Investigation of the dynamics of the manipulator drive with a stepper motor

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Abstract. A mathematical model of the manipulator drive with a stepper motor is developed in the form of inductance equations, which is a source of reactive moment, inertial moment equation and angular velocity. Stepper motors work in the drives of manipulators with continuous movement, when the control action is given by a sequence of electrical pulses. The block diagram of the speed and current control loop of the stepper motor, given by the operator, is calculated in the computer (full step, direction, correction value for reverse speed, acceleration braking), the data is sent to the controller, in the controller the signals pass through the hard logic circuits and are sent to the driver. The stepper motor driver board generates a signal that is fed to the stator windings of the stepper motor. The results of mathematical modeling in MATLAB & Simulink are presented. The dependences of the oscillatory process of the system in the transients of the stepper motor, which are oscillatory in nature, are obtained. A comparison of the results of theoretical modeling of the operation of a step drive with experimental studies is given. As a result of the simulation, additional dynamics arise in the armature current circuit, however, at the point of the nominal mode, it does not significantly affect the angular velocity regulation processes, that is, the speed regulator provides its astatic regulation under the action of a constant load moment.

1. Introduction
Stepper motors work in the drives of manipulators with continuous movement, when the control action is given by a sequence of electrical pulses. A distinctive feature of these engines is the possibility of positioning without a feedback sensor. The step drive (SD), along with its advantages, has disadvantages that significantly limit the scope of the SD: vibration, resonance, low dynamics, the presence of a locking torque, high temperature and low efficiency, low positioning accuracy.

Studies have shown that when a stepper motor operates in real conditions under load without a position sensor, the control system does not know the actual current position of the rotor, which can lead to a deviation of the actual position from the preset due to skipping steps. In systems without feedback, to prevent skipping steps, smooth acceleration and braking are used with a substantial margin. It limits the potential dynamic capabilities of the drive. [1, 2].

The motor windings are always energized, even when there is no load, resulting in high energy consumption, low efficiency and high operating temperature. To resolve the contradiction that has arisen with the use of SD, as well as new requirements for the accuracy of the movement, a new control method called vector control has become widespread [3, 4]. Skipping steps is decided by introducing a position sensor into the drive. The principle of vector control is to maintain a constant rotor flux linkage vector. To do this, it is necessary to apply voltage to both phases A and B. The phase currents create the resulting
stator current. Calculation of the current angle and current control must be performed with a high frequency, for this an electronic processor is used [5].

The objective of the research is to study the dynamics of the drive of a manipulator with a stepper motor.

2. Materials and methods

A manipulator drive with a stepper motor with a small rotation step and a large moment (figure 1) was selected the object of the research.

![Figure 1. Hybrid stepper motor design: 1 - shaft; 2 - stator; 3 - pole tip; 4 - permanent magnet; 5 – winding.](image)

3. Results

To study the dynamics of a stepper motor, mathematical modeling of a stepper motor with vector control in MATLAB * SIMULINK was performed.

The mathematical model of the stepper motor is written in the form of equations of inductance, which is the source of the reactive moment, the equation of inertial moment and angular velocity. When calculating the operating parameters of the system, we neglect the influence of the counter-EMF, considering it insignificant [6].

\[
L \frac{di_a(t)}{dt} = u_a(t) - R_i a(t) + K_m \omega(t) \sin(N_r \theta(t))
\]

(1)

\[
L \frac{di_b(t)}{dt} = u_b(t) - R_i b(t) + K_m \omega(t) \cos(N_r \theta(t))
\]

(2)

\[
J \frac{d\omega(t)}{dt} = -K_m \omega(t) \sin(N_r \theta(t)) + K_m \omega(t) \cos(N_r \theta(t)) - B \omega(t) - C \text{sgn}(\omega(t))
\]

(3)

\[
\frac{d\theta(t)}{dt} = \omega(t)
\]

(4)

where \(i_a, i_b\) – phase currents; \(\omega\) – angular velocity; \(\theta\) – rotor position; \(u_a, u_b\) – phase voltages; \(R_i\) – active resistance; \(L\) – inductance; \(K_m\) – moment coefficient; \(J\) – inertia; \(B\) – coefficient of viscous friction; \(C\) – Coulomb friction coefficient.

The mathematical model of the stepper motor is nonlinear. To simplify, we introduce the following assumptions: the saturation effect at high currents is neglected, and the fixing moment is neglected. The
model takes into account the change in inductance, which is the source of the reactive moment. In addition, the mathematical model takes into account viscous and Coulomb friction [7].

The main task of controlling a stepper motor is to ensure rotor rotation by a given angle. Under the step, it is customary to call the minimum possible angular displacement of the SD rotor, provided by its design in full step mode. When applying one control signal, the rotor of the stepper motor takes one step, that is, it rotates through an angle that is incorporated into it by the structure. As a rule, control is performed on transistor elements, and if the output signal is low, the corresponding phase of the winding is turned off, and if it is high, it is excited.

