Cyber-physical System for Diagnosing and Predicting Technical Condition of Servo-drives of Mechatronic Sliding Complex during Construction of High-rise Monolithic Buildings

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Abstract –

The article is devoted to the problem of improving the reliability and efficiency of the operation of mechatronic sliding complexes. To solve this problem, a cyber-physical system is proposed that implements the diagnosis and prediction of the technical condition of servo drives. Methods for calculating the current and additional loads on servo drives are proposed. Recommendations are given on changing the lifting mode of the sliding formwork de-pending on the technical condition of the servos.

Keywords –

slip form; servo drive; approximate envelope straight line; Morlet wavelet; fuzzy logic; neural network

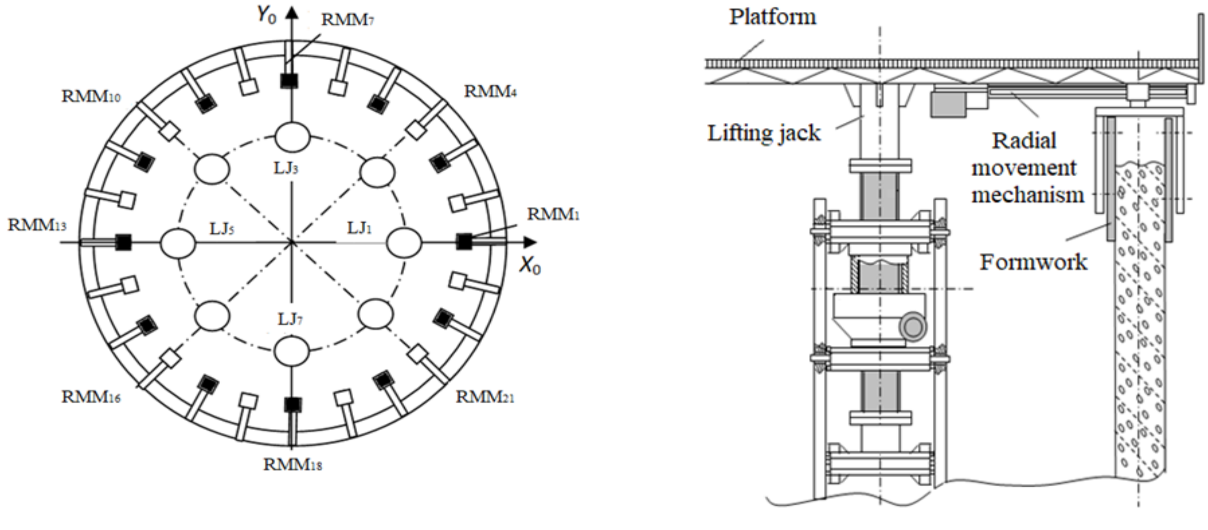
1 Introduction

Construction is one of the main actively developing sectors of the national economy of any country. Every year the number of high-rise buildings is growing steadily. Constantly changing requirements for the quality and speed of construction of the building. It leads to the emergence of new construction technologies using robotic and mechatronic systems, allowing high-precision performance and good quality of construction. To solve this problem, it is necessary to ensure the reliable functioning of all the machines and mechanisms of the complex that operate in tight relationship with each other. Analysis of the construction of high-rise buildings technology showed that the main actuating elements of the buildings mechatronic complex are DC or AC servo motors. Their proper work determines the buildings and structures quality. Failure or malfunction of one of the drives can lead to disruption of the entire complex, damage to building materials and to the construction of inadequate quality. Therefore, the urgent task is to ensure the reliable functioning of all the servos included in the mechatronic complex. This problem can be solved by cyber-physical system synthesis that implements monitoring of each servo motors technical condition and optimizing the technological process at the construction site, taking into account the current and predicted state of building robotic and mechatronic complex servo motors.

2 Mechatronic sliding formwork complex structure

The most common method of high-rise buildings and structures is monolithic construction [1]. Technology this method provides a continuous supply and laying of concrete, installation of rebar, formwork hoist, regulation of project sizes and control settings of the building [2]. The modern method of automation of monolithic construction is the use of mechatronic sliding formwork complex (Fig.1), which is a spatial form installed on the perimeter of the structures and moved up by lifting jacks (LJ) [3].

