Increasing the Damping Capacity of Crane Electric Drive Systems When Moving Cargo with a Flexible Suspension

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***Abstract*—Mechanical vibrations that occur in industrial production mechanisms have a negative impact on both the electrical part and the mechanical part of the electric drive, which is a system of connected masses that move at different speeds, both translational and rotational. Bridge cranes contain mechanisms that are influenced by a load moving on a flexible suspension. Increasing the damping capabilities of control systems leads to a reduction in the load on both the electrical and mechanical parts of the crane. There is also an increase in the reliability of the structure as a whole and the safety of its maintenance and operation. The work proposes a method for limiting load oscillations, one is based on regulating the acceleration of the trolley through corrective feedback signals using a block operating according to the rules of fuzzy logic. The use of the proposed system showed good results.**

Keywords— flexible suspended load, electric drive, vibration damping

I. Introduction

The process of moving cargo on a flexible suspension in all areas of industry and during the construction of facilities is carried out by lifting and transport devices. The most popular among them are overhead cranes. Typically, lifting-and-transport mechanisms operate on the basis of similar movements, each of which is a complete operation. The formation of transient processes of starting and braking of these devices directly depends on the deviation of the load from the equilibrium position to the side. When the device moves, the load is initially deflected in the direction opposite to the movement. As you approach the set speed of the drive of the movement mechanism, the acceleration of the suspension point decreases to zero and, as a result, the oscillations of the load gradually attenuate due to the action of resistance forces. The presence of an oscillating load in the system leads to an increase in the load on the movement drive and the metal structure of the entire device, while the formation of load movement trajectories occurs chaotically and ensuring accurate positioning of the load becomes impossible. The listed phenomena lead to a decrease in the performance of the lifting and transport mechanism. Rocking ladles with molten elements poses a particular danger. Currently, there is significant interest in the issues of ensuring damping of load vibrations [1-3].

The systems used for crane mechanisms changed as they were improved. DC motors, due to their high control capabilities, found long-term leading use in mechanisms of this type, until the advent of more advanced control systems for asynchronous motors, such as frequency-controlled ones [4, 5].

To regulate the speed without ensuring smooth operation, asynchronous motors with a wound rotor were used on the moving and lifting mechanisms. In them, the change in speed was facilitated by the introduction or removal from the rotor circuit of additional resistances, which became very hot during operation. Significant energy losses were observed at the resistances, and the described processes also resulted in a constant need for maintenance of the resistance units. The development of a frequency converter made it possible to create an optimal control system, which, with small dimensions compared to the systems considered, ensured smoothness and a wide range of speed control [6, 7].

II. State of the Art

The use of frequency converters to regulate the speed of movement of crane mechanisms has made it possible to use asynchronous motors with a squirrel-cage rotor at various drive loads and process modes and has also led to an improvement in the dynamics of the crane operation as a whole [8, 9]. Crane mechanisms use both scalar and vector control systems. A significant number of works are devoted to the study of these systems with correction units that make it possible to improve the original control system and achieve energy saving, improve dynamic and other indicators of the electric drive [10, 11].

Since pendulum oscillations of a load suspended on a rope adversely affect the operation of movement mechanisms, it is necessary to use such methods of controlling the transient processes of starting and braking, with the help of which it is possible to ensure the completion of these processes with minimal deviation of the load from the equilibrium position.

An automatic method for controlling the actuators of an overhead crane, in which the current location of the load is determined, under conditions of initial unknown parameters of the transported load and external disturbing influences, is presented in [12]. An approach is proposed that combines the

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ability to determine the current position of the trolley and at the same time allows for damping vibrations of a suspended load. The proposed methodology is based on simplified adaptive control. The control system uses sensors that record the location and speed of the movement mechanism, data on the magnitude of the linear acceleration of the load and the angle of deviation of the load suspension from the vertical plane. Despite the obvious advantages, the system is overloaded with sensors that have some temporary errors in measurements.

