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A Mechatronic Slip Complex Control when Erecting Monolith Objects

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Abstract

The paper considers the principles of a mechatronic slip complex (MSC) control for monolith construction, which features the availability of two groups of effectors requiring coordinated work. It has been shown that for the MSC control it is advisable to use a two-level structure; the upper level tasks of which are planning the complex hoisting and synchronizing the operation of control mechanisms, while the tasks of the lower level incorporate the development of control signals formed at the previous level. In order to remove the complex deviation from the designed location it is suggested to apply the method of the MSC movements planning with due account of limitations for control and effects of disturbing influences on the structure being erected.

Keywords: monolith building, slip forms, automation, mechatronic complex, control.

1. Introduction

Construction of monolith objects is connected with great labor effort and multiple adjusting operations especially when erecting structures with varying cross-section and walls width. The analysis of monolith construction technology has shown the expediency of designing mechatronic complexes on the basis of slip forms as they provide automation of the project erection with continuous-cyclic placement and consolidation of concrete. Consideration of different variants of the MSC development on the basis of slip forms has led to the idea of using a movable platform 1 bearing against columns 2 with help of lifting posts 3 which are equipped with jacks 4 (Figure 1). The forms 5 are suspended from the platform by means of radial displacement mechanisms (RDM) 6 thus providing for the adjustment of panels location. For the purpose of lifting it is advisable to use frequency control electromechanical jacks, which allows to adjust hoisting speed and to synchronize movement. For the RDM it is preferable to use an induction motor drive with relay control. The main tasks of the mechatronic complex control are to lift the platform with forms during the process of concrete placement, change panels location when lifting, adjust the platform position when shifts or torsions occur, and synchronize the equipment operation.

Taking into account the complexity of MSC as an object of control, a great number of disturbing and adjusting influences and control limitations it is of interest to consider the problems of the complex control which include planning its motions, development of the laws of control, and solution of the problem of mechanisms operation synchronization. As opposed to known designs and systems fully automated lifting of slip form is offered [1-9].

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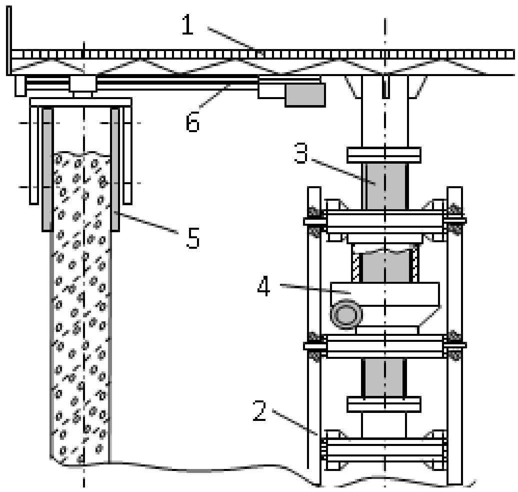

Figure 1. Slip form: 1 - movable platform; 2 – column; 3 - lifting post; 4 - electromechanical jack; 5 – form; 6 - radial displacement mechanism

2. Characteristic features of the MSC control

The distinctive feature of the MSC is the availability of two groups of effectors: hoisting jacks and RDM that require coordinated operation. During the process of operation the jacks experience considerable static and dynamic loads which are irregularly distributed in the jacks. When the platform lifts, the load changes due to concrete – panels interaction (Figure 2).

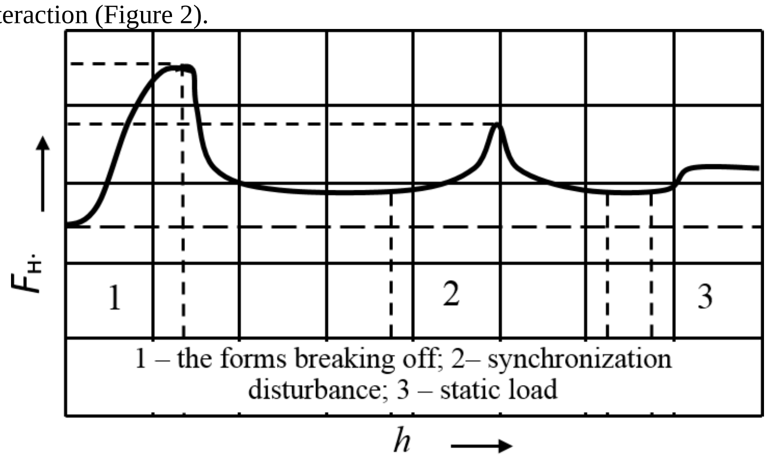

Figure 2. The load changes on the slip platform

During the operation irregularity of hoisting the jack loads can be up to 75-86%, which results in a violation of the platform horizontal displacement, its deviation from the designed axis and twisting of the platform with forms. Such operation condition of hoisting jacks make stringent requirements to drives and causes the necessity to synchronize lift speeds.

