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## ROBOTIZATION OF SLIP FORM FOR MONOLITHIC CONSTRUCTION OF TALL BUILDINGS

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**Abstract:** The paper considers technological features of erecting monolith objects with a variable cross-section, presents the formulated requirements to the robotic complex and the principles of its construction and gives the complex structure. It has been shown that for the control of slip form it is advisable to use a two-level structure; the upper level tasks of which are planning the complex hoisting and synchronization of control mechanisms operation, and the tasks of the lower level incorporate development of control signals having been formed in the previous level. Great attention is paid to the problems of the robotic complex movements planning taking into account restrictions on control and disturbing influences affecting the structure being erected. In order to remove the complex deviation from the designed location we suggest the method of the planning of movements with due account of limitations for control and effects of disturbing influences to the structure being erected. In conclusion the paper deals with the problems of forming adaptive laws of for controlling joint coordinates ensuring development of the planned trajectory.

### 1 INTRODUCTION

Construction of objects for different purposes requires great labour consumption and a number of regulating operations especially for the structures with varying cross-section and wall width. From the standpoint of control slip forms for erecting objects with variable radius represent a multivariable system with a number of control organs. The position and the shape of the forms as an object of control is determined by the aggregate of external and internal effects. The loading irregularity of the forms working floor, imperfect forms geometry and some other factors result in the forms deflection with respect to the projected axis, the working floor inclination and friction forces change of the forms shields against the concrete. The volume and the tasks of the sliding forms automation is determined by the construction objects appearance, their shape geometrical parameters. The main tasks for sliding forms automation so as to erect object of conic shape are:

- information-measuring provision to control the forms erection;
- the forms mechanical trajectory planning with consideration of external effects and current condition;
- control of slip forms shields erection and radial displacement ;
- synchronized work of lifting jacks and mechanisms for the forms radial displacement;
- to keep all lifting jacks in the given plane and to fulfil overall control of jacks;
- compensations of disturbing effects on the control system actuating elements;

- adjustment of the forms position due to control of the working floor inclination within the range of shields taper.

The analysis of monolith construction technology has shown the expediency of designing mechatronic complexes on the basis of slip forms (MSC), they provide automation of the objects erection and continuous-cyclic placement and consolidation of concrete. Solution of the above mentioned tasks is possible on the basis of mechatronic complexes for monolithic construction.

## 2 THE CONSTRUCTION PRINCIPLE OF MSC

The principle of the mechatronic complexes by the kinematic, design and technological distinctions of the object controlled, the controls distinctions and also by the character and properties of the disturbing effects. 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 with help of radial displacement mechanisms (RDM) 6 providing adjustment of panels location.