The position of the formwork panels is fixed by Jack frames that accept the loads of the laid concrete. Lifting of the formwork is carried out by Electromechanical lifting jacks based on DC or AC servo motors. Jacks should provide high load capacity, synchronous movement of the formwork, lifting speed regulation and ease of maintenance [4]. It also includes adjustment mechanisms, dynamic properties, design and technological features that determine the structure of control algorithms and the choice of control laws. For example, for structures of conical and hyperbolic shape, these are radial movement mechanisms (RMM), which are located along the radius with a uniform step (Fig.1,a). Their task is to move the formwork panels in the process of lifting it. Changing the position of the boards should be synchronized with the LJ. To do this, the number of RMM mechanisms (m) is chosen as a multiple of the number of LJ (n). This will allow the platform radial beams to be distributed evenly with angular pitch $2\pi/m$ and used for the RMM installation. Important conditions for the quality of construction work are the continuity of the technological process and maintaining a constant movement speed of the formwork not less than 1 cm/min, as well as the need to strictly horizontal platform. To implement these requirements, it is necessary to ensure consistent operation of all servo motors included in the complex. This problem can be solved by using methods and tools for predictive diagnosis of LJ and RMM servo motor with its operation mode subsequent optimization. For this purpose, it is necessary to provide the technical condition control of all servo motors which are a part of the MSFC, information exchange between drives and decision-making for MSFC operation mode changing.



a) b)

Figure 1. Mechatronic sliding formwork complex (MSFC): a) longitudinal and vertical section of the MSFC; b) the distribution of lifting jacks (LJ) and radial movement mechanisms (RMM) in the plane of the complex platform.

The implementation of this approach involves the integration of computational resources into physical processes using a cyber-physical system. In such a system, sensors, equipment and information systems interact throughout the life cycle of the MFSC and information exchange is carried out using standard Internet protocols. This allows performing self-tuning and MSFC adaptation to changing operating conditions and technical condition of the equipment. Therefore, the development the analysis methods and optimal synthesis of cyber-physical systems for technical condition diagnosis the of MSFC servo motors to improve the operation efficiency and their operational safety ensure is very important.

3 The cyber-physical system structure

The cyber-physical system should implement the collection of diagnostic information, its processing, storage and analysis to determine the current technical conditions, defects development forecasting and the servo failure time determination, MSFC operation mode optimization depending on the its servos technical condition. The cyber-physical system includes the cyber and physical parts (Fig. 2), and the main functions are transferred to the software part. The physical part of the system is represented by the "Hardware" block, which includes MSFC servo-drives functioning in a given technological process. The cyber part is represented by the “Data” and “Internal Software” blocks.

The “Data” block provides diagnostic information from the sensors of the facility, as well as storing the diagnostic results for previous periods of operation of the MSFC in a database used for the technical condition forecasting.

The “Internal software” block analyzes the current and predicted technical condition of all servo drives of the MSFC followed by a decision to change the mode of its operation. The “Internal software” block analyzes the current and predicted technical condition of all MSFC servo drives followed by a decision to change the mode of its operation. In this structure, the technical condition predictive diagnosis is implemented for each servo motor and decision-making is performed for the entire MSFC as a whole**.**