RDM operation is under the influence of friction and elastic forces appearing with the deformation of the forms elements. When the synchronization of the operation of hoisting and adjusting units is broken, reaction forces in concrete additionally act on the RDM, and they have a non-linear character (Figure 3). This causes an increase of load and decrease of the mechanism speed. Therefore, the operation of the RDM drives should be strictly synchronized with the platform hoisting and agreed with the curvature of the walls being erected.

The process of the MSC operation is accompanied by disturbing influences. They are caused by sunlight heating and wind loads [1]. Actions of heat and wind loads can result in considerable deviations in the MSC operation and they must be taken into account when developing control algorithms. Net deviations should be considered as a sum of deviations due to heating (x_t, y_t) and wind deformation of the structure (x_w, y_w):

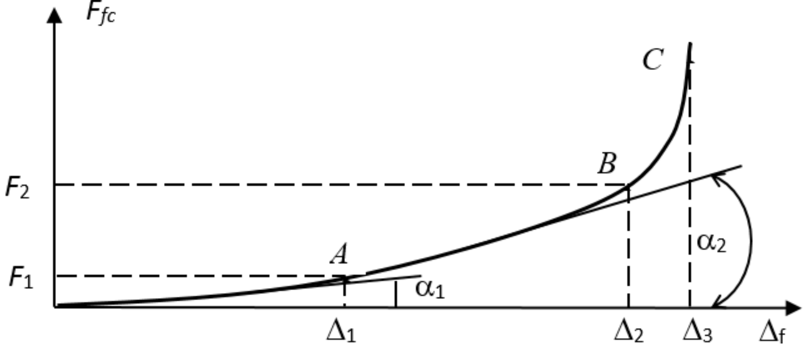

Figure 3. The reaction forces of concrete: F_{fc} - force of reaction; Δ_f - deformation of form

$$x_\Delta = x_H + x_W = \delta_H \cos\alpha_H + \delta_W \cos\alpha_W ;$$
$$y_\Delta = y_H + y_W = \delta_H \sin\alpha_H + \delta_W \sin\alpha_W ,$$

where $\alpha_H = \psi(t)$ is the direction of sunlight heating; α_W is the direction of wind; $\delta_H = f_1(\Delta\tau, h, \alpha_H, \nu_W)$ is heat deformation; $\delta_W = f_2(h, \sigma_W, \nu_W)$ is wind deformation; ν_W is wind velocity; $\Delta\tau = \tau_H - \tau_C$ is difference in temperature between sunny and shady sides of the object; h is the complex elevation.

The platform turn caused by actions of external factors can be conveniently related with the coordinates of hoisting mechanisms by the following equations:

$$\alpha_g = arctg\left[\max\left(\Delta z_j^{(i)}\right)/R_j\right]; \quad \beta_g = \frac{2\pi}{n} i\left[\max\left(z_j^{(i)}\right)\right];$$

$$\psi_g = \frac{1}{n}\sum_{i=1}^{n}\left[arctg(C) - \frac{2\pi}{n}(i-1)\right];$$

$$C = \left(y_j^{(i)} - \frac{\sum y_j^{(i)}}{n}\right) \Bigg/ \left(x_j^{(i)} - \frac{\sum x_j^{(i)}}{n}\right),$$

where α_g, β_g are the angle and the direction of inclination; ψ_g is a platform torsion; R_j is the radius of jacks arrangement.

The characteristic feature of the MSC control is control limitations connected with structural features and technological control cycles. Maximal inclination of the platform with forms in a hoisting step cannot exceed the conicity of the forms panels. Maximal deviation of jacks' travel from the average hoisting step value is limited by the magnitude:

$$\Delta h_{\max} = \left| \left(h_j^{(i)}\right)_{\max} - \frac{\left(\sum h_j^{(i)}\right)}{} \right| \le \frac{\Delta D_j l_b}{2},$$

where Δ is a clearance at the bottom of the forms' panels; l_b is panels height.

