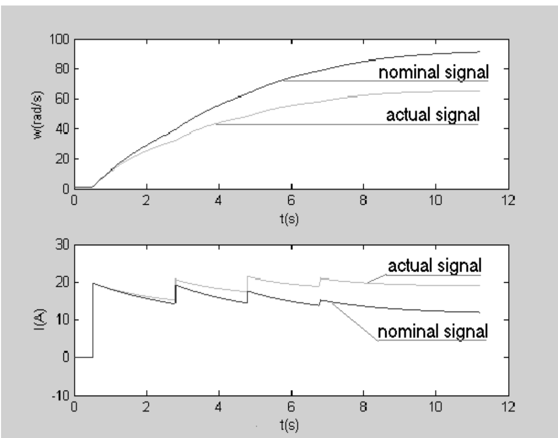

Fig.2. Nominal and actual signals when J_a>J_n

Methods of fuzzy logic are used to investigate parameters of electric motor, namely: switching moments of starter (*T1,T2,T3*), moment of intertia *J*, bearing friction coefficient F_r, and Bl. Some down you can see a few samples of change parameters of the our model.

Fig.3. Nominal and actual signals when Fr_a>Fr_n

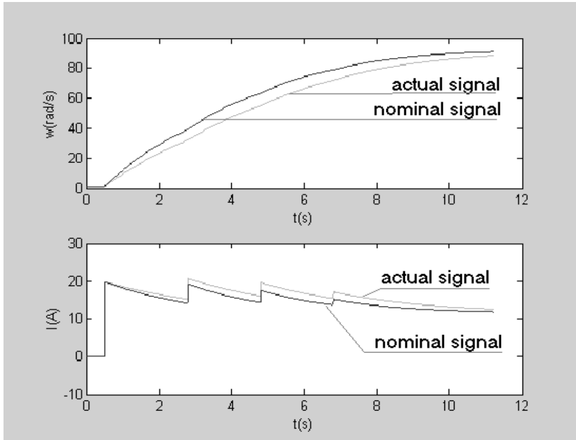

Fig.4. Nominal and actual signals when Bl_a>Bl_n

It is possible to transform mentioned parameters into fuzzy set using trapezoidal membership function.

Fuzzy knowledge base about influence of factors $X = \{x_1, x_2, ..., x_n\}$ on parameter values y is a set of logic expressions which can be written down in the form of equation (4) using operations $\bigcup$ and $\bigcap$:

$$\bigcup_{p=1}^{k_j}\left[\bigcap_{i=1}^{n}\left(x_i = a_i^{jp}\right)\right] \rightarrow y = d_j,\, j = \overline{1,m} \quad (4)$$

where a_i^{jp} is fuzzy term with the help of which a variation of x_j in the row with number j_p ($p = \overline{1,k_j}$) can be estimated; k_j is quantity of rows- conjunction where output y is described by fuzzy term d_j, $j = \overline{1,m}$; m is a quantity of terms used for linguistic evaluation of output parameter y.

There are 32 statements in the base of rules. It is enough to reveal single and double variation of switching moments of starter stages and single variation moment of inertia J, bearing friction coefficient F_r and Bl. Here there are several rules:

If I_{a1} is Neg2I1 and I_{a2} is NegI2 and I_{a3} is Neg1I3 and W_{st} is P1W and I_{ast} is ZI then J is Neg2J – the rule describes situation when moment inertia actual signal is smaller when moment inertia of nominal signal;

If I_{a1} is ZI1 and I_{a2} is P1I2 and I_{a3} is P1I3 and W_{st} is N1W and I_{ast} is P1I then Fr is Frsmall – the rule describes situation when Fr $_a$ > Fr $_n$;

If I_{a1} is ZI1 and I_{a2} is P1I2 and I_{a3} is P2I3 and W_{st} is N2W and I_{ast} is P2I then Bl is Bllarge – the rule describes situation when Bl $_a$ > Bl $_n$.

A fuzzy set $\tilde{y}$ that corresponds to input vector x^*, is defined in the following way:

$$\tilde{y} = \bigcup_{j=1,m} \int_{\underline{y}}^{\bar{y}} \min\left(\mu^{d_j}\left(X^*\right), \mu^{d_j}\left(y\right)\right) / y , \qquad (5)$$

where $\bigcup$ is operation of fuzzy sets conjuction. Clear value of output y which corresponds to input vector X^* is defined as a result of defuzzification of fuzzy $\tilde{y}$.

Defuzzification is conducted using method of weight center described using formula

$$c\ a = \int_{\underline{u}}^{\bar{u}} u\mu_A(u)du \Big/ \int_{\underline{u}}^{\bar{u}} \mu_A(u)du \cdot \qquad (6)$$

V. Features of wavelet usage for signal filtering

When signals are non-stationary and contain a noise, wavelet functions are the most appropriate approach to solve the given problem.

