UDC 629.429.3:621.313
DOI: 10.15587/2706-5448.2025.339377

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DETERMINATION OF THE INFLUENCE OF THE CONTROL PARAMETERS OF THE STEPPER DRIVE FOR ROTATING THE PLATFORM FOR A GAS-DETONATION MORTAR ON ITS ELECTRICAL AND MECHANICAL PERFORMANCE

The object of research is the processes of platform rotation during the operation of the stepper drive of a gas-detonation powderless mortar. The problem solved by the study is to determine the influence of the set current and the rotation frequency of the stepper motor for the rotation of the platform for a gas-detonation mortar on the effective value of the phase current, vibration and maximum engine torques. According to the results of the research, it was determined that the effective value of the phase current has a variable character. The minimum value of the effective phase current is observed at a rotation frequency of 52.5 rpm, and a set current of 5.5 A, and is 0.875 A. The obtained dependence of the effective current on the control parameters has a non-monotonic variable character, due to a change in the shape of the current during engine operation, which, in turn, significantly changes the harmonic composition of the current. The dependence of the vibration torque of the engine also has a variable character. However, the minimum vibration is observed at a rotation frequency of 45 rpm, and a set current of 5 A, and is 7.715 N · m, and the maximum vibrations at the minimum operating frequency and the maximum setpoint current reach 39.72 N · m. The dependence of the maximum torque value on the stepper motor shaft has a decreasing character, due to the operation of the drive in the starting mode. The decrease in the starting torque is due, on the one hand, to a decrease in the setpoint current, and, accordingly, to the maximum motor current and an increase in the electromotive force in phase with an increase in the setpoint speed. The obtained research results can be used in practice when creating an automated electric drive for turning a gas-detonation mortar based on a stepper motor by selecting the parameters of the setpoint current for the semiconductor converter, in accordance with the rotation speed. The conducted research can be used as the basis for the methodology for determining the control parameters of the electric drive for turning based on a stepper motor.

Keywords: *stepper motor, platform, gas-detonation mortar, setpoint current, vibration torque.*

Received: 26.06.2025
Received in revised form: 21.08.2025
Accepted: 13.09.2025
Published: 30.10.2025

How to cite
Liubarskyi, B., Kryvosheiev, S., Eresko, O., Halytsia, V., Sakun, O., Liubarskyi, D. (2025). Determination of the influence of the control parameters of the stepper drive for rotating the platform for a gas-detonation mortar on its electrical and mechanical performance. Technology Audit and Production Reserves, 5 (1 (85)), 36–42. https://doi.org/10.15587/2706-5448.2025.339377

1. Introduction

The operational experience of foreign armed forces in urban combat has highlighted the need to modernize combat vehicles to increase combat effectiveness. For example, following military operations in Iraq, the United Kingdom upgraded its Challenger II main battle tank by integrating a mortar as an auxiliary weapon. This modernization, demonstrated during the Army Combat Experiment in 2018, included the installation of a mortar on the tank's turret, which provided additional support for infantry during urban combat. Ukrainian armored vehicles are equipped with smoke grenade launchers, but their range does not exceed 300 meters, which limits their effectiveness in maneuver warfare, where rapid and effective smoke camouflage of large areas is required. This limitation reduces their usefulness in maneuver warfare, where rapid and wide deployment of smoke screens is essential for effective camouflage. These limitations emphasize the need for continuous improvement of armored vehicles to ensure better adaptation to urban combat situations and to enhance the protective functions of smoke screen systems [1].

Tanks, infantry fighting vehicles, and armored personnel carriers are widely used in urban combat. The effectiveness of tanks in such conditions is often limited by the elevation angle of the tank gun, which is the main drawback. This fact hinders the ability to hit targets located on the upper floors of buildings or hidden behind various obstacles [2]. The operational experience of Western countries involved in urban combat has emphasized the need to increase the tactical versatility of tanks so that they can operate more effectively in difficult urban conditions [3]. One solution was the integration of mortars into the tank armament, which improved their operational flexibility and combat effectiveness [4].

For example, the Israeli Merkava tanks, designed for urban operations, were equipped with 60 mm mortars. This weapon allows the firing of both anti-personnel and smoke grenades, greatly enhancing the tanks' ability to counter enemy infantry and deploy smoke screens to camouflage or disorient the enemy [2]. Therefore, equipping tanks with mortars capable of engaging targets behind buildings, on rooftops, or in other hard-to-reach locations is a critical step in increasing their effectiveness in urban combat [4].