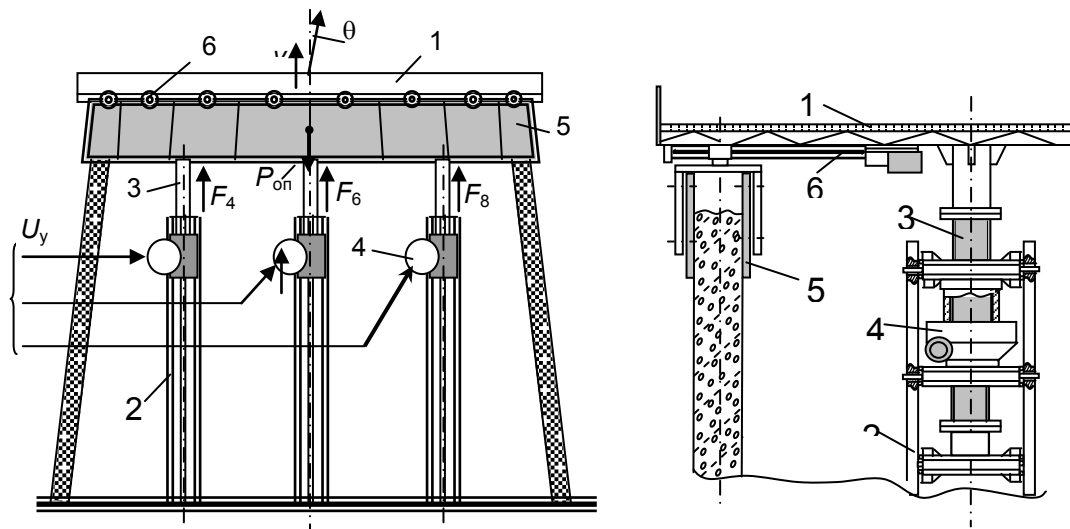


Figure 1: MCS on the basis of a slip form

For the purpose of lifting it is advisable to use frequency control electromechanical jacks, which allow 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 lifting the platform with forms during the process of concrete placement, change panels location when lifting, correction of the platform position when shifts and torsions occur, synchronization of the equipment operation.

The developed principles of the complexes construction make up the basis of the functional diagram for mechatronic complex control task to which is presented in Figure 2.

Information – measuring system provides control of the main parameters of the mechatronic complex condition. Laser system incorporating a laser set point device for the vertical (LDV) and a photodiode matrix panel (PMP) makes the forms measurements. The system of data processing first scans the photodiode panel PMP about the coordinate axis, records the results of scanning into the image storage area of the photopanel.

According to  $t_j$  this information boundary values of the photopanel lit area are determined  $(X_{\min}, X_{\max}, Y_{\min}, Y_{\max})$  and the coordinates of the forms position are calculated relative to the

construction lane:

$$X = 0.5(X_{\max} + X_{\min}), Y = 0.5(Y_{\max} + Y_{\min}).$$

When using two-beam laser control system the values of the coordinates of the beam center on each photopanel  $X_{1\min}, X_{1\max}, Y_{1\min}, Y_{1\max}$  and  $X_{2\min}, X_{2\max}, Y_{2\min}, Y_{2\max}$  become average.