Any function f from $L^2(R)$ can be presented with given detailing level j_0 in the following form

$$f(t) = \sum_{l=1}^{L_0} \lambda_{j0,l}\varphi_{j0,l}(t) + \sum_{j=j_0}^{n}\sum_{l=1}^{L_i} \gamma_{j,l}\psi_{j,l}(t) \qquad (7)$$

Wavelet coefficients $\lambda_{j,l}$ and $\gamma_{j,l}$ can be calculated using formulas

$$\lambda_{j,l}(t) = \int f(t)\varphi_{j,l}(t)dt \ , \qquad (8)$$

$$\gamma_{j,l}(t) = \int f(t)\psi_{j,k}(t)dt \qquad (9)$$

Detailing coefficients γ which are spectral coefficients of function *f(t)* have high-frequency nature and locate oscillations and singularities of function both in time and frequency domain.

Among existing paradigms of noise detection from signal-noise composition the most spread is Donoho-Johnstone paradigm [4].

Degree of noise elimination, and respectively value of signal/noise ratio depends on type of threshold function and ways of its application.

A global thresholding is the most general form of existing approaches of threshold processing. The essense of the given approach lies in series application of threshold function $T(\gamma_j)$ to levels $j_0, j_0+1, \dots n$ of signal decomposition, and taking decisions about saving of coefficients from considered level.

When investigated signal $f(t)$ is presented in the form of expansion (7) it is easy to show that global thresholding can be written down in the following form:

$$\hat{f}(t) = \sum_{l=1}^{L_0} \lambda_{j0,l}\varphi_{j0,l}(t) + \sum_{j=j_0}^{n} T_j\left(\sum_{l=1}^{L_i} \gamma_{j,l}\psi_{j,l}(t)\right) \qquad (10)$$

Unlikely to global threshold processing, local thresholding implements function $T(\gamma)$ to each signal detailing coefficient from $\left\{\gamma_{j,l} \ \middle|\ j = \overline{j_0,n}, l = \overline{1,L_j}\right\}$.

General expression that characterizes local thresholding can be written as follow:

$$\hat{f}(t) = \sum_{l=1}^{L_0} \lambda_{j0,l}\varphi_{j0,l}(t) + \sum_{j=j_0}^{n}\sum_{l=1}^{L_j} T_{j,l}(\gamma_{j,l})\psi_{j,l}(t) \qquad (11)$$

VI. Experimental results

Case A: Diagnostics without noise.

Diagnostics results of mechatronics systems without noise are presented in tab.1. As it can be seen from the table, the system estimates correctly the character of changes (increase or decrease) and what parameter has been changed. The diagnostics is not adequate when parameter changes slightly (shown with bold).

As show experimental research a parameters Fr and Bl belong to ambiguity group. In the result we have trouble with unique solution.

Case B: Diagnostics fuzzy logic with noise.

Both high-frequency and low-frequency noises caused by mechanical parts of the system are present in mechatronics systems. Therefore two sources were used to model noisy signals of the system. The first source of noise simulates just high-frequency oscillations, and the second contains both high-frequency and low-frequency components of noise which were taken experimentally on real motor.

Signal/noise ration can be calculated on the basis of the following formula:

$$S/n = \left(\max(I_a)\right)^2 / (\sigma_1^2 + \sigma_2^2) \qquad (12)$$

where I_a is current in electric circuit of rotor, σ_1^2 and σ_2^2 are dispersions of the first and second noise sources.

In order to compare obtained results a research of system of diagnostics was done when noise level rises gradually without wavelet transform.

Obtained results are presented in table 2. Conducted researches have shown that domain where diagnostics system works correctly exists only for signal-noise ratio >=165 when just fuzzy logic is used for diagnostics. Noise level rising causes a false maximums appearing and respectively results of parameters estimation are wrong. The next stage in research is to use wavelet transform for filtering of signal/noise composition.

Case C: Diagnostics fuzzy logic and wavelet transform with noise.

Researches were conducted with several wavelet families, namely: Daubechies family wavelets, symlets, coiflets, biorthogonal wavelets. Usage of biorthogonal wavelet bior6.8 with decomposition level *j=3* allows to expand domain of correct diagnostics to signal/noise ratio >=25.Increasing of decomposition level from *j*=3 to *j*=4 makes it possible to improve situation and expand border of adequate diagnostics to signal/noise ratio >= 5.

