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Analysis of the concurrent operation of excavator actuating mechanisms as the determining factor in increasing its productivity

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Abstract. The most effective methods of organizing construction work are complex mechanization and automation of construction. Complex mechanization allows selecting the machines participating in the construction process according to their productivity. In this regard, it is necessary to take into account the structural features of construction machines that affect the overall pace of work. In order to shorten the cycle time, the design of a modern excavator's hydraulic system ensures the combined operation of two degrees of mobility in pairs: platform-boom, boom-arm, and arm-bucket. When designing and creating a system for automatic control of excavator actuating mechanisms, it is necessary to take into account the interrelation and mutual influence of hydraulic drives when working together from a source of limited power, the pump station of an excavator. Such a time combination of operations is possible when carrying out transportation to move the bucket to load and unload, while soil excavation is performed by turning the handle or bucket, and in these conditions, a large load of the feeding power station does not allow combining these operations. The paper presents a structural diagram of the concurrent operation of two hydraulic excavator actuators, which reflects the existence of connections between the hydraulic motors of the actuators.

1 Introduction

When organizing the construction process, special attention is paid to the timely performance of construction work. One of the main types of construction works is earthwork, where a large number of machines are used, mainly excavators and bulldozers. The most effective methods of organizing construction works are complex mechanization and automation of construction. Complex mechanization makes it possible to select the machines participating in the construction process rationally in terms of their productivity. In this case, it is necessary to take into account the structural features of construction machines that affect the overall pace of works.

The structural feature of the hydraulic excavator is the combination of two working operations [1]: turning the platform and lifting the boom, lifting the boom and turning the

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handle, turning the handle and the bucket. These modes are used to improve the performance of an excavator and are only possible when carrying out transport operations (moving the bucket to load and unload), due to the large load on the feed pump during excavation.

In terms of working equipment management, the excavator is a 4-dimensional control object for actuators (platform turning, boom lifting, handle and bucket turnings), where the presence of interchannel connections is conditioned by the interaction of working equipment while changing the bucket spatial position and filling; it is also conditioned by the possibility of pairwise operation of hydraulic motors from one hydraulic pump [2]. When designing automatic control systems for excavators, it is extremely important to take into account the dynamic characteristics of the hydraulic drive when the excavator actuator mechanisms work together to ensure efficient operation modes.

Through the example of ЭО-4121 excavator, we have developed mathematical models (in the form of structures and computational models) of the concurrent operation of the three above-mentioned pairs of actuators using structural diagrams and computational models of actuator systems, hydraulic pump and algorithms for forming fluid flow rates [3].

2 Materials and methods

In our work, we used simulation modeling of the concurrent operation of platform drives turning and boom lifting, on computational models in the MatLab Simulink software environment. The generalized structure (Fig.1) presents channel operators in relation to control A_{11}, A_{22} and disturbing influences - C_{11}, C_{22}; operators B_{12}, B_{21} and C_{12}, C_{21} show cross-channel links manifested when two working mechanisms operate together.

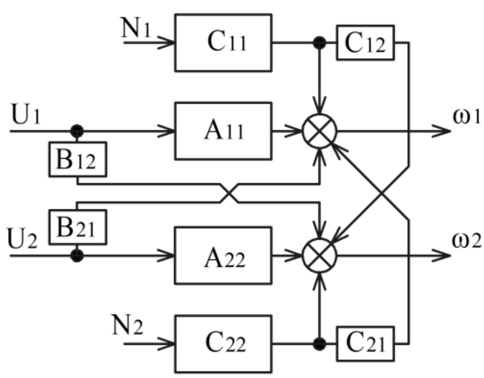

Fig. 1. The structure of the concurrent work of two simulation models.

It is analytically difficult to define the operators describing these connections. Therefore, we use the method of computational experiment [4-8]. Figure 2 shows the generalized structure of the computational model of the platform and the boom simultaneous operation dynamics, created in the MatLab Simulink software environment. Here, blocks *1,2* are models of the hydraulic drive of the platform and the boom, block *3* is the model of the hydraulic pump, block *4* is the model of the hydraulic distributor controlling the supply of fluid to the hydraulic motors of the actuators (PP-turning platform, S-boom), according to Table 1.

Table 1. Modes of hydraulic motors concurrent operation.

Flow limitation for hydraulic motors	
PP	S

$Qpp \le QH1$	$Qs \le QH2 + QH1 - Qpp$

Where Q_{H1}, Q_{H2} are flows of working fluid from sections of the pumping unit; *Qpp, Qs* represent supply of hydraulic fluid to hydraulic motors of the turning platform and the boom, respectively.