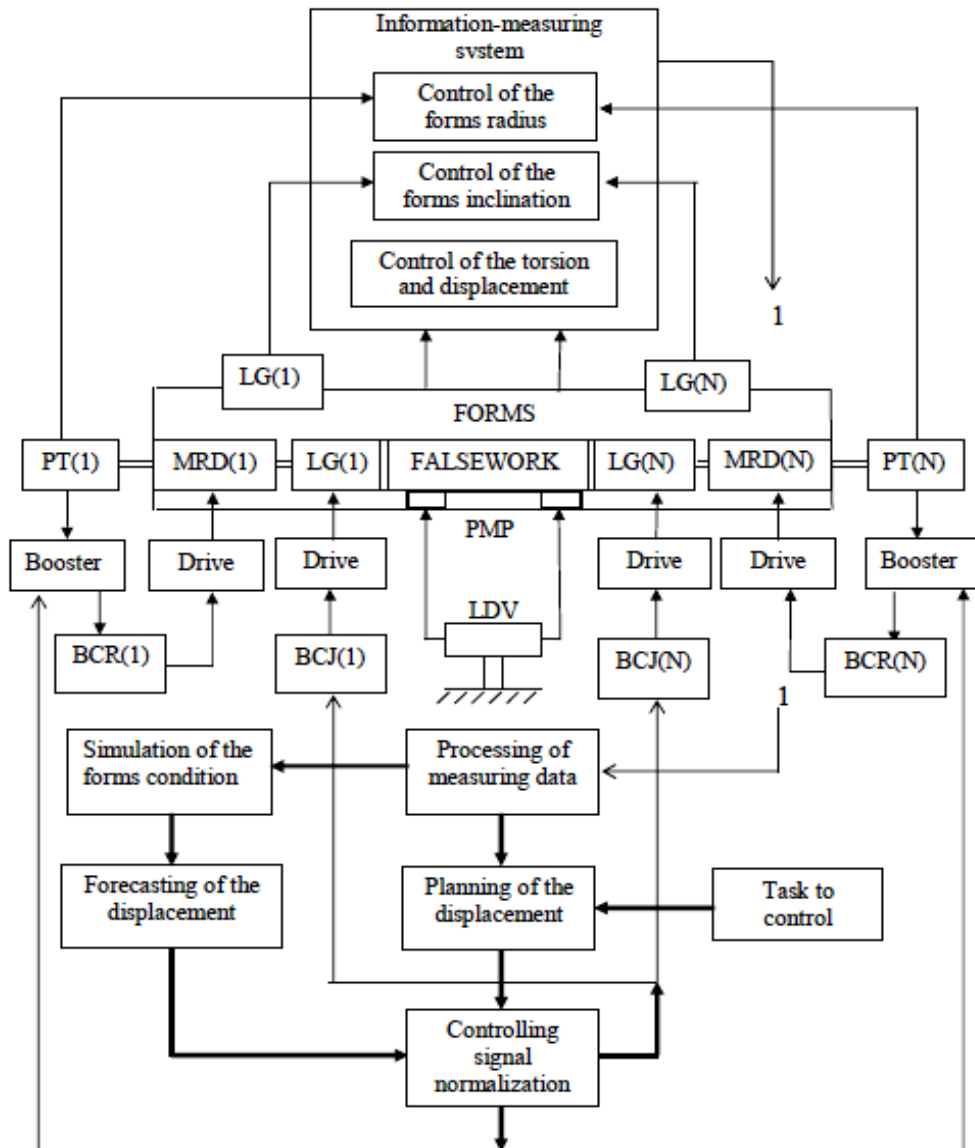


Figure 2: Functional diagram of mechatronic complex.

Checking the vertical position of the erected object and the platform position is carried out with laser devices equipped with photomeasuring panels. The laser device consists of two laser set-point devices for the vertical axis and two photoreceiving panels with modules for reading-out and processing data. Location of the laser beam center on the photoreceiving matrix is determined by the way of photopanel scanning. And the coordinates of the beam center are calculated from the formulae:

$$x_{pr} = 0,5 \left[ \left( 8(d_i^{(x)} - 1) + b_i^{(x)} \right) + \left( 8(d_l^{(x)} - 1) + b_l^{(x)} \right) - N_{pr} \right];$$

$$y_{pr} = 0,5 \left[ \left( 8(d_i^{(y)} - 1) + b_i^{(y)} \right) + \left( 8(d_l^{(y)} - 1) + b_l^{(y)} \right) - N_{pr} \right],$$

where  $d_i^{(x)}$ ,  $d_i^{(y)}$ ,  $d_l^{(x)}$ ,  $d_l^{(y)}$  are initial and last active bytes when scanning along the axes X and Y;  $b_i^{(x)}$ ,  $b_i^{(y)}$ ,  $b_l^{(x)}$ ,  $b_l^{(y)}$  are initial and last bytes corresponding;  $d_i$ ,  $d_l$ ;  $N_{pr}$  is the number of digits (in bits) on the photopanel.

On the basis of the beam location coordinates on the photoreceiving panels we determine the position of the platform center:

$$x_{pl} = x_p^{(0)} = 0,5(x_{pr}^{(1)} + x_{pr}^{(2)}) \cdot \cos \psi_p, \quad y_{pl} = y_p^{(0)} = 0,5(y_{pr}^{(1)} + y_{pr}^{(2)}) \cdot \sin \psi_p,$$

where  $\psi_p$  is the twist angle of the platform relative to  $Z_0$  axis.