In [13], a universal controller was proposed for damping load vibrations when installed on site, both AC and DC motors, which can be used in control systems for the movement mechanisms of cranes of any type. The correct functioning of the proposed controller was tested on a model simulating a load suspended on a cart, which is a mathematical pendulum in which the suspension point is movable. The process of acceleration or deceleration of the mechanism for moving the load was accompanied by acceleration of the movement of the load, the magnitude of which directly depends on the value of the torque of the electric motor. Since the moving load is affected by inertial forces, this phenomenon leads to the deviation of the load from the vertical axis. The deviation occurs in the direction opposite to the movement of the trolley. After the movement of the cart reaches the nominal speed value, the acceleration will be zero, and the oscillations due to the influence of resistance forces will gradually die out.

The use of an adaptive controller operating on the basis of fuzzy rules to dampen vibrations that occur during flexible suspension of transported cargo is considered in [14]. The proposed method is based on creating a fuzzy model that operates using the parameters of the crane mechanisms according to the principle of a neural network. After debugging the model, an adaptive algorithm is introduced into it, the functions of which include adjusting the parameters of the system, in particular its fuzzy part, which operates on the basis of machine learning. The proposed method requires significant system resources, since this approach requires storing information, due to the fact that the neural network constantly accesses it to improve the results obtained.

III. Outlook of the Work

* Design of a construction of the classical control system for the moving mechanism for cargo on a flexible suspension.

* Design of the block for damping the load oscillations.

* Modelling of that proposed control system, during the changes of the input parameters: the length of the suspension and the mass of the cargo.

IV. Main Description

When developing the proposed solution, a vector control system was taken as a basis, which has a number of significant indicators compared to a scalar control system; its important advantage is the simpler mathematical apparatus necessary to implement vector control. Also, one of the positive aspects of vector control is the ability to regulate transient processes. The creation of the proposed control system for the trolley movement mechanism began with its development in the MATLAB Simulink environment, based on typical dependencies of a vector control system and preliminary calculation of the parameters of an asynchronous motor. During calculations and modeling, the reduced moment of inertia of the loaded trolley was considered. The computer model of the control system for the electric drive of the overhead crane trolley, implemented in Simulink, is shown in Fig. 1.

In the circuit, to control the processes occurring in the electric drive, a three-phase frequency converter is used, which includes an inverter, the implementation of which is based on a three-phase bridge circuit containing IGBT transistors and freewheeling diodes. The role of the rectifier in the model is played by a constant voltage source, the use of which allows to simplify the modeling of the control system. At the same time, the adopted simplification does not affect the validity of the modelled to the processes occurring during the modeling and does not affect the quality of the model. This is guaranteed by the fact that the frequency converters sold in the modern market provide a stable voltage level of the internal DC link.

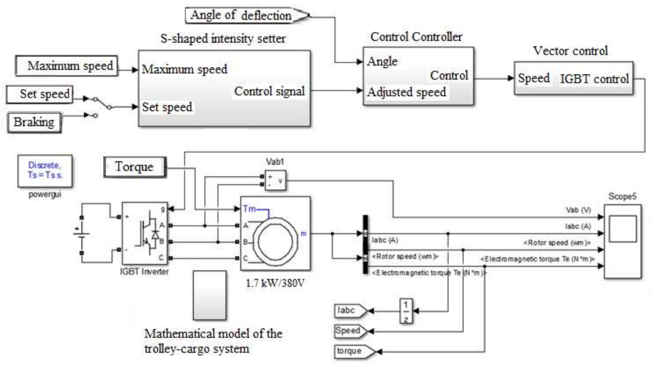

Fig. 1. Proposed control system.

A fixed voltage value is set as output of the element, marked as a DC power source in the model. The required output voltage value was calculated as the 3-phase full wave rectified linear AC voltage, in this case $380\sqrt{2}$ minus the voltage drop in the rectified voltage average value and the rectifier semiconductor devices, usually considered 1.5 V at each device. That will be considered the DC link voltage inside the frequency converter.

During the modeling process, the parameters of the electric motor, calculated according to its nominal parameters, are considered fixed values inside the 1.7 kW/380V block, which performs the functions of an asynchronous motor, remain unchanged. The control signal of the inverter is the value of the pulse generated in the vector control system. The signal arriving at the inverter generates a command to turn on certain keys of the IGBT transistor.