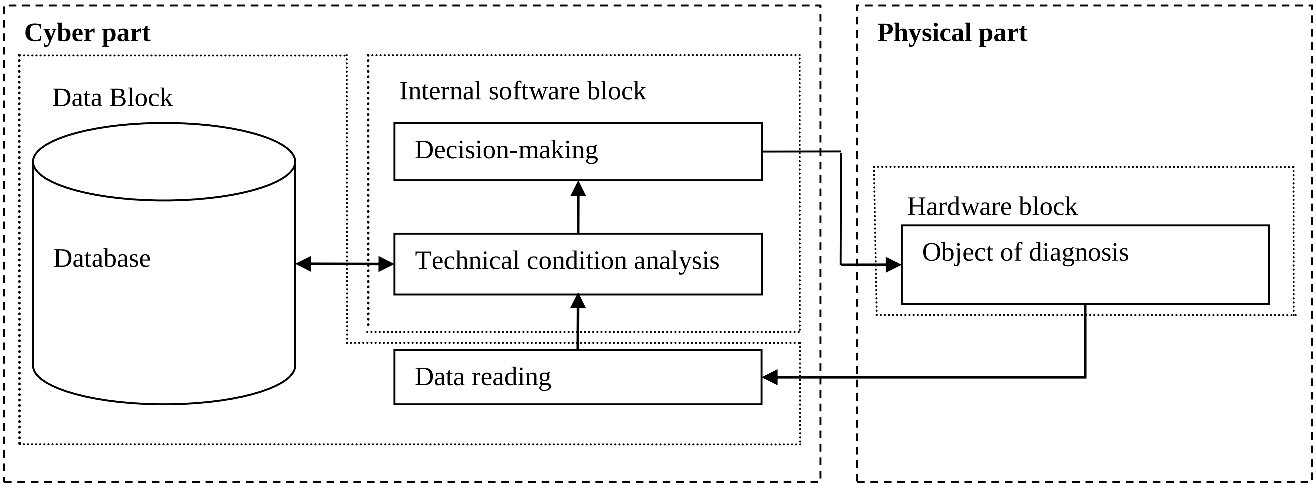


Figure 2. The structure of the information processing in cyber-physical system MSFC predictive diagnosis

Based on this, the architecture of the cyber-physical system has two levels. The main computing function of the system is performed by the lower level associated with the object of diagnosis. At the same time, a higher level of the system will receive information exclusively on the results of diagnostics and prediction of the status of servos and make a decision on reconfiguring the system and changing the operating mode of the mechatronic sliding complex

4 The lower level of the cyber-physical system

4.1 Servo motors diagnosis method

At the lower level of the cyber-physical system, the tasks of determining the current and predicted technical condition of each MSFC servo drive are solved.

For its implementation, it is necessary to develop methods that satisfy the following requirements:

- ability to assess the technical condition in real time;
- minimum composition of measured parameters;
- lack of complex bulky measuring equipment installed on the body of the servo drive, affecting the operation of the MSFC;
- ability to use on a moving object in conditions of high humidity and dustiness of the working environment;
- applicability for AC and DC servo motors;
- ability to automatically analyze the measured parameters in real time;
- ability to record and store diagnostic results on a cloud server and provide the user with an Internet protocol.

Analysis of existing methods and diagnostic tools showed that the only method that satisfies most of the above requirements is the analysis of current consumption. To synthesize a method for analyzing temporary servo signals using wavelet transform, a number of experimental studies have been carried out to diagnose servo motors at different loads. The measured time signals of the servo current were decomposed using a Morlet wavelet in a selected range of scales and a comparative analysis of the results was performed. The results of the analysis of the current signals of the servo drive at various rotational speeds and loading modes made it possible to establish a regularity between the type of wavelet-coefficient graph and the technical state of the servo motors [5]. The established graph types of wavelet coefficients can be classified into three groups: decaying, linear, increasing. Damped oscillations are characteristic of a healthy servo motor, linear - for a faulty unloaded motor, and increasing - for a faulty loaded motor.

To formalize the derived regularity, it is advisable to use the Hilbert transform, which allows for the function of the continuous wavelet transform $\psi_{ab}(t)$, calculated for each characteristic scale to calculate the analytically conjugate function $\hat{\psi}_{ab}(t)$, the mathematical form of which has the following form:

$$\hat{\psi}_{ab}(t) = \int_{-\infty}^{\infty} \frac{\psi_{ab}(\tau)}{t-\tau} d\tau = \Gamma[\psi_{\mathrm{ab}}(\mathrm{t})],$$

Based on these two functions, an analytical signal is generated.

$$s(t) = \psi_{ab}(t) + j \cdot \hat{\psi}_{ab}(t)$$

from which it is possible to find the instantaneous amplitude (envelope of the signal):

$$A(t) = |s(t)| = \sqrt{{\psi_{ab}}^2(t) + {\hat{\psi}_{ab}}^2(t)}$$

As a result, pairs of points $t(t_1, t_2, \ldots . t_n)$ and ψ_{ab} $(\psi_{ab1}, \psi_{ab2}, \ldots \ldots \psi_{abn})$ between which there is some dependence $\psi_{ab_i} = f(t_i)$ are obtained.

