Mechatronic Sliding Formwork Complex Operating Mode Optimization Using its Servos Technical Condition

Alexey Bulgakov[a], Thomas Bock[b], Tatiana Kruglova[a]

[a] Platov South-Russia State Polytechnic University, Novocherkassk, Russia
[b] Technical University of Munich, Germany
E-mail: agi.bulgakov@mail.ru, thomas.bock@br2.ar.tum.de, tatyana.kruglova.02@mail.ru

Abstract-

The mechatronic sliding formwork complex is a compound dynamic system, the quality of the structure being erected depends on the correct coordinated operation of its elements. The determining factor of the structure vertically is to ensure a constant formwork movement speed and compliance of its working floor horizontalness. To fulfil these conditions, it is necessary to ensure that all lifting jacks are in the same plane with a deviation of no more than 20 mm. Failure of one of the lifting jack's servos can lead to skewed of the working floor, jamming of the formwork and concrete stripping. To solve the lifting jack's technical condition monitoring problem can help its servo predictive diagnostics system.

The purpose of the research is to develop a method for mechatronic sliding complex operating mode optimizing considering its servos technical condition predictive diagnostics results.

In the article, the authors propose a method for mechatronic sliding formwork complex operating mode optimizing considering the technical condition and external load on its servos. The additional load calculating and making decisions models are described. The results of experimental studies of this method on a fragment of the mechatronic sliding formwork complex are presented.

Keywords –

mechatronic sliding formwork complex, operating mode optimization, technical condition monitoring, predictive diagnostics system

1 Introduction

Monolithic construction is a *more common* method of high-rise buildings and structures. [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 (MSFC) (Fig.1), which is a spatial form installed on the perimeter of the structures and moved up by lifting jacks (LJ) [3].

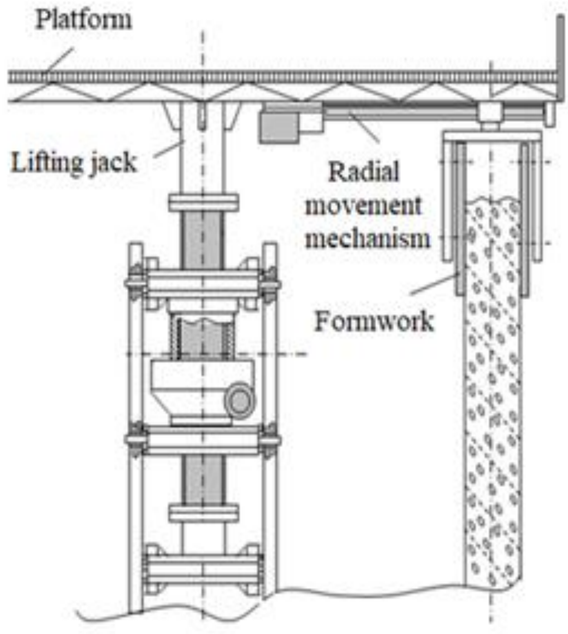

Figure 1. Arrangement of support columns with a electromechanical lifting jack

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]. 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 fulfil these conditions, it is necessary to ensure that all lifting jacks are in the same plane with a deviation of no more than 20 mm. 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 [5-7] 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.

2 Mechatronic sliding formwork complex operating mode optimization

A necessary condition for ensuring the verticality of the structure is the observance of the horizontality of the working floor of the formwork by controlling the forces in the LJ, which are substantially non-linear and depend on the static and dynamic loads acting on the system. The lifting mechanisms of the MSFC are subject to the distributed weight of the platform with the formwork Q_{fw}, concrete (Q_{ct}), reinforcement (Q_{rt}), equipment (Q_{et}) and control system (Q_{cs}). The total static load acting on the platform can be calculated from the ratio:

$$Q_s = Q_{fw} + Q_{ct} + Q_{rt} + Q_{et} + Q_{cs}. \quad (1)$$

Also, in the process of lifting the platform with the formwork between the panels and concrete, adhesion occurs and friction occurs, which changes during the lifting process. Then the equivalent load on the platform will be a function of static load (Q_s), friction forces (F_{ff}) and adhesion (F_{an}) and will be written as follows:

$$N_{el} = f(Q_s, F_{ff}, F_{an}). \quad (2)$$

To fulfil the horizontal condition of the MSC platform, it is necessary to ensure load uniformity with the design (n) and current (n^*) number of jacks, which at any time can be

$$n^* \leq n. \quad (3)$$

Then the equivalent load on each working jack will be

$$N_{LJ_j} \approx N_{el} \cdot (n^*)^{-1} \quad (4)$$

To maintain the static stability of the jack during operation, it is necessary to fulfil the following ratio (5)

$$N_{LJ_j} \leq F_{CR} \quad (5)$$

where F_{CR} - the critical force according to Euler [9], calculated by equation (6)

$$F_{CR} = (\pi^3 \cdot E \cdot d^4) \cdot (64 \cdot S \cdot \mu^2 \cdot l^2)^{-1} \quad (6)$$

where E - the modulus of elasticity of the screw material; S - the safety factor; l - the length of the loaded portion of the screw; d - inner diameter of the screw; μ - the stiffness coefficient of a helical gear ($\mu = 0.5$)

Knowing the current platform load and critical force, it is possible to calculate the critical number of lifting jacks.

$$n^*_{CR} = round\big(f(Q_s, F_{ff}, F_{an})\big) \cdot F_{CR}{}^{-1} \quad (7)$$

Then the boundary condition for static stability is the restriction on the number of simultaneously working jacks

$$n^* \in [n^*_{CR}, n] \quad (8)$$

Also, when choosing the of the MSFC jacks operating mode, it is important to prevent the servos from overloading. Hence the current boundary condition has the form:

$$I_c \leq K_C \cdot I_{nom}, \quad (9)$$

where I_c, I_{nom} - is the current and rated currents of the servomotor, K_C - is the overload capacity of the motor for current.

To ensure the high quality of formwork it is necessary to maintain the speed of movement of the platform at a constant predetermined level, which determines the boundary condition for speed:

$$v_p = const, \qquad v_p \geq 1\ cm/min \quad (10)$$

In the process of selecting the operating mode, the technical condition of the servos is important, which can be unambiguously characterized by the number of periods of maintaining the working capacity T, determined using the methods of predictive diagnosis [7].

Then the boundary condition for reliability has the following form

$$T > 0 \quad (11)$$

If some servos are failure, the load on the lifting jack should be redistributed to the drives of serviceable jacks so that the total load difference tends to zero. Then the objective function of choosing the optimal operating mode of the MSFC will take the following form

$$\theta = \sum_{i=1}^{n} Load_{LJ_i} - \sum_{j=1}^{n^*} Load^*_{LJ_j} \to 0 \quad (12)$$

Since the load on the servo shaft n^* with simultaneously working jacks can be determined by the equation (13)

$$Load^*_{LJ} = Load_{LJ} + \Delta Load_{LJ}, \quad (13)$$

where $Load_{LJ}$ - load on the drive with n working jacks; $\Delta Load_{LJ}$ - additional load on the drive, the optimization function will depend on these two parameters and can be written in the following form (14)

$$\theta = f(Load_{LJ}, \Delta Load_{LJ}) \to 0 \quad (14)$$

Thus, to select the optimal operating mode of the MSFC, considering the technical condition of its executive drives, it is necessary to determine the current ($Load_{LJ}$) and additional ($\Delta Load_{LJ}$) loads on the servos, followed by a decision [10] on choosing the operating mode of the MSFC.

3 Load determining model

As a research result [5-7], it has been established that the technical condition of the servo can be determined by the signs of the coefficients k of the straight lines, which approximate the envelopes of the wavelet transform values coefficients on the characteristic scales.