A vector control system assembled in the Matlab environment, obtained on the basis of the mathematical apparatus of classical vector control, is shown in Fig. 2.

During the modeling process, the operating cycle of the electric drive of the trolley was formed as follows: upon completion of lifting the load by the lifting mechanism, the trolley with a flexible suspended load is started. The presence in the circuit of an S-shaped intensity controller (Fig. 3) makes it possible to ensure a smooth increase in the speed of the cart, avoiding the possible shock that often occurs during the initial movement of the trolley. Using an intensity setter makes it possible to avoid sharp accelerations at the initial moment of start-up, since in a real object, in the gearbox and other components, there are gaps between parts that affect the intensity of acceleration. The use of a setter in the control system will also allow the trolley to smoothly continue moving with a given acceleration, which will directly depend on the mass of the load and the length of the suspension. The time of the cart acceleration process corresponds to the time from the moment the cart is started, that is, from zero speed until its nominal values are reached. At the acceleration stage, a unit is connected to the control system that dampens load vibrations.

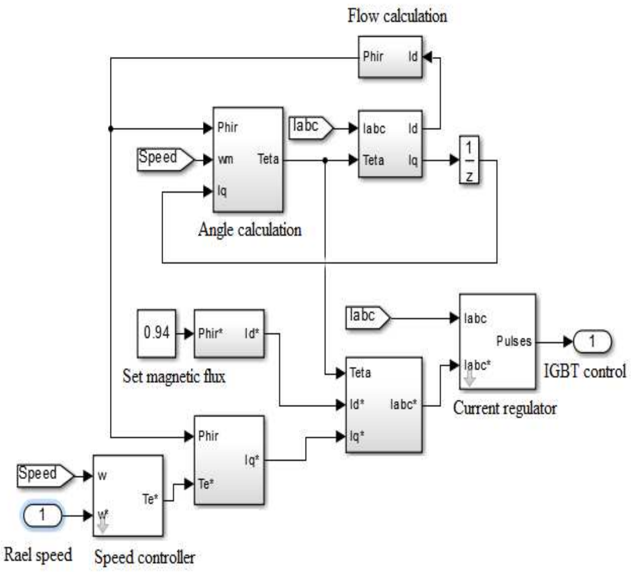

Fig. 2. Vector type system.

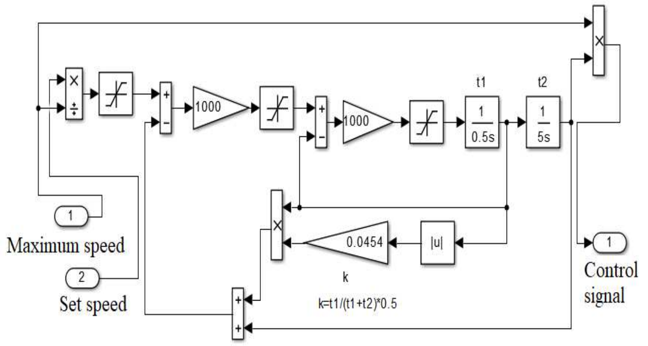

Fig. 3. Intensity selector.

In the mathematical model, the described algorithm is implemented by a controller present in the control system for the trolley movement drive (Fig. 4).

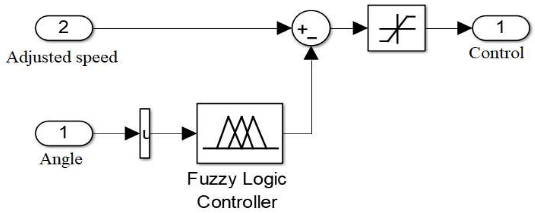

Fig. 4. Controller included.

The control controller contains a developed Fuzzy Logic Controller block (Fig. 5), which operates on the basis of fuzzy logic rules. For correct operation of the fuzzy controller, only indicators of the angle of deflection of the cable on which the load is suspended using a load-grasping device are required.