On the basis of the obtained average values of the platform deviation from the designed axis we calculate modulus and the direction of displacement:

$$\delta_{pl} = \left[ (x_{pl})^2 + (y_{pl})^2 \right]^{1/2}; \quad \beta_d = \arccos \left( \frac{x_{pl}}{\delta_{pl}} \right) = \arctg \frac{y_{pr}^{(1)} + y_{pr}^{(2)}}{x_{pr}^{(1)} + x_{pr}^{(2)}}.$$

The data received from the photopanel make it also possible to determine the twist angle of the platform with the forms

$$\psi_p = \arctg \left[ (y_{pr}^{(1)} - y_{pr}^{(2)}) / l_{pr} \right],$$

where  $l_{pr}$  is the distance between photoreceiving matrices.

Vertical position of each jack of the forms is controlled by the hydrostatic system of levelling, which is equipped with level gauges LG(1) - LG(n), mounted on each jack frame. The coordinates of the level gauges LG(1) - LG(n) disposition are:

$$x_i = (R - h / \operatorname{tg} \varphi) \cdot \cos(2\pi i / n),$$

$$y_i = (R - h / \operatorname{tg} \varphi) \cdot \sin(2\pi i / n), \quad z_i = h \pm \delta_i,$$

where  $x_i$ ,  $y_i$ ,  $z_i$  are the coordinates of the level gauge,  $n$  is a number of jacks,  $R$  is the forms radius in the construction base,  $\varphi$  is a slope of the construction,  $h$  is an elevation mark of the forms working floor,  $\delta_i$  is a position of the  $i$ -th jack relative to the working floor. The vertical position of the forms centre is determined as an arithmetic mean of the elevation position of  $z_i$  jacks:

$$z_0 = \sum_{i=1..n} z_i / n.$$

The platform deviation is closely connected with disturbance of its horizontal position therefore a hydrostatic leveling device has been introduced into the system. It permits checking the platform deformations and the swivel angle and also deviations of some jacks relative to others. Using level

detector readings  $\Delta z_{ld}^{(i)}$  we determine upper and lower marks of the platform hoisting jacks position

$$\Delta z_{hj}^{(\max)} = \max(\Delta z_{ld}^{(i)}); \quad \Delta z_{hj}^{(\min)} = \min(\Delta z_{ld}^{(i)}) \rightarrow i = 1, 2, \dots, n$$

and calculate the platform swivel angle and the direction of the swivel angle vector:

$$\alpha_p = \arctg \left( \frac{\Delta z_{ld}^{(\max)} - \Delta z_{ld}^{(\min)}}{4R_{hj}} \right), \quad \beta_p = \frac{2\pi}{n} \left[ i \left[ \max(\Delta z_{ld}^{(i)}) \right] - 1 \right].$$

The data about the jacks' deviation  $\Delta z_{hj}^{(i)}$  from the horizontal plane are used to synchronize movements of the hoisting jacks. To provide the platform correcting inclination hoisting jacks' speeds are set according to the required swivel angle  $\alpha_p^*$ :

$$v_{hj}^{(i)} = v_p \left[ 1 + R_{hj} \cdot \sin \alpha_p^* \cdot \cos \left( \frac{2\pi}{n} (i-1) - \beta_p \right) \right],$$

where  $v_p$  is the average speed of the platform hoisting.

Measurements of jack frames radial displacements is fulfilled by potentiometric or photoelectric encoding transducers PT(1)–PT(n). The measurement accuracy of these transducers must be  $\pm 1-2$  mm. When considering the system dynamic characteristics there transducers can be regarded as inertia free links. Measurement data processing allows to determine parameters of the mechatronic complex condition and the construction being erected:  $X_0, Y_0$  deviations from the construction line, the forms torsion angle  $\alpha$ , the forms inclination angle  $\gamma$ , the forms average radius  $R_h$ .

Taking into account complexity of MSC as an object of control, a great number of disturbing and adjusting influences, restrictions for control it is of interest to consider the problems of the complex control which include planning its motions, development of the laws of control, solution of the problem of mechanisms operation synchronization.