The National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine) has developed an innovative powder-free mortar with the ability to regulate the energy of the shot, which significantly expands the possibilities of using this weapon in combat conditions. A working experimental sample of the mortar was created, which successfully passed tests that confirmed the operability of the new technology of throwing mines without the use of a powder charge. The main feature of the development is the use of a gas-detonation charge to regulate the range of the shot. Unlike classic mortars, in this new mortar, the range change is achieved not by changing the elevation angle of the barrel, but by regulating the energy of the shot, while the elevation angle remains constant. This solution became possible due to the replacement of the powder propelling charge with a gas-combustible mixture, which also allowed the integration of the mortar shot control system into the fire control system [5]. This approach provides the possibility of firing in the semi-direct guidance mode, which allows for the prompt use of weapons on the battlefield, especially in urban combat, where quick response and accuracy are crucial factors [1, 5]. An important factor in increasing the accuracy of the shot is the integration of the mortar with an automatic guidance system. The guidance system is based on a rotary platform, which allows for guidance by rotating the barrel to a given angle depending on the given parameters of the shot. To rotate and fix the platform at a given angle, it is proposed to use a stepper motor. The advantage of such systems is the high accuracy of working out the given step of turning the platform to the possibility of creating additional force to fix the rotary platform. Fig. 1 shows a rotary platform with a mounted mortar.

Fig. 1. Drive for turning a gas-detonation mortar: 1 – mortar; 2 – turntable with worm gear; 3 – toothed belt; 4 – stepper motor

The platform includes a table that rotates due to a worm gear and which provides table fixation. The transmission of torque to the worm gear from the stepper motor is carried out by a toothed belt transmission, which allows reducing the impact of power loads on the stepper motor.

To implement the operation of the mortar on the barrel 1 (Fig. 1), a device for supplying a combustible mixture and a device for electromagnetic mine retention are installed, the operation and weight parameters of which are described in [6].

To describe the operation and create mathematical models of electric drives based on stepper motors, mathematical models have been developed [7]. The main drawback of the work is the determination of the change in flux linkage without taking into account the saturation of the elements of the magnetic system. In [8], the main provisions for determining the electromagnetic torque based on the harmonic change in flux linkage with a constant component are given, however, the work does not take into account the higher harmonic components of flux linkage, which cause additional components of the engine vibration moments.

The development of models for stepper motor control is the work [9], which developed a model of a two-phase hybrid stepper motor control system in an open loop. In order for the stepper motor to have a smaller step angle, two typical acceleration and deceleration curves were developed for online real-time calculations based on distributed control technology. In the works [9, 10], it is noted that stepper motor control includes both open-loop and closed-loop control. The closed-loop system is implemented by determining the position of the motor rotor using a fuzzy proportional-integral-differential controller [10] and space-vector pulse-width modulation (SVPWM) [9]. These technologies are used in traditional closed-loop control and provide an opportunity to improve the quality of control. The disadvantage of these systems is complexity and cost. As noted in [11], the use of closed-loop control systems makes it possible to implement improved control performance, but an additional disadvantage is the increase in the frequency of the converter. This disadvantage can lead to additional losses in semiconductor switches and can affect the energy performance of the drive as a whole, as noted in [12] for asynchronous motors. The development of such control systems is work aimed at reducing costs in the drive system as a whole by introducing direct torque control (DTC), which is noted, for example, in [13].

As noted in [9, 14, 15], the introduction of known control systems for stepper motors leads to excessive complexity of the system, namely the control loop for speed or angle of rotation. Therefore, for further research, it is possible to choose a system based on feedback through the current channel with control parameters in the form of the setpoint current (I_u) and the specified engine speed (n). This allows to state that it is advisable to conduct a study devoted to determining the dependence of the influence of the control parameters I_u and n on the operating properties of the engine.

The aim of research is to determine the influence of the setpoint current and the specified rotation speed on the effective current value and the maximum and vibration moments during the operation of the stepper drive of the rotation platform of a gas-detonation powderless mortar.