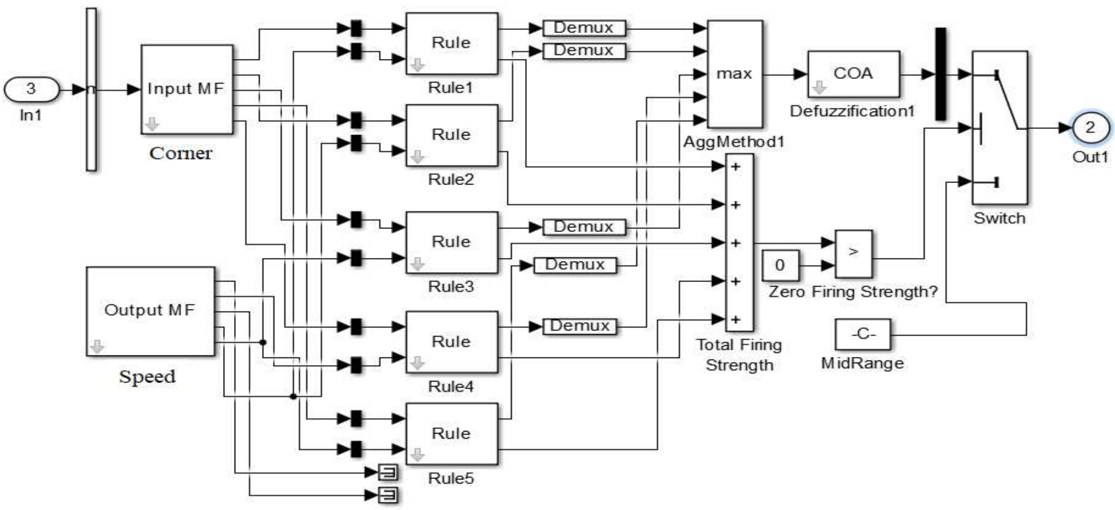

Fig. 5. Internal structure of the Fuzzy Logic Controller block.

Based on the developed rules, listed in Table 1, a control signal is generated at the controller output. The generated signal is one of the input signals supplied to the adder. The second input signal to the adder is the signal generated by the S-shaped intensity generator. The value obtained at the output of the adder is fed to the input of the block that implements the vector control system.

Analysis of the developed rules shows that the more the load tries to deviate from the vertical position, the higher the value of the control action of the controller formed at the output, implemented on the basis of the presented fuzzy rules, and the more significant will be the value of the signal arriving at the adder, after which the control signal is generated.

The cart acceleration process consists of two phases. At the first stage, a process occurs when the cart just begins to move at a given speed through an S-shaped intensity controller. At the very beginning of the acceleration of the moving mechanism, the flexible suspended load is deflected by a certain angle; when this phenomenon is detected, the fuzzy controller is activated. In this case, the value of the signal generated at the output of the fuzzy controller is supplied with a minus sign to the adder, where the second signal will be the value of the speed task generated at the output of the S-shaped intensity controller; these actions lead to limiting the rate of speed increase by the mechanism for moving the load. With this process, the moving flexible load will always be behind it when the trolley moves. The next stage is the process that occurs at the end of the period of operation of the S-shaped intensity generator. During its operation, a compensated control signal has accumulated in the controller, which enters the control system, which causes the load to return under the trolley, while preventing its movement from going into an oscillatory process. Now the acceleration rate, which was previously set by the intensity setter, will depend solely on the fuzzy controller. The movement mechanism will be characterized by a slower speed increase, that is, its smooth approach to a given parameter. When phenomena occur, the load will begin to catch up with the cart and, if no measures are taken, the movement of the suspended load will take on an oscillatory character. As the load enters under the trolley, the controller begins to issue control signals to the input of the block that implements vector control, which leads to the damping of the kinetic energy of the load. In this case, the difference between the position of the trolley and the position of the load in space is gradually compensated, and the load takes on a vertical position. Braking of the trolley with suppression of load vibrations occurs similarly to the described principle.

