Mechatronic complex based on sliding formwork for the construction of monolithic high-rise buildings and tower-type structures made of reinforced concrete

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Abstract. The article is devoted to the use of mechatronic sliding complexes for the construction of high-rise monolithic buildings and tower-type structures made of reinforced concrete. It is shown that high-rise monolithic towers of variable radius, characterized by the increased complexity of technological operations can be erected with high efficiency using automated sliding formwork, which makes it possible to achieve the highest possible pace of construction technology, while ensuring the high quality of work using self-compacting high-strength concrete. A mathematical description of the mechatronic complex as a completely observable multidimensional object with control limitations is given, which allows predicting deviations and deformations of the sliding formwork working platform design during the lifting process, evaluating the internal and external disturbances' effect on the complex’s operation, and also modeling the interaction of the lifting and regulating mechanisms in violation of their synchronous operation. It is proposed to use the two-level systems to control the formwork lift and synchronize the movements between the actuators groups. The results of modeling the sliding formwork lifting process are presented.

1. Introduction

High-rise monolithic buildings and structures made of reinforced concrete are distinguished by high operational characteristics, primarily, increased rigidity of the bearing shell and crack resistance of the outer surface. This construction method is widely used when performing work in seismic areas during the construction objects’ erecting when their increased strength is required. The latter include, for example, chimneys, cooling towers, television towers and many others (Figure 1) [1].

Often the erection of buildings and structures is required in the shortest possible time. A good example of this is the situation that has arisen in connection with the rapid spread of coronavirus infection around the world, when the construction and early commissioning of new medical facilities was urgently required everywhere. In this regard, it is of particular interest to use the sliding formwork...
method, which ensures the high construction rates, when it is possible to build up to 12 m per day, i.e. 3-4 floors of the building. This requires high-density concrete, capable of stacking in formwork with minimal labor and timely gaining the necessary strength to maintain the required speed of their rise, as well as to ensure the perfect quality of the wall surface [2-4].

The sliding formwork itself is the leading mobile unit of the whole complex of concrete work at the construction site, characterized by cyclically repeated, and therefore amenable to algorithm, technological operations. This makes it possible to create the mechatronic complexes on its basis, which automate the formwork lifting, changing its radius, as well as the processes of laying and compacting concrete [5-7].

![Figure 1. High-rise reinforced concrete structures of a tower type](image)

**2. Mathematical description of a mechatronic sliding complex with a round shape**

For the construction of high-rise tower-type structures, sliding formwork with a varying radius is used. This ensures, inter alia, the achievement of the necessary aerodynamic characteristics’ values of the objects used to divert the exhaust gases into the atmosphere. In addition to the formwork itself, various electromechanical devices are used, which makes it possible to consider them all together as a single mechatronic sliding complex (MSC). Its main element is a movable platform, resting on the columns equipped with lifting jacks (Figure 2). Taking the operating conditions of lifting jacks, determined by the overall dimensions of the structures being erected, into consideration, preference is given to electromechanical jacks. Regulation of the formwork panels is carried out using the helical radial displacement mechanisms (HRDM) with an asynchronous drive. The loads acting on the lifting and regulating mechanisms are extremely uneven, due to the distribution nature of the building materials, mechanisms and working personnel on the working floor of the formwork. This leads to a violation of its horizontalness and, as a consequence, the deviation of the formwork from the project axis, the occurrence of torques and twist of the platform.
To create a system for automatic control of a mechatronic sliding complex, its mathematical identification is required as a control object. It is a multidimensional control object, the states of which are described by a system of equations of the form:

\[
\begin{bmatrix}
U_{LJ}^{(1)} \\
U_{LJ}^{(2)} \\
\vdots \\
U_{LJ}^{(n)} \\
U_{RM}^{(1)} \\
U_{RM}^{(2)} \\
\vdots \\
U_{RM}^{(n)} \\
\end{bmatrix},
\begin{bmatrix}
x_p, y_p, z_p, R_0, \phi_p, \theta_p \end{bmatrix},
\begin{bmatrix}
F_1, F_2 \end{bmatrix}
\]

where \( U_{LJ} \), \( U_{RM} \) – define the control action vectors for lifting jacks and HRDM; \( \vec{Y}_{mc} \) – is the vector of the MSC output state parameters; \( \vec{F}_1 \) and \( \vec{F}_2 \) – are the vectors of external influences on the erected structure and mechatronic complex.