The servo motor is enabled if $k < 0$ and faulty if $k \geq 0$. The cause of the malfunction can be identified by the scale numbers [5-7].

To optimize the MSFC operating mode it is necessary to determine the loading mode of all lifting jacks. It is necessary to analyze all the parameters of the approximating straight line for a serviceable unloaded servo drive operating in the nominal mode.

The obtained data will be used as reference coefficients k_0, b_0 with which the current values of the parameters k, b. will be compared. The values of the maximum allowable coefficients k_{Max}, b_{Max} can be calculated from the overload capacity of the servo drive by current K_T:

$$k_{\text{мах}} = k_0 \cdot K_T;\ b_{\text{мах}} = b_0 \cdot K_T. \tag{15}$$

Then the approximating straight line coefficients k, b of the diagnosed servo will be in the range:

$$\begin{gathered} k_0 \leq k \leq k_0 \cdot K_{\text{T}} \\ b_0 \leq b \leq b_0 \cdot K_{\text{T}} \end{gathered} \tag{16}$$

Then the increments of these coefficients can be calculated from the relations:

$$\begin{gathered} \Delta k = (k - k_0) \cdot (k_0\ (K_T - 1))^{-1}, \\ \Delta \mathrm{b} = (\mathrm{b} - \mathrm{b}_0) \cdot (\mathrm{b}_0(\mathrm{K_T} - 1))^{-1}. \end{gathered} \tag{17}$$

Based on this, the operating mode is permissible if

$$\begin{gathered} k \in [k_0, k_{max}];\ \Delta k \in [0,1]; \\ b \in [b_0, b_{max}];\ \Delta b \in [0, 1] \end{gathered} \tag{18}$$

To check the possibility of increasing the load on the servo drives, it is advisable to use a fuzzy logical model *Sugeno*, the inputs of which are the relative coefficients Δk and Δb (Fig.2), and the output is the level of the load on the servo drive as a percentage of the maximum allowable.

The output parameter will be the corresponding coefficient on the interval [0; 100] showing the percentage of load on the servomotor. If this parameter is zero, then the servomotor runs at nominal no load. If it is 100%, then the engine has maximum load and it is necessary to change its operating mode.

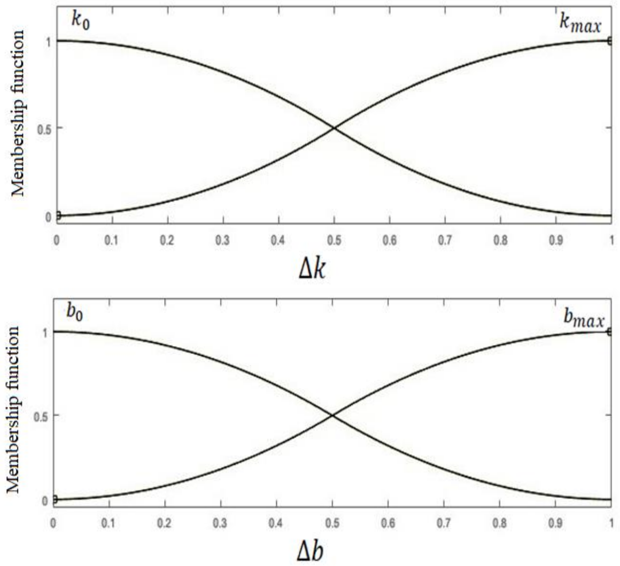

Figure 2. Input data of the fuzzy model for determining the load on the servo

The correlation of the entered sets can be written using the following fuzzy rules:

R1: if k is k_0 *and b is* b_0*, then* $Load_{LJ} = l_1$*;*

R2: if k is k_{max} *and b is* b_{max}*, then* $Load_{LJ} = l_2$*;*

The *Takagi – Sugeno* fuzzy inference algorithm is used to determine the value of the output variable:

1. The input variables take some clear values k^*, b^* and the "truncation" levels for each rule are found:

$$\begin{gathered} \alpha_1 = min[k_0(k*), b_0(b^*)] \\ \alpha_2 = min[k_{max}(k*), b_{max}(b^*)] \end{gathered} \tag{19}$$

2. The system output is calculated by equation (20)

$$Load_{LJ} = \frac{\alpha_1 \cdot l_1^* + \alpha_2 \cdot l_2^*}{\alpha_1 + \alpha_2} \tag{20}$$

The proposed model allows, based on the results of the analysis of the coefficients of the straight line, which approximates the envelope of the wavelet coefficients, to determine the current load on the servo as a percentage of the maximum allowable.

$$\Delta Load_{LJ} = Load_{LJ} \cdot (n - n^*) \cdot (n^*)^{-1} \tag{21}$$

The resulting ratio allows, knowing the total number of jack drives (n) and the number of currently serviceable drives (n^*), find the additional load on each drive.

The purpose of optimizing the operating mode of the MSFC is to ensure the possibility of continuing the technological process in case of failure of one or more LJ servos. To do this, it is necessary to develop a model for making an optimal decision on the choice of an operating mode based on the predictive diagnostic results as well as calculating the current and additional load on the MSFC servo drive.

4 Intelligent decisions making model

After the current and predicted state of all MSFC servos has been determined, additional loads permissible for them have been calculated, it is necessary to decide on the choice of the mode of further operation of the complex and each group of its servos. For this, it is advisable to develop a mathematical decision-making model based on the methods of fuzzy logic.

To formalize the model, the following are calculated:

– average load on servo drives of the LJ group

$$Load = (\sum_{j=1}^{n^*} Load^*_{LJj}) \cdot (n^*)^{-1} \quad (22)$$

where $Load^*_{LJj}$ $j \in [1, n^*]$ is the load on each LJ drive.

– average additional load on servo drives of the LJ group:

$$Load = (\sum_{j=1}^{n^*} \Delta Load_{LJj}) \cdot (n^*)^{-1}, \quad (23)$$

where $\Delta Load_{LJj}$ $i \in [1, n^*]$ - additional load on each LJ servo

– the average predicted life of the LJ servos

$$T_g = (\sum_{j=1}^{n^*} T_j) \cdot (n^*)^{-1}, \quad (24)$$

where $T_j, j \in [1, n^*]$ - predicted service life of each LJ servo

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]. 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 $D \in [-1, 1]$.

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 (Fig. 3) has been developed on the operation mode of each of the MSFC servo groups based on the technical condition of its servos.

To make the best decision on the MSFC operating mode choosing considering of the LJ servos technical condition. The following steps must be performed using the models of diagnosing and predicting the technical