TABLE I. Basic rules

Rule number	Rule
1	If (Angle is negative) then (Speed is slightly negative)
2	If (Angle is slightly negative) then (Speed is slightly negative)
3	If (Angle is slightly positive) then (Speed is slightly positive)
4	If (Angle is zero) then (Speed is zero)
5	If (Angle is positive) then (Speed is slightly positive)

The operation process of the fuzzy input system is carried out in the following sequence:

- fuzzification stage – a process associated with the definition of terms. The developed model uses the following linguistic terms “negative”, “small negative”, “zero”, “small positive”, “positive”.

- aggregation stage - a process aimed at determining the weighting coefficient for each of the terms listed at the previous stage. To find the degree of truth of terms, triangular membership functions were chosen due to the simplicity of their mathematical expression;

- activation stage – the process during which the membership function for sub conclusions is determined;

- accumulation stage – the process of functioning of the rule base. At “negative” and “small negative” angle values, a “small negative” speed signal is generated. At “positive” and “small positive” angle values, a “small positive” speed signal is generated. If there is no deviation angle, then there is also no correction signal. The range of terms is specified within the boundaries of the input variables;

- defuzzification stage – the process of converting fuzzy values into control signals.

The structure of the defuzzification unit is shown in Fig. 6.

The model of the “cartload” block in the Simulink environment, necessary to receive a signal of the angular position of the load, is shown in Fig. 7. This block allows you to track the dynamics of the movement of the cart and cargo. The diagram gives a visual representation of the physical processes occurring in the system when moving cargo.

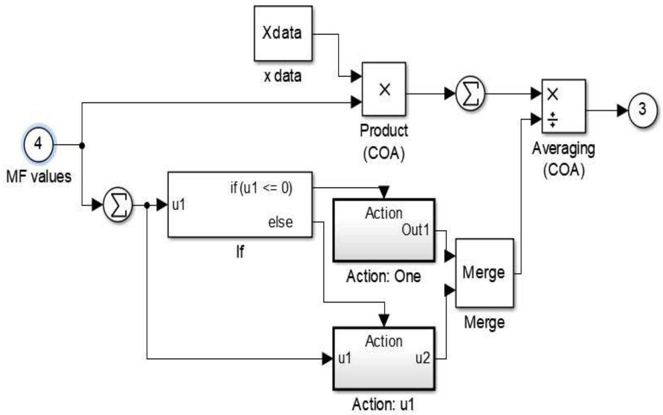

Fig. 6. Implementation of the Defuzzification block.

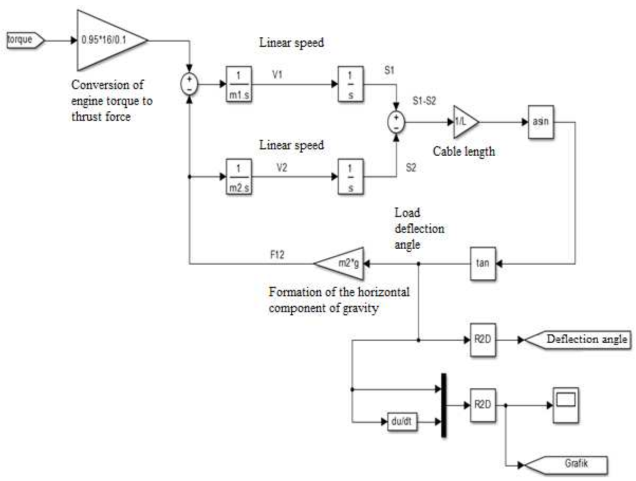

Fig. 7. Representation in the form of an elemental apparatus of the “trolley-load” system.

V. SIMULATION RESULTS

During the study, the modeling parameters of the operation of the trolley varied, changing the mass of the load from 5 tons to 150 kg and the length of the suspension of the load was regulated, so that the transported load was considered hanging at a height of 10 m, 5 m, 1 m. A mass of 5 tons corresponds to the maximum possible load of the trolley in consideration. A mass of 150 kg corresponds to the mass of the suspended hook only. For all variations of cargo mass and suspension length, the modeling process was the same, i.e., at the launch, the cart was accelerating, then reached the specified speed, moved at this speed for some time, and then the braking process began.