In this case, the movement of the MSC under the action of the governing \((U_{LJ}, U_{RM})\) and \((\vec{F}_1, \vec{F}_2)\) disturbance actions can be described by the equation:

\[
\vec{Y}(t) = A(s) \cdot U_{LJ}(s) + B(s) \cdot U_{RM}(s) + H_1(s) \cdot \vec{F}_1(t) + H_2(s) \cdot \vec{F}_2(t),
\]

where \( A(s), B(s) \) – are the transfer function matrices characterizing the dynamics of the lifting and regulatory bodies MSC; \( H_1(s) \) and \( H_2(s) \) – are the transfer function matrices for disturbing influences.

Taking the multidimensionality of the control object into account, the formation of control actions \( U_{LJ}^{(i)} \) and \( U_{RM}^{(i)} \) should be made considering the need to manage the entire group of parameters: \( x_p, y_p, z_p, R_0, \alpha_p, \beta_p, \psi_p \). To correct the complex position, the platform is tilted in the direction opposite to the offset, and to eliminate the complex twist around the vertical axis, it is proposed to use...
the backward wave method, when the lifting jacks are switched on alternately in the direction opposite to the twist.

The mathematical description of the mechatronic moving complex as a whole includes kinematic and dynamic relationships establishing a relationship between the state parameters of the complex and controlling and disturbing influences, as well as their mutual influence on each other. Kinematic relationships of the model establish a relationship of the displacement vectors \( \vec{z}_p \) and orientation \( \Theta_p \) platforms with the coordinates of the jacks’ position:

\[
\vec{z}_p = [x_p, y_p, z_p]^T \rightarrow x_p = \frac{1}{n} \sum_{i=1}^{n} x_{iLJ}, \quad y_p = \frac{1}{n} \sum_{i=1}^{n} y_{iLR}, \quad z_p = \frac{1}{n} \sum_{i=1}^{n} z_{iLR},
\]

\[
\Theta_p = [\alpha_p, \beta_p, \psi_p]^T \rightarrow \alpha_p = \arctg \left( \frac{\Delta z_{iLJ}}{R_{iLJ}} \right), \quad \beta_p = \frac{2\pi}{n} i (\max(z_{iLJ})) ,
\]

\[
\psi_p = \frac{1}{n} \sum_{i=1}^{n} \left[ \arctg \left( \frac{y_{iLJ} - \sum y_{iLJ} / n}{x_{iLJ} - \sum x_{iLJ} / n} \right) - \frac{2\pi}{n} (i-1) \right],
\]

where \( x_p, y_p, z_p \) define the MSC platform position in the object coordinate system \( X_oY_oZ_o \); \( x_{iLJ}, y_{iLJ} \) - are the coordinates of the \( i \)-th jack; \( \alpha_p \) and \( \beta_p \) - denote the size and direction of the platform’s inclination; \( \psi_p \) - is the platform’s twist.

During the complex operation, the formwork panels may shift from the center of the platform; therefore, the equations that determine the position of the formwork center through the radii \( R_{iLJ}^{(j)} \) HRDM are introduced into the model:

\[
x_{op} = \sum_{j=1}^{m} R_{iM}^{(j)} \cos \left( \frac{2\pi}{m} (j-1) \right) = \sum_{j=1}^{m} x_{iM}^{(j)}; \quad y_{op} = \sum_{j=1}^{m} R_{iM}^{(j)} \sin \left( \frac{2\pi}{m} (j-1) \right) = \sum_{j=1}^{m} y_{iM}^{(j)}.
\]

The displacement of the formwork platform, caused by its inclination, during the lifting process is described by the equations in the projections on the coordinate axes:

\[
x_p(t) = \int v_p(t) \cdot dt \cdot \cos \alpha_p \cdot \cos \beta_p; \quad y_p(t) = \int v_p(t) \cdot dt \cdot \cos \alpha_p \cdot \sin \beta_p.
\]

The synchronization equation is introduced into the model, which determines the law of change in the radial position of the HRDM:

\[
r_{iM}^{(s)}(t) = \int_{t_0}^{t} v_L dt \cdot \cos \beta_p,
\]

where \( v_L \) is the platform lifting speed.

The displacement of the formwork and its slope due to solar heating and the wind load action is represented by the total of the transfer functions:

\[
W_{T(W)}(s) = W_{T(W)}^{(dis)}(s) + W_{T(W)}^{(til)}(s) = \left( K_{T(W)}^{(dis)}(H) + K_{T(W)}^{(til)}(H) \left( \frac{Y_p}{s} \right) T_{E(W)}^n + 1 \right),
\]

where \( K_{T(W)}^{(dis)}(H), K_{T(W)}^{(til)}(H) \) - are the transfer coefficients of the displacement and inclination of the platform during heating (index – \( T \)) or exposure to wind load (index – \( W \)).