Therefore, to control the MSC it is necessary to provide the measurement and compensation for wind and temperature influences upon the erected object. The complex lift control should be carried out with due account of limitations for controllability and provision for the trajectory minimal curvature. We suggest to correct the the platform position by inclining it in the direction opposite to the displacement; in order to eliminate the platform torsion it is suggested to use the backward wave method which resides on the sequential change of the platform inclination direction in each step of hoisting. As a result there appears a spiral motion of the forms in the direction opposite to torsion. This kind of control is based on the forms mathematical model that allows to combine complex condition parameters with controlling and disturbing influences.

3. Movements planning and the MSC control

When solving the tasks of control we consider the MSC as a completely observable multidimensional object having limitations for controllability. The complex control provides for the correction of the platform position in the process of hoisting. Proceeding from the complex features and properties we have chosen a two-level structure so as to control it [2]. The tasks of the upper level are the planning of complex movements with view of limitations for control and disturbing influences. Taking into consideration the intricacy of the complex control we suggest to plan movements by simulating the MSC hoisting with due account of the current condition, affecting disturbances and influence casual factors. The tasks of the upper level of control also comprise the formation of control actions and synchronization of the mechanisms motions. The tasks of the lower (executive) level include the development and refinement of control signals. Such structural organization of the MSC control allows us to achieve the pre-set quality of control and the required accuracy.

One of the main tasks of control is to plan the movements of the MSC, which incorporates movement trajectory development and formation of the control laws for lifting and adjusting mechanisms on its basis [3]. The trajectory for the platform and forms lifting is planned so that to eliminate the developed deviations by the end number of steps, to locate the platform on the designed axis and to ensure its horizontal position. Taking into consideration a monotonic character of the desired trajectory, smoothness requirements for the transitional trajectory and also restrictions for curvature determined by the conicity of the forms panels, the planned movement trajectory can be represented by two datum functions:

$$\delta(l) = \begin{cases} a_{12}l^2 + a_{11}l + a_0, & l < l_s \\ C_{21}e^{\lambda_{21}(l-l_s)} + C_{22}e^{\lambda_{22}(l-l_s)}, & l \ge l_s \end{cases}$$

where $C = [C_k]$ is a vector of the parameters being determined; $l_s = \left(b_1 + \sqrt{b_1^2 + 2\gamma b_0}\right)/\gamma$ is a conjugation point of the trajectory sectors.

To control the complex we determine coordinates of points $x_g^{(k)}, y_g^{(k)}$ and inclination angles $\alpha_g^{(k)}$ of the platform at the end of each step of lifting: $x_g^{(k)} = \delta(l_k)\cos\beta_g$, $y_g^{(k)} = \delta(l_k)\sin\beta_g$, $z_g^{(A)} + l_k$, here $l_k = k\,h_p$ is the height of lifting from the beginning of correction; $z_g^{(A)}$ is an altitude position of the MSC at the beginning of correction; h_p is step of lifting. The coordinates of the planned trajectory points at the end of each hoisting step are corrected with due account of temperature and wind deformation of the object:

$$\begin{cases} x_{tr}^{(k)} = x_g^{(k)} - x_\Delta^{(k)} = \delta(l_k)\cos\beta_g - \delta_H(l_k)\cos\theta_H - \delta_W(l_k)\cos\theta_W, \\ y_{tr}^{(k)} = y_g^{(k)} - y_\Delta^{(k)} = \delta(l_k)\sin\beta_g - \delta_H(l_k)\sin\theta_H - \delta_W(l_k)\sin\theta_W. \end{cases}$$

Taking into consideration kinematic and dynamic features of the mechatronic complex its control is developed on the basis of kinematic algorithms. The laws of time variation of the complex phase coordinates and its space location relative to the designed axis are described by the system of equations in the form of:

$$\begin{cases} z_g(t) = \sum_{i=1}^{k-1} h_g^{(i)} + \int_0^t v_g^{(k)}dt, \\ x_g(t) = \delta_g(l_k)\cos\beta_g - x_{sb}^{(k)}, \\ y_g(t) = \delta_g(l_k)\sin\beta_g - y_{sb}^{(k)}, \\ r_{mr}(t) = \sum_{i=1}^{k-1} r_{mr}^{(i)} + K_\varphi \int_0^t v_{pl}^{(k)}dt. \end{cases}$$