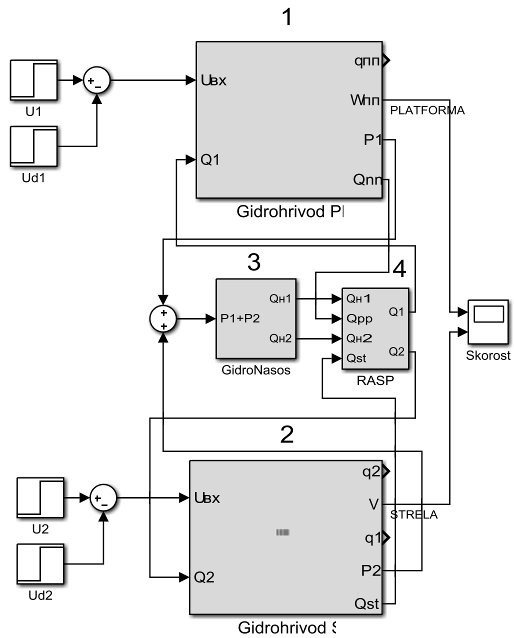

Fig. 2. Computational model for studying the dynamics of platform and boom simultaneous operation.

The presented model gives the opportunity to determine experimentally the operators shown in Fig. 1 from the analysis of transient characteristics in the two-dimensional system. When performing experiments, we use stepwise change in “small” and “large” control U_1, U_2 and perturbing N_1, N_2 influences.

3 Results

It has been experimentally established that during simultaneous operation of the hydraulic drives of the turning platform and the boom, the boom dynamics is significantly influenced by the degree of load of the hydraulic drive of the rotary platform [9]. This is explained by the fact that the amount of hydraulic fluid flow to the hydraulic motor of the boom is determined by the capacity of the two pump sections, except for the required flow rate of the hydraulic motor of the turning platform (Table 1). The hydraulic motor of the turning platform runs off one section of the pump unit only, so the boom does not affect the dynamics of its operation.

Using the computational model (Fig. 2), we obtained many transient characteristics reflecting the concurrent operation of the turning platform and the boom (Fig. 3.a, b).

When experiments were carried out, the same control influences $U_1 = U_2$ were simultaneously supplied to the inputs of both degrees of mobility. At the time $t = 3s$ (after the transient processes were completed), an additional stepwise control influence $U_{1D} = -0.3U_1$ was supplied to the input of the rotary platform model. This corresponds to the reduction in supply of hydraulic fluid to the platform hydraulic motor. In dynamic characteristics, this is reflected by 11% decrease in the speed of the rotary platform in statics (curve 1); the dynamic emission is 9%, while the boom speed in statics is increased by 29% (curve 2), and the transmission ratio of the boom as a separate control object increases by 39%. The performed experiment corresponds to the operation mode of the two-dimensional control object "in small". We determined interchannel dynamic connections of the *k-th* actuating mechanism influence on the *i-th* link; they can be represented as links of the second order:

$$W_{ik}(p) = \frac{k_{ik}}{T_{ik}^2 \cdot p^2 + 2 \cdot T_{ik} \cdot \xi_{ik} \cdot p + 1}, \tag{1}$$

where the parameters vary depending on the magnitude of the jump U_{1D}. It was experimentally established that when jump U_{1D} value varies from $-0.4U_1$ to $-0.1U_1$, the parameters of the transfer function change in accordance with the data in Table 2.

Table 2. Dynamic link $W_{ik}(p)$ parameters.

U_{1D}	T_{ik}, s	ζ_{ik}	k_{ik}, rad/V·s
$-0.4U_1…-0.1U_1$	0.04…0.15	0.59…0.35	0.005… 0.0039

If there is no supply of the power fluid to the hydraulic drive of the turning platform, the transmission ratio of the boom doubles, taking the value of k_{OY2} = 0.068 rad / V · s, because in this case the entire flow from both sections of the pump unit is fed to the boom hydraulics. When the value of jump U_{1D} of the control influence varies from level U_{1D} = -0.5U1, the object switches to the "large" mode, because the dynamics of its operation is influenced by the non-linearity "level limitation", manifested in the spool valve. This leads to a change in the form of the transition characteristic (Fig. 3b), which allows us to conclude that the control object is nonlinear. At the same time, it is difficult to assess the dynamics by the type of the transition process.