The resulting mathematical model of the MSC makes it possible to synthesize a control system and predict the complex deviation from the design position during the rise, taking into account the
disturbing influences’ influence. Based on the features and properties of the formwork, it is advisable to use the two-level structures to control the MSC. The upper (tactical) level is used to plan the trajectory of the formwork, taking into account the control restrictions and disturbing effects on the structure, as well as for the formation of the corresponding control actions. At the lower (executive) level, the control signals are processed and the movements are synchronized between the groups of mechanisms. This approach gives an opportunity to achieve the specified quality of construction.

3. Modeling the operation of a mechatronic sliding complex

The operation of the executive mechanisms of the MSC should be synchronized. Taking into account their large number, this problem is solved by using the continuous-pulse synchronization method, which includes using the control pulses for controlling an asynchronous servo-drive, the duration of which determines the average movement speed. The obtained time diagram of such a control is shown in Figure 3.

![Figure 3. Timing diagram of continuous-pulse control of radial movement mechanisms](image)

It shows that the intervals mechanisms \( t_M \), replaced by temporary pauses when the mechanisms are in the off mode. The pauses’ length is determined by the value of the mismatch in the mechanisms’ movement speeds. The analysis of the pulse drive control mode showed its effectiveness for synchronizing the movement of the regulating and lifting the MSC mechanisms. By varying the control pulses’ width, it is possible to rather effectively control the average speed of the radial movement mechanisms and thereby synchronize their joint work with lifting jacks. The sampling step is selected from the condition of obtaining the lowest switching frequency of the motor and limiting the error in positioning the shields. Setting the parameter values for the continuous-pulse control mode of the mechanisms makes it possible to limit the maximum value of the reaction forces at the level of permissible values.

To control the complex, the coordinates of the points \( x_p^{(k)} , y_p^{(k)} \) are determined as well as the inclination angles \( \alpha_p^{(k)} \) of the platform at the end of each climb step. The coordinates of trajectory points at the \( k^{\text{th}} \) lifting steps’ end are out of expression:
where \( l_k = k \cdot h_{si} \) — is the lift height from the start of adjustment; \( z_p^{(A)} \) — is the altitude position of MSC at the beginning of the adjustment (point \( A \)); \( h_{si} \) — defines a lifting step. During the adjustment process, the inclination angle of the platform changes according to the law:

\[
\alpha_p(l) = \arctg[\dot{\delta}(l)], \quad \dot{\delta}(l) = \begin{cases} 
2a_{12}l + a_{11} & l < l_s \\
\lambda_{12}C_2e^{\lambda_{22}(l-l_s)} + \lambda_{22}C_2e^{\lambda_{22}(l-l_s)} & l \geq l_s
\end{cases}
\]

The modeling of the lifting platform is performed in accordance with the above-mentioned ratios. As a result, the curves of the transition sections, on which the offsets and angular deviations were adjusted, were obtained. Relevant graphs of transition sections are presented in Figure 4.

![Figure 4](image-url)  
*Figure 4. Schedules for adjusting the MSC platform position*

4. The results discussion

The studies’ results of the developed mechatronic complex based on sliding formwork for the construction of high-rise monolithic buildings and tower-type structures show that the chosen approach to its construction allows achieving the required quality and ensuring the technologically highest possible construction rates. The difference from the control systems of sliding formwork known and used in construction practice is the use of two-level control of actuators [8-12]. BIM-technologies, recently received widespread use in construction practice, can be effectively implemented using this approach.

5. Summary

An approach for the development and practical application of a mechatronic complex based on sliding formwork for the monolithic objects’ construction is proposed. The technological feature of the sliding
formwork, which consists in the need for almost continuous movement, makes it possible to algorithmize cyclically repeating technological process and automate it. The developed mathematical description of the MSC takes into account the effects of static loads, deformation forces of structural elements, as well as the interaction of formwork panels with concrete. The MSC management is based on forecasting the movement of the platform with the formwork taking into account wind and thermal effects, which allows stabilizing the mechanisms, achieving synchronization of their interaction and providing the adjustment of the platform position. The proposed two-level control system makes it possible to automate the entire MSC control process, including planning its movements when the deviations of the working floor of the formwork from set values occur, taking into account the restrictions associated with the permissible curvature of its lifting path.

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