Adjustment of the platform position is a long process running through many steps of the MSC lifting, so it is convenient to calculate the platform inclination within a step on the basis of recurrent relationships:

$$\begin{cases} \alpha_g^{(k+1)} = \alpha_g^{(k)} + arctg\left(a_1 + 2a_1l_k + \Delta l\right), & l < l_s \\ \alpha_g^{(k+1)} = \alpha_g^{(k)} + arctg\left(\lambda_1C_1e^{\lambda_{21}\xi} + \lambda_2C_2e^{\lambda_{22}\xi}\right), & l < l_s,\ \xi = l_k + \Delta l - l_s. \end{cases}$$

The platform inclination angles $\alpha_g^{(k+1)}$ and $\beta_g^{(k+1)}$ being calculated during the process of motions design are used for forming lift value $h_i^{(k+1)}$ of each jack:

$$h_i^{(k+1)} = h_p + \Delta h_i^{(k+1)} = h_p + R_j \sin\left(\alpha_g^{(k+1)}\right)\cos\left(\frac{2\pi}{n} i + \beta_g\right).$$

Control actions $r_{rj}^{(k+1)}$ of mechanisms for radial displacement are calculated in each step of hoisting on the basis of high-altitude position of the platform $z_g(t)$, shift relative to the design axis x_g, y_g and with due account of inclination angle α_g. Moreover, the radius change of each MRD is synchronized with level of the platform position:

$$r_{rj}^{(k+1)}(t) = K_{mr} v_j t + x_g \cos\varphi_j + y_g \sin\varphi_j,$$

where $r_{rj}^{(k+1)}$ is radius change caused by the platform shift; φ_j is an angle of the *j*-th MRD location.

Control actions $h_i^{(k+1)}$, $r_{rj}^{(k+1)}$ are developed by the lower level of control uniting local control devices for hoisting units and mechanisms of radial displacement. Hoisting jacks control differs in using frequency induction drive with synchronization of operation. A hoisting jack (HJ) drive control must provide for the execution of a hoisting step with a pre-set speed and a smooth speed adjustment. The characteristic feature of the HJ drives is a high accuracy of control in a wide range of load change. Considering the analysis results of the drive dynamic properties the preference should be given to the system of a subordinate HJ control comprising the main speed circuit and the inner subordinate current circuit. Synthesis of the HJ drives regulators is performed by the method of a step-by-step correction with subordinate control. Factors calculation for exterior and interior circuit is performed for static modes of operation on the basis of the developed technique.

Characteristic feature of the MRD drive is that it has a three-position control with feedback in terms of position. In order to synchronize the operation of the MRD and the HJ a recurrent-transitory mode of drive operation is used; it meets strict requirements to the quality of control. Analysis of dynamic properties of the MRD has shown that the presence of a relay element results in the vibrating transient process connected with drive inertia. To improve dynamic properties of the drive we have developed a correction method according to which we first calculate the drive run-out value for the rated speed:

$$\delta_{ro}(t) = V_{mr}^{(nom)} T_{mr}\left(1 - \exp\left(-\frac{t}{T_{mr}}\right)\right) = 0{,}999 V_{mr}^{(nom)} T_{mr},$$

where $V_{mr}^{(nom)}$ is rated speed of the MRD; T_{mr} is time constant of the MRD. Then, according to $\delta_{ro}(t)$ we define structure and parameters of correcting device. As a result of synthesis we obtain a transfer function of correcting feedback

$$W_{cd}(s) = \frac{K_{cd} s}{T_{cd} s + 1},$$

where K_{cd} and T_{cd} are transfer coefficient and time constant of the correcting device determined by the value of drive run-out.

4. Conclusion

The described method of control makes the basis of algorithms for the form automatic control system. The difficulty of controlling a mechatronic complex is connected with the fact that it takes a lot of time to correct mistakes that occur during the process of lifting. Their elimination is only possible after 10-20 steps of lifting. Therefore it is necessary to forecast the behavior of the complex system under control on the basis of mathematical description with applying laws of control. The lifting trajectory for the platform and forms is planned so that to eliminate arisen deviations through the end number of steps, to maintain the platform along the designed axis and to ensure its horizontal position. The control influences formation is carried out on the basis of planning algorithms considering heat and wind impacts on the erected object. In the construction of industrial facilities the control accuracy of the mechatronic slip complex is 50 mm with the formwork lifting speed up to 12 m in 24 hours. The quality of the concrete surface eliminates the need for additional finishing, which saves effort and material consumption in construction works.

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