MSC is a multimeasuring controlled object the states of which at any period of time can be described by the system of equations

$$\begin{cases} \bar{U}_{hj} = [U_{hj}^{(1)}, U_{hj}^{(2)}, \dots, U_{hj}^{(m)}]; \\ \bar{U}_{rm} = [U_{rm}^{(1)}, U_{rm}^{(2)}, \dots, U_{rm}^{(n)}]; \\ \bar{Y}_{ms} = [x_n, y_n, z_n, R_o, \alpha_n, \beta_n, \theta_n]; \\ \bar{F}_1 = [F_w, F_s], \bar{F}_2 = [Q_h, F_{mp}, F_{cu}, F_{mm}, F_\sigma], \end{cases}$$

where  $\bar{U}_{hj}, \bar{U}_{rm}$  are the vectors of control actions directed to the hoisting jacks and the mechanisms of radial displacement (MRP);  $\bar{Y}_{ms}$  is the vector of the output parameters of the MSRS state;  $\bar{F}_1$  and  $\bar{F}_2$  are the vectors of disturbing influences acting on the erected construction and the mechatronic system.

The system state at any moment is determined by the coordinates  $x_p, y_p, z_p$  of the center position in the system of coordinates of the erected object  $X_o Y_o Z_o$ , by the forms radius  $R_o$ , by the angle of the platform inclination  $\alpha_p$ , by the direction of the inclination vector  $\beta_p$  and by the platform turning (twisting) angle  $\psi_p$  round the vertical axis. For the structures of conical shape the relation between radius  $R_o$  and the object height has the form of

$$R_o = R_o^* - (h \cdot \operatorname{tg} \varphi_o),$$

where  $R_o^*$  is the radius of the structures at zero mark.

The process of the system operation is accompanied by influencing on it several kinds of disturbing influences. The first group comprises influences leading to deformation of the erected structure and displacement of the platform with the forms. They cover influence  $F_s$  connected with the structure sun-heating and influence  $F_w$  caused by the wind load. Due to the temperature difference  $\Delta \tau = \tau_s - \tau_c$  of the sunny and shady sides there occurs deformation of the structure and its deviation from the designed axis. The deviation quantity  $\delta_s$  is the function of the height  $h$ , the object diameter  $D$ , the walls width  $b$ , and

the period of heating  $t_s$ :  $\delta_s = f_s(\Delta\tau, h, D, b, t_s)$ . In order to evaluate the influence of the object temperature gradient on the MSRS operation we have introduced the coefficient of deformation, which is calculated by the formula:  $k_d^{(s)} = h \cdot \varepsilon_s / (16\pi \cdot R_o)$ . The platform deviations connected with temperature heating will be

$$\Delta x_s = 0,5k_s^{(h)} \cdot h \cdot \Delta\tau \cdot \text{Cos}\theta_s; \Delta y_T = 0,5k_s^{(h)} h \cdot \Delta\tau \cdot \text{Sin}\theta_m;$$

$$\Delta z_s = k_s^{(h)} \cdot R_o \cdot \Delta\tau; \Delta\alpha_s = k_s^{(\varphi)} \cdot \Delta\tau.$$

As a result of the wind load there occurs inclination of the structure by the angle of  $\alpha_w$  and deviation of the MSC platform center from the vertical. The deviation parameters can be evaluated by the formulae:

$$\Delta x_w = k_w^{(h)} \cdot F_w \cdot \text{Cos}\theta_w; \Delta y_w = k_w^{(h)} \cdot F_w \cdot \text{Sin}\theta_w,$$

where  $k_w^{(h)}$  and  $k_w^{(\varphi)}$  are the coefficients determined by the structure shape and its rigidity;  $F_w$  and  $\alpha_w$  are the quantity and direction of the wind load.