To search for the analytical dependence, the least squares method was used, according to which the arguments of the function $f(t, c_1, c_2, \ldots c_k)$ must be chosen so that the sum of the squares of the deviations of the measured values

$Y = f(t, c_1, c_2, \ldots c_k)$ minimal

$$S(c_1, c_2, \dots c_k) = \sum_{i=1}^{n} (Y_i - \psi_{ab_i})^2 \to min$$

For a formal description of the envelope obtained as a result of experimental researches, it is advisable to choose a polynomial of degree m, the generalized formula of which has the following form:

$$\psi_{ab}(t) = c_0 + c_1 t + c_2 t^2 + \dots + c_m \mathrm{t^m}$$

The goal of the envelope description being performed is the mathematical formalization of its shape, which allows us to unambiguously describe the process taking place on a given scale. Since the envelope graph has three characteristic features: it is downward, linear, or upward, the change in the amplitude of the wavelet coefficients in time can be unambiguously described using the linear law. Therefore, to formalize the shape of the envelope of the signals, it suffices to choose a polynomial of the first degree.

$$\psi_{ab}(t) = c_1 t + c_0$$

Thus, the problem of approximating the shape of the envelope of the wavelet coefficients can be reduced to obtaining a straight line equation of the type $y = kx + b$, (where $c_1 = k, c_0 = b$), the coefficients of which allow us to describe the main changes in the wavelet coefficients on the selected scale. An analysis of the coefficients *k* and *b* of the approximating straight envelope of the wavelet coefficients at characteristic scales showed that a working servo corresponds to a coefficient $k < 0$, and the approximating straight line descends to the abscissa axis, $k \geq 0$ is typical for a faulty state of the servomotor. Coefficient *b* is always positive, however, with an increase in load on a serviceable drive, coefficient *b* increases and *k* decreases.

For a faulty servo motor, an increase in load will lead to an increase in all the parameters of the approximation line. Thus, the sign of the coefficient *k* of the approximating direct envelope at the characteristic scales of the wavelet coefficients will determine the current state of the servo motor.

4.2 Current servo motor load determination

To determine the current load of the servo motor, it is necessary to calculate the coefficients of the approximating straight envelopes at characteristic scales for a known-good unloaded servo drive (k_0, b_0) and at maximum load (k_{max}, b_{max}).

The passport data of any servo contains the overload capacity of the servo current K_T, which is calculated by the following formula:

$$K_T = \frac{I_{max}}{I_{nom}}, \text{ then } I_{max} = K_T I_{nom}$$

where I_{max}, I_{nom} - maximum permissible and rated currents of the servo drive.

If the coefficients k_0, b_0 correspond to the rated current, then k_{max}, b_{max} will correspond to the maximum permissible current. Then

$$k_{max} = \frac{k_0 \cdot I_{max}}{I_{nom}} = \frac{k_0 \cdot I_{nom} \cdot K_T}{I_{nom}} = k_0 \cdot K_T;$$

$$b_{\text{м}ax} = \frac{b_0 \cdot I_{max}}{I_{nom}} = \frac{b_0 \cdot I_{nom} \cdot K_T}{I_{nom}} = b_0 \cdot K_T.$$

The coefficients of the approximation straight line *k* and *b* of a healthy servo motor are in the following range:

$$k_{max} \leq k \leq k_0 \qquad b_{max} \leq b \leq b_0$$

If the coefficients go beyond the specified limits, it is urgent to stop the operation of the servo drive.

Relative coefficients showing the load on the servo drive can be calculated from the following relationships:

$$\Delta k = \frac{k - k_0}{k_{max} - k_0}; \qquad \Delta b = \frac{b - b_0}{b_{max} - b_0}$$

If $k = k_0$ and $b = b_0$, then $\Delta k = 0, \Delta b = 0$, which indicates the absence of load on the drive. If $k = k_{max}$ and $b = b_{max}$, then $\Delta k = 1$, $\Delta b = 1$, which shows the maximum load on the servo drive. If $k \in [k_0, k_{max}]$, $b \in [b_0, b_{max}]$,, then $\Delta k \in [0,1], \Delta b \in [0, 1]$. If $\Delta k < 0$, then the servomotor is faulty and must be turned off. If $\Delta k > 1, \Delta b > 1$ then the load level is higher than the maximum permissible value and it is necessary to change the operating mode of the servo motor.

If both factors are within the specified limits, then you can determine the level of load on the servo motor.

A fuzzy logical model has been developed, the inputs of which are the relative coefficients Δk and Δb, and the output is the level of load on the servo as a percentage of the maximum permissible. To describe such a model, a *Sugeno*-type fuzzy logic inference system with two inputs and one output is used. For each input parameter on the interval [0; 1] the corresponding membership functions are set (Fig. 3). The output parameter *Load* is the corresponding coefficient on the interval [0; 100], showing the percentage of engine load. If this parameter is equal to zero, then the servo drive operates in the nominal mode without load. If it is 100%, then the engine has a maximum load and it is necessary to change its operation mode.