The block diagram of the stepper motor control is shown in figure 2.

![Figure 2. Block diagram of stepper motor speed control.](image)

The system works as follows: all the modes set by the operator are calculated in the computer (full step, direction, correction value for reverse speed, acceleration braking), the data goes to the controller, in the controller the signals pass through the hard logic circuits and are sent to the driver. The stepper motor driver board generates signals that are fed to the stator windings of the stepper motor. Using a closed loop in vector control eliminates the fluctuation of the moment, eliminates vibration, provides high dynamic performance, eliminates skipping steps and increases efficiency [8-9].

The model of the electromechanical drive with a stepper motor in MATLAB * SIMULINK is shown in figure 3.

![Figure 3. Model of electromechanical drive with a stepper motor in MATLAB * SIMULINK.](image)

The dependences of currents, angle of rotation of the rotor and angular velocity at the starting moment are obtained by implementing a model of an electromechanical drive with a stepper motor in MATLAB * SIMULINK (figure 4).
4. Discussion

Modeling the operation of a stepper motor in the starting period for 0.024 s allowed us to determine the nature of the oscillatory process. The oscillatory process of currents and angular velocity is sinusoidal. The process of rotation of the rotor is unstable and close to astatic. The unstable operation of the rotor rotation reduces the accuracy of the positioning of the manipulator and additional vibrations of the frame of the manipulator. The experiments of the oscillatory process of the manipulator frame showed that vibration can reach 60dB [10].

The dependences of the angular velocity and current over time in the stationary mode obtained during the simulation are shown in figure 5. At a given acceleration speed, the system fulfills a given displacement. The working time is 3 s, which is significantly longer than the working time when simulating a drive system. This is because the drive system with a stepper motor has more complex processes and simulates values close to real parameters. System overshoot is 4%.
The results of theoretical modeling of the operation of a stepper drive were compared with experimental studies. Figure 6 shows the recording of the current spectrum for 15 minutes. The starting current of the stepper motor is oscillatory. At starting times, the current reaches 10A. In normal mode, the current value is 2A (figure 6).

In the starting mode, the current increases to 10A compared to the nominal mode 1A. The use of a PI-regulator provides high accuracy in steady-state conditions, and with a certain ratio of the coefficients $k_p$ and $k_i$ provides good performance in transients. As can be seen from the graphs, additional dynamics arise in the armature current circuit, however, at the point of the nominal mode it does not significantly affect the angular velocity regulation processes, that is, the speed controller provides its astatic regulation under the action of a constant load moment.

Figure 6. Experimental recording of current changes during operation of a stepper motor.

5. Conclusion

The research results showed that the form of velocity fluctuations is different from sinusoidal. Due to the specifics of the nonlinear properties of the drive system, the amplitude of the speed fluctuations grows for 0.2 s synchronously with the current amplitude. Since perturbation is present in the current loop, it must be performed by an astatic current regulator of proportional-integral type.

References

[1] Prokopyev A P, Ivanchura V I and Emelyanov R T 2018 Investigation of the dynamics of a second-order object control system taking into account the location of the actual poles SFU Journal Ser.: Technics and Technologies 11(5) 500-11
[2] Astrom K J and Hagglund T 2006 Advanced PID Control Research Triangle Park (North Carolina: The Instrumentation, Systems, and Automation Society) p 354
[3] Derammelaere S, Vervisch B, Jasper De Vlae and Stockman K 2017 Sensorless load angle control for two-phase hybrid stepper motors Mechatronics 43 6-17
[4] Klimov A S, Klimova O L and Chentsov S 2017 Installation for the continuous application of graphic images on the roadbed of the Russian Federation FIPS Patent № 2627790
[5] Bobrov E B 2016 Methods of controlling a hybrid stepper motor Proceedings of the VII inter-university scientific and practical conference (SPb.: Publishing house of the GUMRF named after S O Makarov) p 540
[6] Pololu Robotics & Electronics 2019 Retrieved from https://www.pololu.com/product/2133
[7] Kazmierkowski M P, Franquelo L G and Rodriguez J 2016 High-Performance Motor Drives
IEEE Industrial Electronics 5(3) 6-26

[8] Lewandowski D and Awrejcewicz J 2015 Dynamical simulation of a nonlinear stepper motor system International Journal of Dynamics and Control 3 31-5

[9] Mojtaba J H, Lubarsky B G, Ryabov E S, Severin V P, Chernay V F and Yakunin D I 2009 Mathematical model of an automated electric drive based on a linear stepper motor Electroinform pp 88–90

[10] Bendjedia M, Ait-Amirat Y, Walther B and Berthon A 2012 Position Control of a Sensorless Stepper Motor IEEE Transactions on Power Electronics 27(2) 578-87