Net deviations should be considered as a sum of deviations due to heating ( $x_t, y_t$ ) and wind deformation of the structure ( $x_w, y_w$ ):

$$x_{sb} = x_t + x_w = \delta_t \text{cos}\alpha_t + \delta_w \text{cos}\alpha_w;$$

$$y_{sb} = y_t + y_w = \delta_t \text{sin}\alpha_t + \delta_w \text{sin}\alpha_w,$$

where  $\alpha_t = \psi(\text{time})$  is the direction of sunlight heating;  $\alpha_w$  is the direction of wind;  $\delta_t = f_1(\Delta\tau, h, \alpha_t, v_w)$  is heat deformation;  $\delta_w = f_2(h, \sigma_w, v_w)$  is wind deformation;  $v_w$  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 is convenient to connect with coordinates of hoisting mechanisms by equations:

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

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

where  $\alpha_g, \beta_g$  are the angle and the direction of inclination;  $\psi_g$  is a platform torsion.

The second groups of the disturbing influences constitute those applied to hoisting jacks and mechanisms of radial displacement. During the system operation hoisting jacks are under action of static and dynamic loads created by the weight of the platform, forms, equipment and materials:  $Q_\Sigma = \sum Q_i$  and also under the influence of friction forces  $F_{fr}$  and cohesive forces  $F_c$  of panels with concrete.

An important factor in lifting jacks work is the interaction of concrete formwork. In the early lifting platform effort sharply increases and reaches a maximum at the time of separation from the concrete formwork (Figure 3). With a further rise formwork occurs overcoming the forces of adhesion between the concrete and sliding formwork. Further, in the contact area and the friction force is observed decreases proportionally to the reduction of contact area.

When the platform lifts, the load changes due to concrete – panels interaction. During the operation irregularity of hoisting jacks' loads can achieve 75-86% that results in violation of the platform horizontal displacement, its deviation from the designed axis and twisting of the platform with forms. Such condition

of hoisting jacks work 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 when the forms' elements deformation takes place. When synchronization of operation of hoisting and adjusting units is broken, then reaction forces of concrete additionally act on the RDM and they have a non-linear character (Figure 4). This causes 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 coordinated with curvature of the walls being erected.

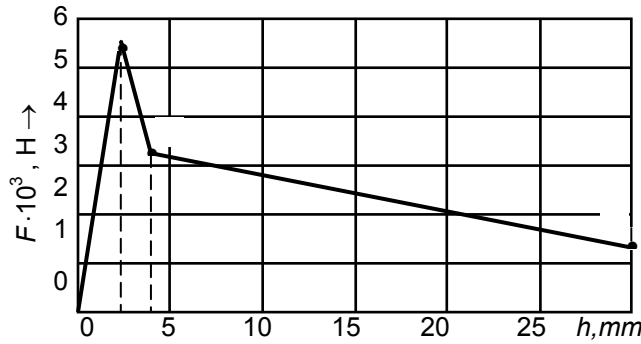


Figure 3

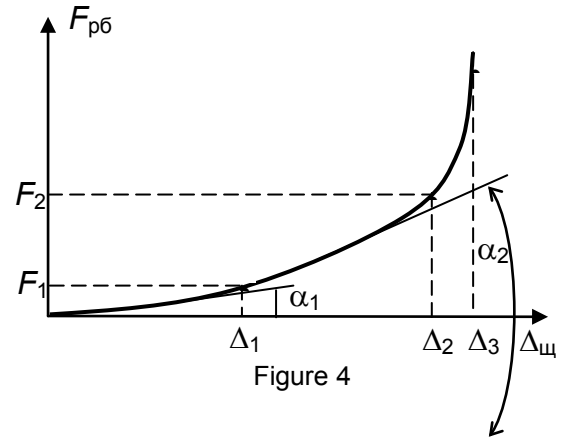


Figure 4

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

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

where  $\Delta$  is a clearance at the bottom of the forms' panels,  $l_b$  is panels height,  $R_j$  is the radius of jacks arrangement.

Therefore, to control the MSC it is necessary to provide measurement and compensation of wind and temperature influences upon the object being erected. 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 position by the way of the platform inclination in the direction opposite to displacement, and in order to eliminate platform torsion it is suggested to use the method of backward wave which resides in 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, which performs connection of the complex condition parameters with controlling and disturbing influences.