The relationship between the introduced sets is described by the following fuzzy rules:

R1: $If\ k\ is\ k_0\ and\ b\ is\ b_0,\ then\ Load = l_1;$
R2: $If\ k\ is\ k_{max}\ and\ b\ is\ b_{max},\ then\ Load = l_2;$

To convert clear input values to clear output, *n* is used - the *Takagi – Sugeno* algorithm [6].

The resulting model allows us to determine the degree of loading of the servo motors as a percentage of the maximum permissible value from the analysis of the coefficients of the approximation direct envelope.

This will allow you to choose the operating mode of each specific drive and optimize the operating mode of construction robotic and mechatronic complexes in order to increase their reliability and efficiency.

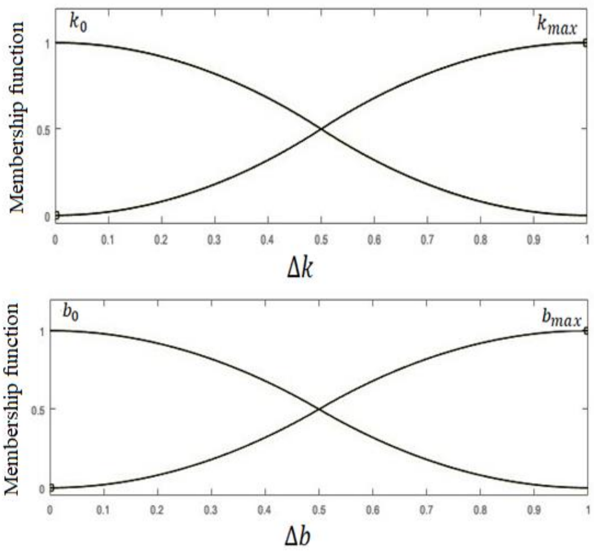


Figure.3. Input data of a fuzzy model for servomotor load determination

4.3 Prediction of technical condition

A method for servo motor technical condition prediction using neural networks is proposed. The forecasting initial data are the trend of the coefficients k of the approximating direct envelope of the wavelet coefficients of the current signals at characteristic scales for previous periods of operation, distributed over equal time intervals. The forecasting process includes three levels. At the first level, the values of the coefficients k of the approximation direct envelope of the wavelet coefficients for each characteristic wavelet scales are predicted. A direct signal transmission network with three inputs and one output is simulated.

The input vector of the neural network

$$P = \left[k(t_1),...k(t_{N-3}); k(t_2),...k(t_{N-2}); k(t_3),...k(t_{N-1})\right]$$

The target vector H, the values of the determining parameter are set, which should be obtained at the output

$$H = \left[k(t_4),...k(t_N)\right].$$

For a given input P, the neural network calculates the output value of the predicted parameter C

$$C = \left\lfloor k(t_{N-2});\ k(t_{N-1});\ k(t_N) \right\rfloor,$$

corresponding to a given target vector H.

To train the neural network, the back propagation algorithm is used.

Similar calculations are performed for each scale of wavelet coefficients. If during the calculation all the coefficients are negative, then the servomotor will remain operational in the next period of operation. If at least one is zero or positive, then in the next period of operation the object will fail.

The forecast at the next levels is an approximation of the values obtained at the previous level. To predict the time of the onset of faults, network outputs are needed that predict the values of the corresponding coefficients of the approximation straight envelope of the wavelet coefficients, apply to the input of the radial basis network. Since the output of the first level consists of values of the coefficients k, negative values of which indicate a working condition, and zero or positive ones indicate a faulty state of the servo, the result of the next level of forecasting can be obtained by maximizing the previous level. The determination of the development coefficients of the motor malfunction K_{MOTOR} .

$$K_{FAULT_j} = \max(\exp(-(\sum(K_i \cdot IW^{1.1} + b))^2));$$

$$K_{MOTOR} = \max(\exp(-(\sum(K_{FAULT\,i} \cdot IW^{1.2} + b))^2)),$$

where $IW^{1.1}$ $IW^{1.2}$ - weights vector of the first (development of a malfunction) and second (forecast of the state of the servo motors) of the approximation steps.

To determine the servo motor failure time, it is necessary to add the predicted values of the coefficients of the approximation direct envelope of the wavelet coefficients in the training set and repeat the entire forecasting process until the coefficient determining the state of the servo motor becomes $K_{MOTOR} \geq 0$. The number of iterations passed will be equal to the number of time intervals T during which the servomotor remains operational. The implementation structure of the above method is shown in Fig. 4

The proposed method for forecasting the technical condition will allow short-term and long-term forecasting of defects of each MSFC servo motor. The results will be used for subsequent optimization of the operating mode of MSFC.