In Fig. 8 and Fig. 9 the transient processes are shown, obtained during the modeling, displaying the angle of deflection of the load at the load weight of 5 tons and a suspension length of 10 m. In Fig. 8, the data were obtained when using a fuzzy logic block in the control system. In Figure 9, the angle deviation graph was obtained when applying a speed intensity generator in the control system.

In Fig. 10 and Fig. 11 the transient processes are shown, obtained when simulating the operation of the electric drive of the trolley mechanism. The figures display the angle of deflection of the load for a load weight of 5 tons and a suspension length of 5 m. As in the previous situation modelled, the data were obtained when applying a fuzzy logic block in the control system (Fig. 10) and when using a speed intensity generator in the control system (Fig. 11).

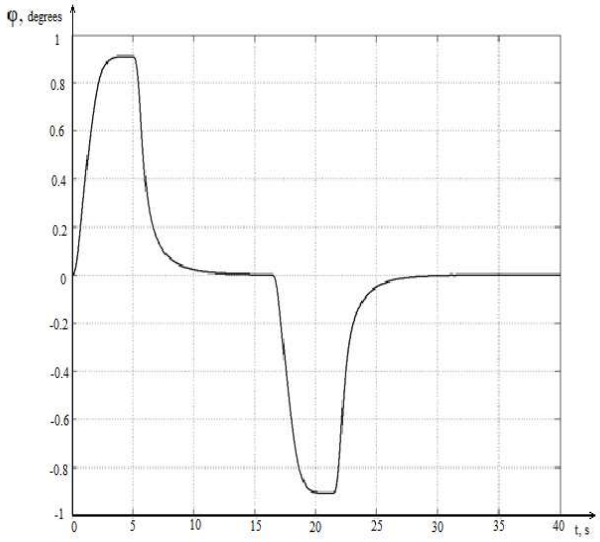

Fig. 8. The process of forming the angle of deflection of a load from the vertical with its mass equal to 5 tons and suspension length 10 m using a fuzzy controller in the control system.

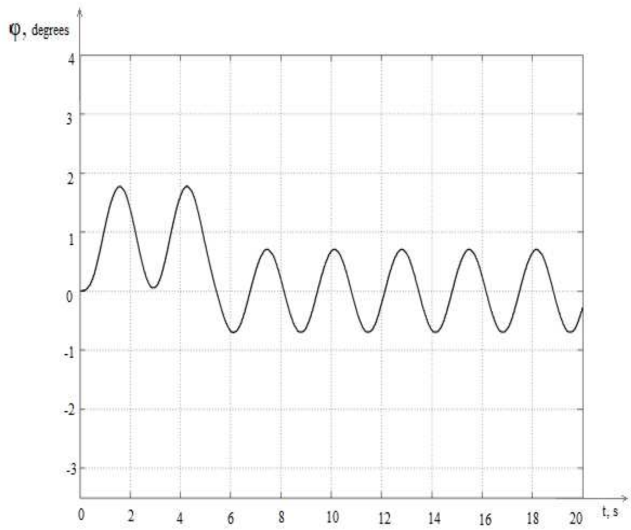

Fig. 9. The process of forming the angle of deflection of a load from the vertical with its mass equal to 5 tons and suspension length 10 m without using a fuzzy controller in the control system.

Modeling with various parameters of the mass of the load and the length of the suspension of the processes occurring during the braking of the trolley without the use of fuzzy logic in the control system is not relevant, since oscillations, as during start-up, are constant phenomena, and in the absence of an oscillation damping unit in the control system of the mechanism for moving the load, they will not disappear on their own.