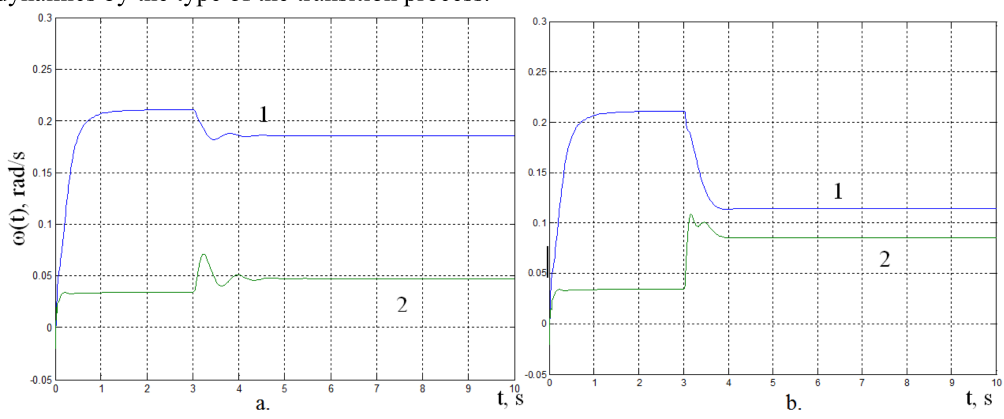

Fig. 3. Graphs of transient processes.

The study of the dynamics of the concurrent operation of the turning platform and the boom with variation of the hydraulic drive load [10] showed that in this case there is an interinfluence of these systems with each other.

Figure 4 shows the curves of transient processes in the turning platform drive (curve 1) and the boom drive (curve 2). By the time $t = 5s$, when transient processes in the boom drive were completed, stepwise control influence $U_1 = U_2$ was supplied to the input of the turning platform model. This causes reduction in the speed of the boom drive in static by

50%. At the time $t = 6s$, the load of the hydraulic drive of the turning platform $N_1 = 0.3N_{1nom}$ is set stepwise. This causes an additional decrease in speed by 13% in 0.4s.

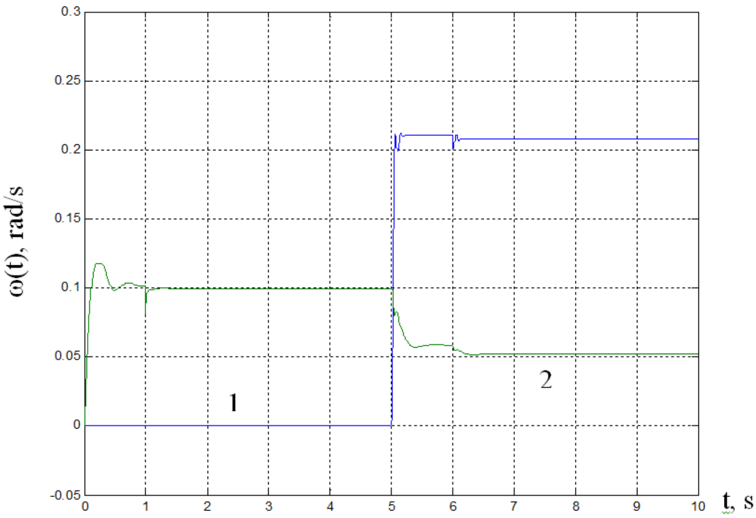

Fig. 4. Graphs of transient processes.

According to the form of transient processes, it was established that their dynamics of the *m-th* actuating mechanism influence on the *j-th* link can be represented, with a sufficient degree of accuracy, by a dynamic link of the second order with a transfer function: Interchannel dynamic links were defined, and they can be represented by links of the second order:

$$W_{jm}(p) = \frac{k_{jm}}{T_{jm}^2 \cdot p^2 + 2 \cdot T_{jm} \cdot \xi_{jm} \cdot p + 1}, \tag{2}$$

where the parameters vary depending on the magnitude of the jump N_1. It has been experimentally established that when the magnitude of the jump varies from $0.1N_{1nom}$ to $0.3N_{1nom}$, the parameters of the transfer function change in accordance with the data in Table 2.

Table 3. Dynamic link $W_{ik}(p)$ parameters.

N_{1nom}	T_{jm}, s	ζ_{jm}	k_{jm}, rad/V·s
$0.1\ N_{1nom}\ldots 0.3\ N_{1nom}$	0.02…0.2	0.2…0.45	0.005… 0.0039

When the load is increased by more than 0.3_{Nom_dist}, it is impossible to estimate the dynamics by the type of the transient process due to the action of the control object nonlinearities.

4 Discussion

It has been experimentally established that the nature and level of dynamic connections between the hydraulic excavator actuating mechanisms in their simultaneous operation depend on the magnitude of the control influence, causing a decrease in the hydraulic boom speed up to 50% and the degree of the drives load, which causes a further decrease in the operating speed. This allows us to conclude that the dynamic links between the actuators are unsteady.

5 Conclusions

The computational experiments carried out and the results obtained make it possible to assess the nature and level of dynamic links between hydraulic excavator actuating mechanisms, which are extremely important to ensure effective modes of excavator operation, both of the leading machine and of the entire set of construction machines in the organization of construction.

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