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5 Cyber-physical system upper level

According to the developed architecture, the upper level collects information about the current state, load and the forecast period of maintaining operability from all MSFC drives and makes a decision on its further operation.

Let be m - number of radial movement mechanisms; n - is the number of lifting jacks of the MSFC. An important condition for the operation of the system is the identity of the RMM and LJ drives, as well as the uniformity of their loading

If $Load_{RMM}$ and $Load_{LJ}$ corresponding load on each servomotor RMM and LJ, then the total load on all drives of the system will be calculated as follows:

$$\sum Load_{RMM} = m \cdot Load_{RMM};$$
$$\sum Load_{LJ} = n \cdot Load_{LJ}.$$

If the number of simultaneously operating drives RMM as m^*, where $m^* = 1 \ldots . m$ and LJ as n^*, where n^*, then the total load on simultaneously working drives can be determined from the relations

$$\sum Load^*{}_{RMM} = \frac{m}{m/} \cdot \sum Load_{RMM};$$
$$\sum Load^*{}_{LJ} = \frac{n}{n/} \cdot \sum Load_{LJ}.$$

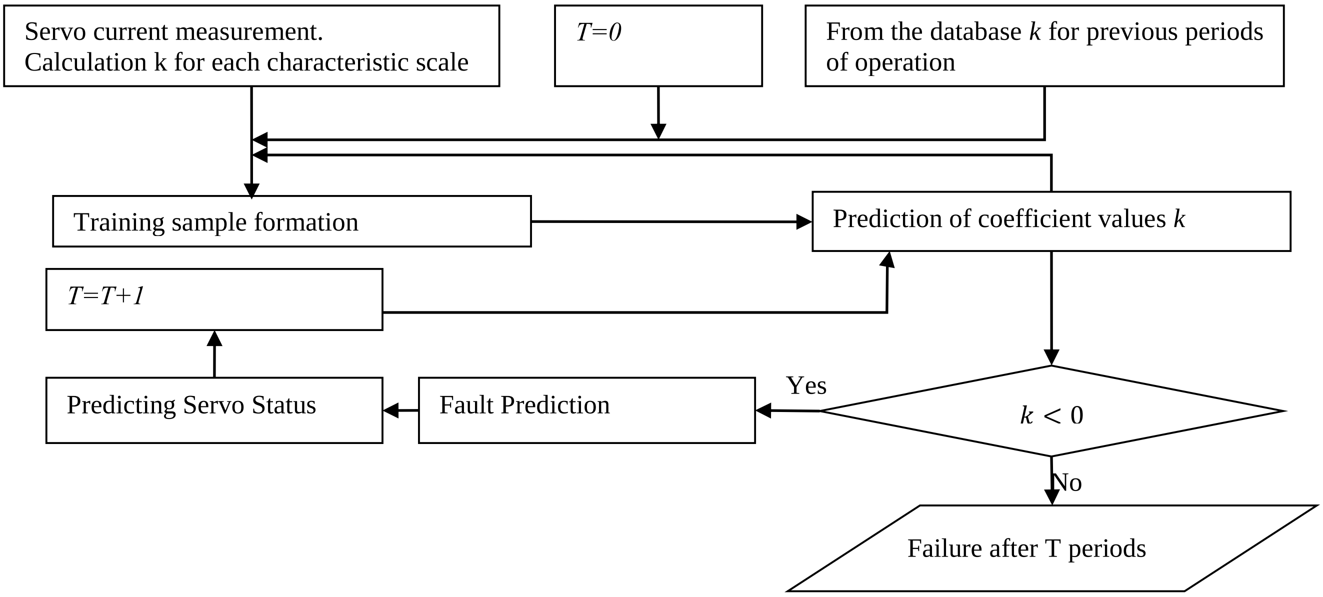

Figure. 4 Structure of the implementation of the method for predicting the technical condition of MSFC servo motors

The additional load on each drive can be found from the ratio

$$\Delta Load_{RMM} = \sum Load^{*}{}_{RMM} - Load_{RMM};$$
$$\Delta Load_{LJ} = \sum Load^{*}{}_{LJ} - Load_{LJ}.$$

Thus, a ratio is obtained that, knowing the total number of RMM and LJ drives and the number of currently motors operation determines the required load increment for each motor.