Investigations have shown a necessity to increase decomposition level *j* when noise level rises and what influence have a correct choice of decomposition level. It should be noted that when noise level is low usage of deep decomposition level causes considerable signal smoothing and diagnostics system can't continue to work. Because of this fact it is necessary to implement some level of decomposition of wavelet transform accordingly to noise level. Increasing of decomposition level when wavelet transform bior6.8 is used doesn't increase a domain of correct work of diagnostics system when noise level continue to rise. Therefore it is necessary to use another "mother" wavelet simultaneously increasing of decomposition level j. When biorthogonal wavelet bior2.8 with j=5 is used in domain of high level noises a correct diagnostics is possible up to signal/noise ratio >= 3 (table.3).

TABLE 1. RESULTS OF DIAGNOSTICS OF THE FUZZY LOGIC SYSTEM

T1,c	T2,c	T3,c	J, kg·m^2	Fr, N·m·s	Bl	DT1,c	DT2,c	DT3,c	DJ, kg·m^2	dFr, N·m·s	dBl
-0.8	-0.4	0	1,5	0,0	0,22	-0.70	-0.153	0	1,5	0	0,22
0	0.6	0.6	1,5	0,0	0,22	0	0.183	0.319	1,5	0	0,22
0,0	0,0	0.0	1.0	0,0	0,22	0,00	0,00	0,00	1,15	0,25	0,21
0,0	0,0	0.0	1,25	0,0	0,22	0,00	0,00	0,00	1,40	0,04	0,21
0,0	0,0	0.0	2,0	0,0	0,22	0,00	0,00	0,00	**1,77**	0,04	0,20
0,0	0,0	0.0	1,5	0,2	0,22	0,00	0,00	0,00	1,50	0,09	0,26
0,0	0,0	0.0	1,5	0,3	0,22	0,00	0,00	0,00	1,50	0,19	**0,31**
0,0	0,0	0.0	1,5	0,0	0,25	**-0,17**	0,00	0,00	**1,56**	0,06	0,23
0,0	0,0	0.0	1,5	0,0	0,40	0,00	0,00	0,00	1,50	0,09	0,26
0,0	0,0	0.0	1,5	0,0	0,50	0,00	0,00	0,00	1,50	**0,20**	0,32

TABLE 2. RESULTS OF DIAGNOSTICS OF THE SYSTEM WITH NOISE WITHOUT WAVELET TRANSFORM

(RESULTS DIAGNOSTICS SWITCHING MOMENTS OF STARTER DESCRIBED IN [1])

J, kg·m^2	Fr, N·m·s	Bl	DJ, kg·m^2	DFr, N·m·s	dBl	σ_1^2,A	σ_2^2, A	S/N
1.1	0	0.22	1.3	0.03	0.21	0.001	0.008	200
1.5	0.3	0.22	1.5	0.2	0.26	0.005	0.008	180
1.5	0	0.4	1.5	0.09	0.31	0.007	0.008	165

TABLE 3. RESULTS OF DIAGNOSTICS OF THE SYSTEM WITH NOISE WITH WAVELET TRANSFORM

(RESULTS DIAGNOSTICS SWITCHING MOMENTS OF STARTER DESCRIBED IN [1])

J, kg·m^2	Fr, N·m·s		DJ, Kg·m^2	dFr, N·m·s	DBl	σ_1^2,A	σ_2^2,A	wavelet	j	S/N
1.1	0	0.21	1.31	0.04	0.21	0.02	0.21	Bior6.8	3	41
1.5	0	0.35	1.55	0.08	0.26	0.02	0.21	Bior6.8	3	41
0	0.25	0	1.5	0.18	0.31	0.18	0.45	Bior6.8	3	26
2.0	0	0	1.84	0.05	0.21	0.5	0.57	Bior6.8	4	19
1.5	0.35	0	1.5	0.2	0.3	1.0	1.21	Bior6.8	4	14
1.8	0	0.21	1.75	0.04	0.21	2.94	5.17	Bior6.8	4	7
1.5	0.4	0.21	1.5	0.21	0.29	4.6	10	Bior6.8	4	6
1.1	0	0.21	1.43	0.04	0.21	6.6	12.0	Bior2.8	5	5
1.5	0	0.4	1.54	0.08	0.26	7.0	29.0	Bior2.8	5	4
1.8	0	0.22	1.8	0.09	0.26	11.0	30.0	Bior2.8	5	3.5
1.5	0.3	0.22	1.5	0.21	**0.3**	16.0	35.0	Bior2.8	5	3

VII. CONCLUSIONS

Diagnostics of mechatronics system with a noise even when fuzzy logic is used makes it possible to obtain adequate results for signal/noise ratio >= 165. In real mechatronics system signal/noise ratio is much smaller. Wavelet implementation allows to conduct diagnostics of parameters changes in mechatronics system even for signal/noise ratio >= 3.

VIII. REFERENCES

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