### 3 THE MATHEMATICAL MODEL OF MSC

On the basis of the slip forms dynamic characteristics and disturbing effects a mathematical model of the complex has been developed (Figure 5).

It makes possible to perform analysis of dynamic characteristics and forecast the forms deviations during the process of its lifting. The mathematical model presents channels controlling the forms lifting and its radius changing, it also reflects connections between them. The controlling effects are voltages of the forms jacks control  $U_h$  and radial displacement mechanisms control  $U_r$ . Coordinates of the forms

centre  $Z_0, X_0, Y_0$  and its radius  $R$  are considered as adjustable values. While controlling the forms lifting the following external actions are taken into consideration:  $F_r$  – the pressure of the lower gripper onto the jack bar;  $F_w$  – the forms weight;  $F_{fc}$  – friction of the forms shields;  $F_v$  – wind load;  $F_t$  – additional forces due to thermal gradients. Influence of the force loads on the forms is described by the transfer functions:

$$W_r^{(f)}(s) = k_{fr}; \quad W_w^{(f)}(s) = \frac{k_{fw}}{T_{fw}s + 1}; \quad W_{fc}^{(f)}(s) = \frac{k_{fc}}{T_{fc}s + 1}.$$

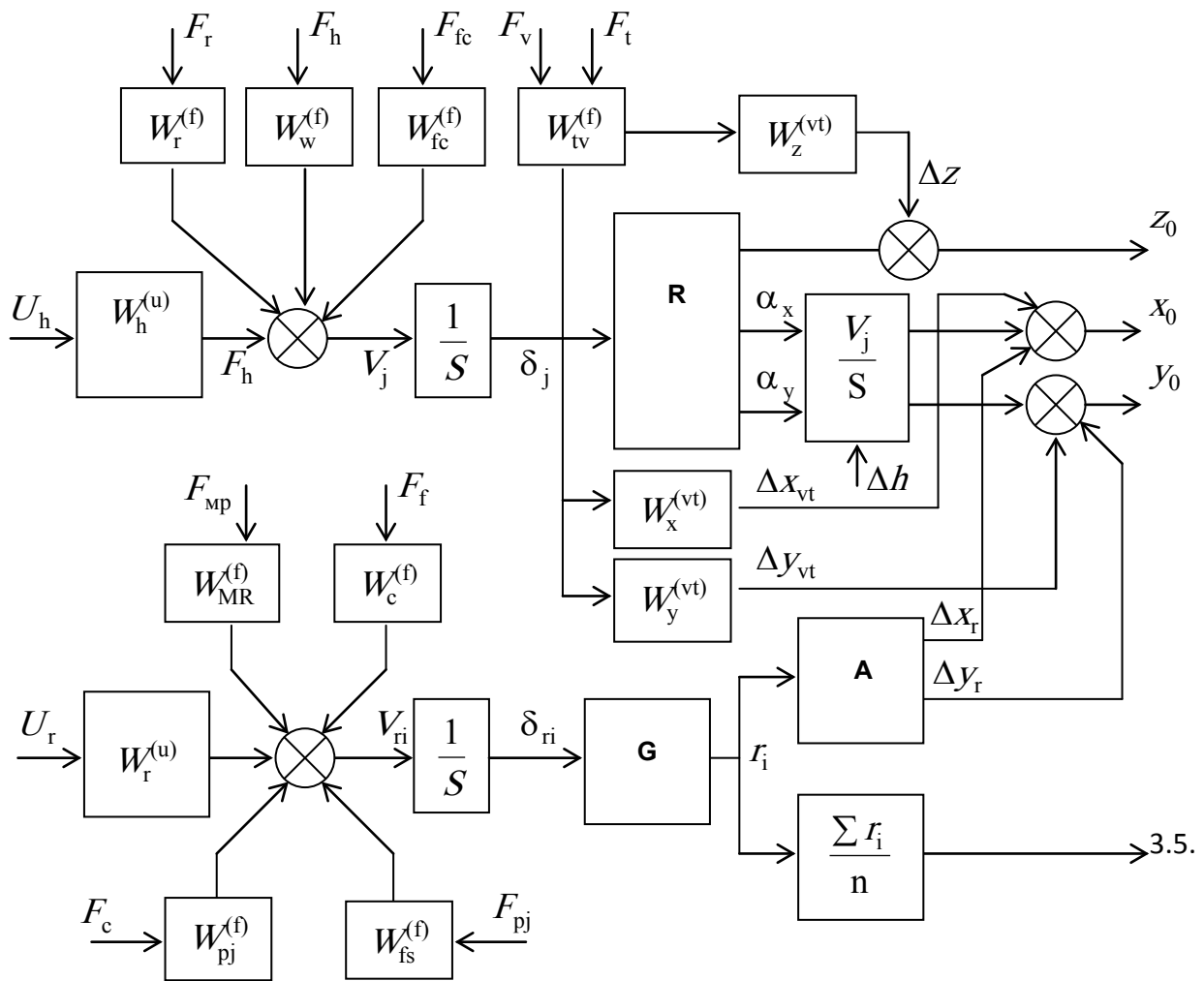


Figure 5: Mathematical model of the complex

Influence of wind and thermal effects on the forms position can be represented by transfer functions:



$$W_{vt}^{(f)}(s) = f_{vt}(s); W_z^{(vt)}(s) = k_{vz} + k_{tz}; W_x^{(vt)}(s) = k_{vx} + k_{tx}; W_y^{(vt)}(s) = k_{vy} + k_{yz}.$$

The forms jacks displacement on the step  $\delta_i$  is described by the transfer function

$$W_h^{(u)}(s) = \frac{k_{uh}}{(T_{uh}s + 1)s}.$$

Coefficients matrix  $R$  has the dimensional representation of  $3^*n$  and sets up the parameters interrelation. The values of it elements are determined from the formulae:

$$k_{zi} = 1/n; k_{xi} = [2 \cos(2\pi i/n)]/R_h; k_{yi} = [2 \sin(2\pi i/n)]/R_h.$$

While simulating the channel of mechanisms for radial displacement the following external effects are taken into consideration:  $F_{mp}$  – the mechanism reaction to the displacement forces;  $F_c$  – concrete reaction to the shields displacement;  $F_{pj}$  – elasticity force of jacks;  $F_f$  – shields friction force. The influence of these external effects is described by the transfer functions:

$$W_{MR}^{(f)}(s) = \frac{k_{uh}}{(T_{uh}s + 1)s}, W_c^{(f)}(s) = \frac{k_{uh}}{(T_{uh}s + 1)s}, W_{pj}^{(f)}(s) = \frac{k_{uh}}{(T_{uh}s + 1)s}.$$

The effect of the controlling voltage  $U_r$  on the operation of the radial displacement mechanisms is

described by the transfer function  $W_c^{(f)}(s) = \frac{k_{uh}}{(T_{uh}s + 1)s}$ . Transformation functions  $G$  and  $A$

represent matrices of coefficients describing effects of the shields radial displacement on the parameters of the state.

#### 4 CONCLUSIONS AND RESULTS

The approaches and methods of the MSC control discussed in the paper are based on the investigations carried out by the authors in different periods for solving the tasks of monolith construction automation. The presented principles of the MSC control can be used when developing automation projects for erecting monolith objects with a variable radius (chimneys, TV and observation towers, cooling towers etc.). The suggested method of designing the complex lifting makes it possible to develop control algorithms with due account of restrictions for control and disturbing influences acting on the structure. Computer simulation of the described algorithms and laws of the MSC control has shown the efficiency of the suggested methods of movements design and controlling actions formation.

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