The average ($Load$) and average additional ($\Delta Load$) load on the servos of the RMM or LJ group are determined from the relations:

$$Load = \sum Load_{i(j)} / n^{*}(m^{*}),$$
$$\Delta Load = \sum \Delta Load_{i(j)} / n^{*}(m^{*}),$$

where $Load_i,\ i \in [1, n^{*}]$; $Load_j,\ j \in [1, m^{*}]$ - load for each motor RMM and LJ; $\Delta Load_i,\ i \in [1, n^{*}]$; $\Delta Load_j,\ j \in [1, m^{*}]$ -additional load for each motor RMM and LJ.

The average predicted period of good operation of the servos group RMM and LJ

$$T_g = \sum T_{i(j)} / n^{*}(m^{*})$$

where $T_i,\ i \in [1, n^{*}]$; $T_j,\ j \in [1, m^{*}]$ - the predicted period of good operation of each servo RMM and LJ calculated according to the forecasting model.

The simulated fuzzy logical decision-making system will have three inputs and one output. To convert clear input values into clear output, the *Mamdani* fuzzy logic algorithm is used [7-12]. The fuzzy knowledge base that describes the relationship between the input term sets and the output sets is presented in Table 1. The result of the decision-making model is the value of the decision $D \in [-1, 1]$.

Table 1. The truth table of the fuzzy decision-making model

Current motor load	**Change motor load, %**		
	Less 20	**25**	**More 30**
Forecasted period of service 1 month			
Less 30	+1	+1	-1
50	-1	-1	-1
More 60	-1	-1	-1
Forecasted period of service 3 month			
Less 30	+1	+1	+1
50	+1	+1	0
More 60	-1	-1	-1
Forecasted period of service more 6 month			
Less 30	+1	+1	+1
50	+1	+1	+1
More 60	0	0	0

If $D > 0$, then it is necessary to change the load on serviceable servos of the group by the value $\Delta Load$. If $D=0$, then the operating mode must be left unchanged. If $D<0$, then the condition of the drives of the group is unsatisfactory and it is necessary to stop the process. Based on this model, an intelligent decision-making method has been developed on the operation mode of each of the MSFC servo groups based on the technical condition of its servos, the implementation structure of which is shown in Fig. 5.

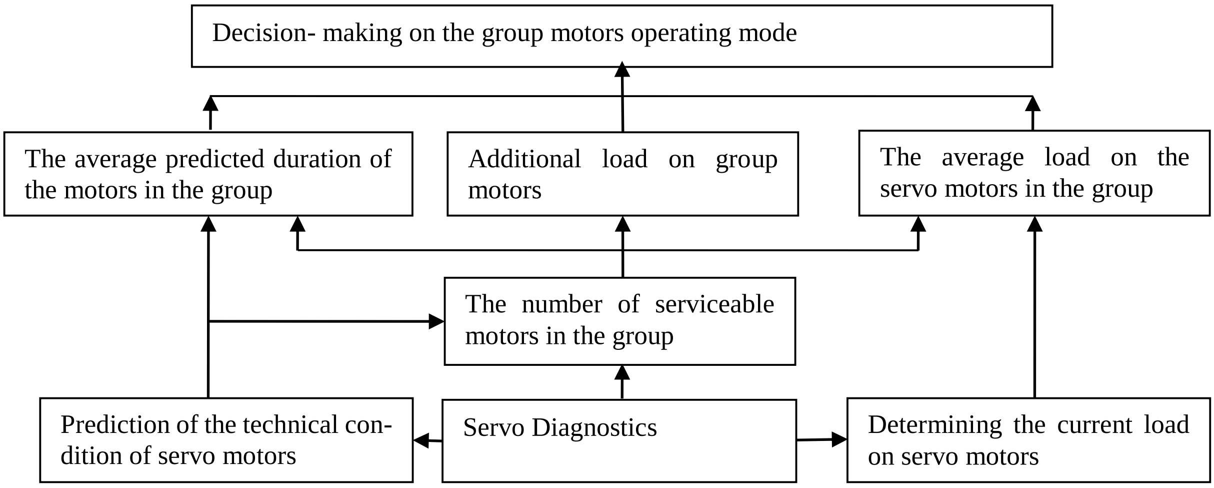

Figure 5. The structure of the implementation of the intellectual decision-making method for managing building mechatronic and robotic complexes according to the results of diagnosing their servos