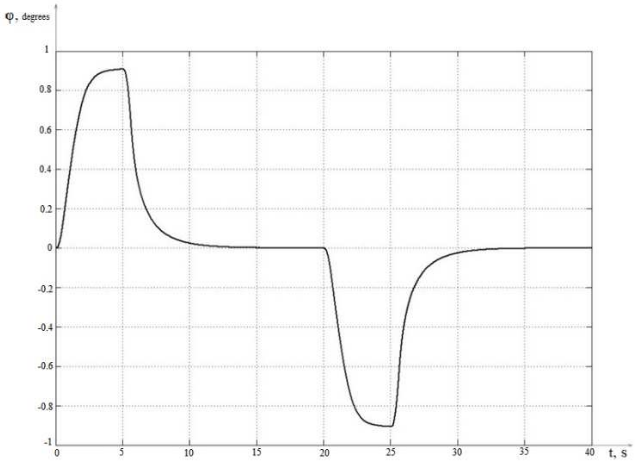

Fig. 10. The process of forming the angle of deflection of a load from the vertical with its mass equal to 5 tons and suspension length 5 m using a fuzzy controller in the control system.

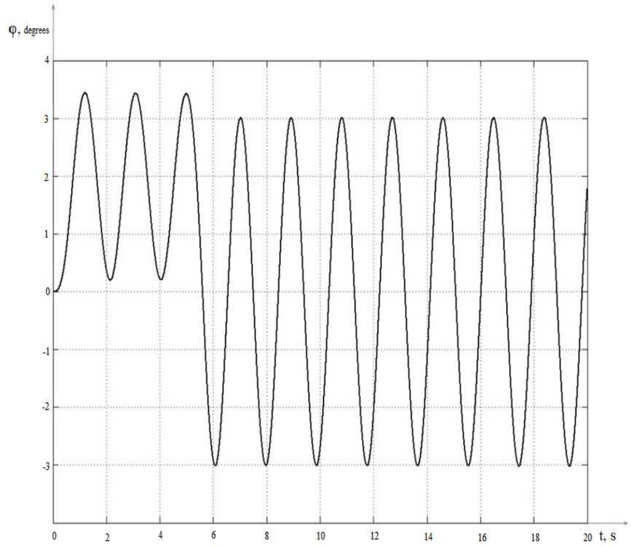

Fig. 11. The process of forming the angle of deflection of a load from the vertical with its mass equal to 5 tons and suspension length 10 m without using a fuzzy controller in the control system.

Analysis of the results presented in Fig. 8, 10 shows that the use of a fuzzy controller makes it possible to suppress vibrations of a flexible load, both at the start-up stage and during the braking period. At the same time, according to the nature of the transient processes shown in Fig. 9, 11 we can say that in a system containing only an intensity controller during the acceleration period, oscillations are visible that are twice as large as the oscillations that appear when using a fuzzy controller; it can also be seen that after the engine reaches the specified speed parameters, the oscillations of the load also do not die out. It is possible to simulate the considered control systems with other parameters of cargo mass and suspension length, but it gave similar results. In all options, the regulator clearly fulfills the tasks assigned to it, which leads to damping of vibrations of a flexible load.

The reduced load vibrations improve the unit performance and improve the load positioning accuracy.

CONCLUSIONS

The proposed fuzzy controller showed good damping capabilities when applied in a vector-type system. During the study, the length of the load suspension and the weight of the load changed. Changing these parameters did not affect the performance of the proposed fuzzy controller. At the next stage of the study, it is planned to implement the developed fuzzy controller into a system with direct torque control and into a scalar control system, as well as analyze the performance of the controller when the engine power changes.

In Short:

1. The modeling process in the MATLAB Simulink environment made it possible to change the parameters of the weight of the load and the length of the suspension, without additional time costs that would be required during the same type of research on a real object, and the modeling also made it possible to visually analyze the processes of starting and braking the trolley moving mechanism using the proposed controller in the system management, the implementation of the controller gave positive results.

2. The developed fuzzy controller model, due to its simplicity, does not require large computing power, therefore it is relevant for use at existing facilities.

3. The proposed control system with a developed fuzzy controller automatically responds to changes in the angle of deflection of the load, which avoids increasing the range of swing of the load.

4. By changing the engine parameters, you can also visually analyze for what power range the controller in question is applicable.

5. Fuzzy logic allows you to flexibly configure the control system, which allows you to obtain the required control characteristics.

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