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

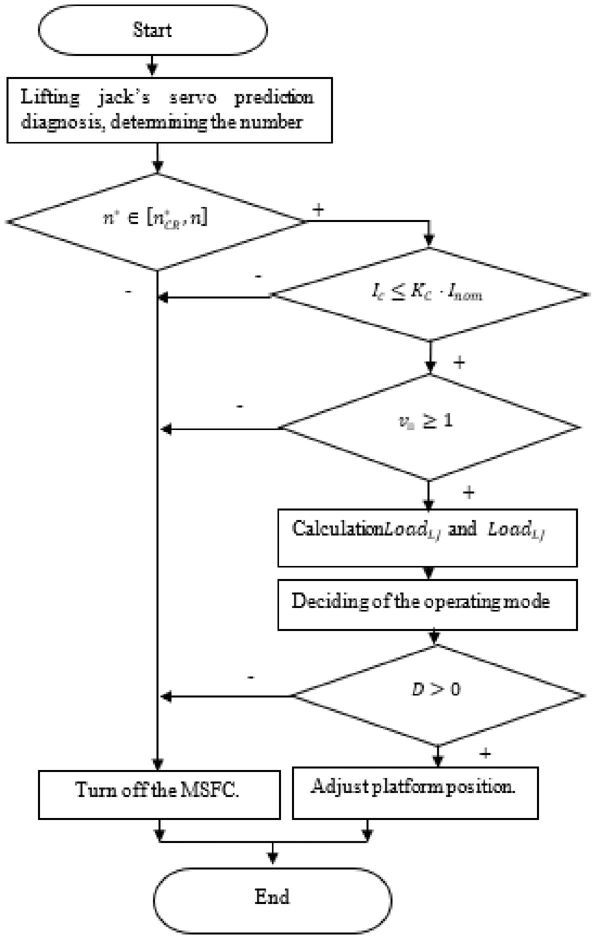

Figure 3. Algorithm of the intelligent decision-making method

condition, determine the current technical condition of each servo of the MSFC and find the number of serviceable drives for which the period of operability T>0. Check the boundary conditions of the optimization function and, if all the boundary conditions are fulfilled, calculate the current and additional load on the servos. Next, using an intelligent decision-making model, determine the mode of further operation of LJ drives. If D>0, send a signal to the control system to level the platform. If it is impossible to fulfil any of the boundary conditions or D≤0, send a signal to turn off the MSFC.

5 Experimental research

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. 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 behaviour 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 $\Delta Load = 9{,}84$ %. Based on the results of the calculation performed, the operating mode of the mechatronic sliding complex was optimized. 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.

6 Conclusions

The article presents a method for MSFC operating mode optimizing considering it is LJ servos technical condition. The boundary conditions of the optimization function are formulated, considering the LJ static stability, platform speed, servos current of the and technical condition. A model for calculating the current and additional load on the servo drives is described. A model for deciding on the choice of an operating mode is described. An algorithm for making the optimal decision on the choice of the operating mode of the lifting jacks depending on the technical condition of the servos is presented. The algorithm involves adjusting the servo current and platform lift speed depending on the number of serviceable jacks, as well as the current and predicted technical condition of their servos.

References

[1] Bulgakov, A., Parshin, O., Gudikov, G. Automation of sliding formwork for the construction of industrial structures – Overview. Moscow: VNIINTPI, 2000. Ser. Technology and mechanization of construction. - Issue 1. 64 p.

[2] Travush, V., Erofeev, V, Bulgakov, A., Afonin, V. Automatic control of sliding formworks for establishment of high monolithic structures with a variable radius // Russian engineer, 2021, No. 1, pp. 37-41.

[3] Travush, V., Erofeev, V., Bulgakov, A., Kruglova, T. and D Svetlov, D. Cyber-physical predictive diagnostics system for servos of mobile construction robots. IOP Publishing. Journal of Physics: Conference Series, Volume 1687 (2020), International Conference on Engineering Systems 2020 14-16 October 2020, Moscow, Russia. doi:10.1088/1742-6596/1687/1/012014

[4] Travush, V., Erofeev, V., Bulgakov, A., Buzalo, N. Mechatronic complex based on sliding formwork for the construction of monolithic high-rise buildings and tower-type structures made of reinforced concrete. IOP Conf. Series: Materials Science and Engineering 913 (2020) 022009 DOI:10.1088/1757-899X/913/2/022009

[5] Bulgakov, A., Kruglova, T. Intelligent method of Electric drive diagnostic with due Account for its operation mode. Journal of Applied Engineering Science - 2017. Vol. 15, № 4. - Art. 465. - pp. 426-432.

[6] Bulgakov, A., Kruglova, T., Bock, T. Synthesis of the AC and DC Drives Fault Diagnosis Method for the Cyber-physical Systems of Building Robots-MATEC Web of Conferences, 2018. Vol. 251: №03060

[7] Kruglova, T., Bulgakov, A, Vlasov, A., Shmelev, I. Artificial Intelligence Method for Electric Drives Mode Operating and Technical Condition Determination MATEC Web of Conferences, 2017. Vol. 132: Dynamic of Technical Systems (DTS-2017): XIII International Scientific-Technical Conference, Rostov-on-Don, 2017. № 04012.