6 Experimental research

A study of the prediction diagnosis methods of MSFC has been performed. For servo motor KY110AS0415-15B-D2-2000 was carried out according to the measurement of the current signal from January 2008 to January 2015. The obtained records of the supply current signals were processed using the proposed diagnostic method. The coefficients of the approximation straight envelope are found for each scale. According to the data obtained, it is clear that in January 2015 this servo motor was in the boundary state, since the approximation coefficient k for the rolling bearing malfunction is close to 0. According to the record in the equipment maintenance journal, the KY110AS0415 - 15B - D2 - 2000 servo drive failed on 27.02.2015 due to wear of the bearings, which confirms the accuracy of the proposed diagnostic method. According to the values of the coefficients *k* for the period from 2008 to 2012, the values of these coefficients are predicted for 2013-2015. A comparison of the results of diagnosis and forecasting (Fig. 7). It can be seen from this graph that, according to the forecast, the failure of the servo drive occurred earlier than in fact, which will prevent a sudden failure of the equipment. The analysis of the effectiveness and reliability of the proposed methods of predictive diagnosis.

It is established that the use of these methods will increase the coefficient of technical use by 16%. The reliability of the diagnosis is 93%. The accuracy of short-term forecasting is 1.7%, long-term forecasting does not exceed 10%. Prediction accuracy can be increased by increasing the volume of the training sample, as well as adding it to the current values of the diagnostic parameters.

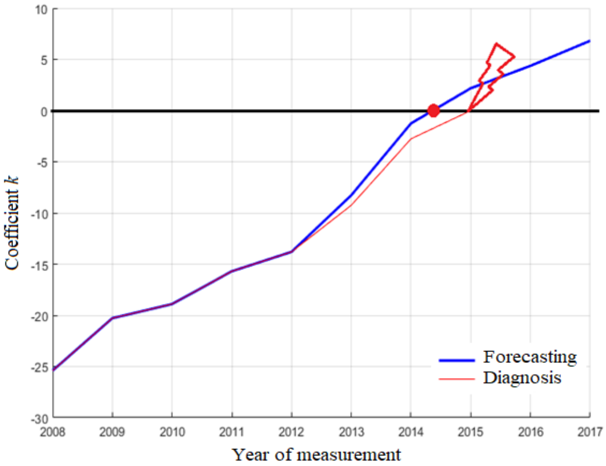

Figure 7. Comparative analysis of the diagnosis and forecasting results

A study of the prediction diagnosis methods of MSFC has been performed. The experimental stand was a fragment of a sliding formwork of four lifting jacks interconnected by formwork panels suspended on crossbars. This stand was put into step-by-step motion at a speed of 1 cm / min. For each scale of wavelet coefficients, the relative coefficients of the approximation straight envelope were calculated, which were substituted into the model for calculating the load. As a result of the calculation, it was found that the average load on the drive is approximately the same and amounts to 29.52% of the maximum, which corresponds to the average statistical load on the formwork drives during operation. The health checks of the models for calculating the load change and the decision on the control of servo drives were carried out with the KY110AS0415-15B-D2-2010 formwork drive turned off. The objective of the experiment was to calculate the necessary change in the load on the three remaining drives and to study the behavior of the system when working on three servos. To compensate for the failure of one of the drive jacks, it is necessary to increase the load on each of the three remaining drives by 9.84%. As a result of the calculation using a fuzzy decision-making model, it was found that the current load on the group drives can be increased by $\Delta Load = 9{,}84$ %.

For the three switched-on drives, the load on the calculated percentage was increased and the speed of the fragment of the sliding formwork was measured. The results of the study showed that the control system allows for uniform constant movement of formwork panels with a given speed of 1 cm / min with four drives with a load of 29.52% each, and with three motors with a load of 39.36%.

The nature of the movement of the mechanism remains almost unchanged when the load is redistributed within the motors group. This makes it possible to carry out repair work on replacing a faulty drive without stopping the process, reducing complex performance and losing quality of the monolithic structure being constructed.

7 Conclusions

The article presents the structure of the cyber-physical system for predictive diagnosis of the technical condition of MSFC servo motors. This system contains two levels. The first level is connected to the servos and provides their predictive diagnosis. At the second level, decision making and changing the operating mode of the servo drive are implemented. The innovative methods of diagnosing and predicting the technical condition are described. Methods of calculating the current and additional load are presented, as well as a decision-making model on the advisability of changing the load on the servos depending on the current state of operable motors.

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