To achieve the aim, the following objectives were set:

– to improve the simulation model of the stepper drive, which takes into account the design parameters of the load, stepper motor and semiconductor converter;
– to verify the reliability of the simulation model by comparing the simulation results with a physical experiment;
– to conduct a set of numerical experiments on the simulation model to determine the influence of the control parameters of the setpoint current and the specified engine speed on the energy and mechanical performance of the engine.

2. Materials and Methods

2.1. Simulation model of a stepper drive for rotating the platform for a gas-detonation mortar

The object of research is the energy conversion processes during the operation of the stepper drive for rotating the platform of a gas-detonation powderless mortar.

ISSN-L 2664-9969; E-ISSN 2706-5448

For further research of the stepper drive in the work, a simulation model was developed in the MATLAB Simulink system, based on the model given in [16], which is shown in Fig. 2. The model was supplemented with a load block in the form of a MATLAB function of the rotation resistance, which was determined experimentally on the drive model shown in Fig. 1. In connection with the use of another type of stepper motor in the stepper motor system – Hybrid Stepper Motor, updated data was introduced, which correspond to the SY130ST199-6004A model. The simulation model of the power supply and control subsystem block was also modernized by establishing the correspondence of the supply of control pulses to the motor to a real semiconductor converter.

The model consists of the following elements. Stepper motor system – Hybrid Stepper Motor (Fig. 2). Power and control subsystem (Drive), which simulates the operation of the control system and semiconductor converter. MATLAB (USA) function F_c, which implements the change in load torque depending on the angle of rotation of the rotary platform. In the simulation model of the rotation of the platform, there are additional data transfer blocks, determination of the effective current value, power supply (24VDC) (Fig. 2), as well as blocks for stopping the modeling process (STOP) (Fig. 2).

The simulation model of a stepper motor is developed based on the solution of the differential equations of the motor phase, which is proposed in [9]. The motor phases are magnetically independent. The main parameters of the motor used in the drive are given below and are as follows:

– motor type – SY130ST199-6004A (China);
– number of phases (Number of phases) – 2;
– phase winding inductance (Winding inductance) – $12 \cdot 10^{-3}$ H;
– phase resistance (Winding resistance) – 0.75 Ohm;
– geometric angle of rotation of the motor rotor when applying one pulse (Step angle) – 1.8°;
– maximum flux linkage (Maximum flux linkage – ψ_m) – $7.2 \cdot 10^{-2}$ Vb;
– motor reactive torque – 0.25 N · m;
– moment of inertia of the drive reduced to the motor shaft (Total inertia) – $33 \cdot 10^{-4}$ kg · m^2;
– total friction coefficient of the drive (Total friction) – 10^{-6} N.m.s.

The model of the power supply and control subsystem is shown in Fig. 3. The model consists of a control system, which is created on the basis of two independent control units of single-phase bridge inverters (Converter A and Converter B). The operation of the inverters is coordinated by input blocks that receive direction of motion (DIR) and stop (STEP) signals.

Each of the control systems has feedback along the current channel on transistors, which is implemented by the LPF and LPF1 blocks for phases A and B, respectively. Single-phase inverters Converter A and Converter B are created from the same basic blocks using the Converter Simulink subsystems in the MOSFET/Diodes mode.

MATLAB (USA) function F_c is designed to simulate the load moment. The load of the stepper motor changes linearly from 6 to 6.7 N · m, with an increase in the platform rotation angle from 0° to 180°. With further rotation of the platform by an angle and from 180° to 360°, the load decreases from 6.7 to 6 N · m. Such data was determined experimentally when the platform with the mortar was tilted by an angle of 10°, which can occur in real circumstances of using a mortar on a vehicle.

The simulation of the drive operation is performed using a solver with a variable step and automatic control of the solution step at a maximum step of $2 \cdot 10^{-6}$ s.

The adequacy of the simulation model, which is shown in Fig. 2, is checked by comparative analysis of the effective value of the motor phase current, as determined by the simulation results, and measurements when working on the physical model of the slewing drive. The measurement results are shown in Fig. 4.

The minimum sample size with accuracy $d = 0.25$ and statistical reliability $\gamma = 0.95$, required to estimate the standard deviation, is determined to be

$$n = 1 + 0.5\left(\frac{z_\alpha}{d}\right)^2 = 1 + 0.5\left(\frac{1.96}{0.25}\right)^2 \approx 30,$$

where z_α – a normalized normally distributed variable, the value of which for $\alpha = 1 - \gamma = 0.05$ is 1.96.

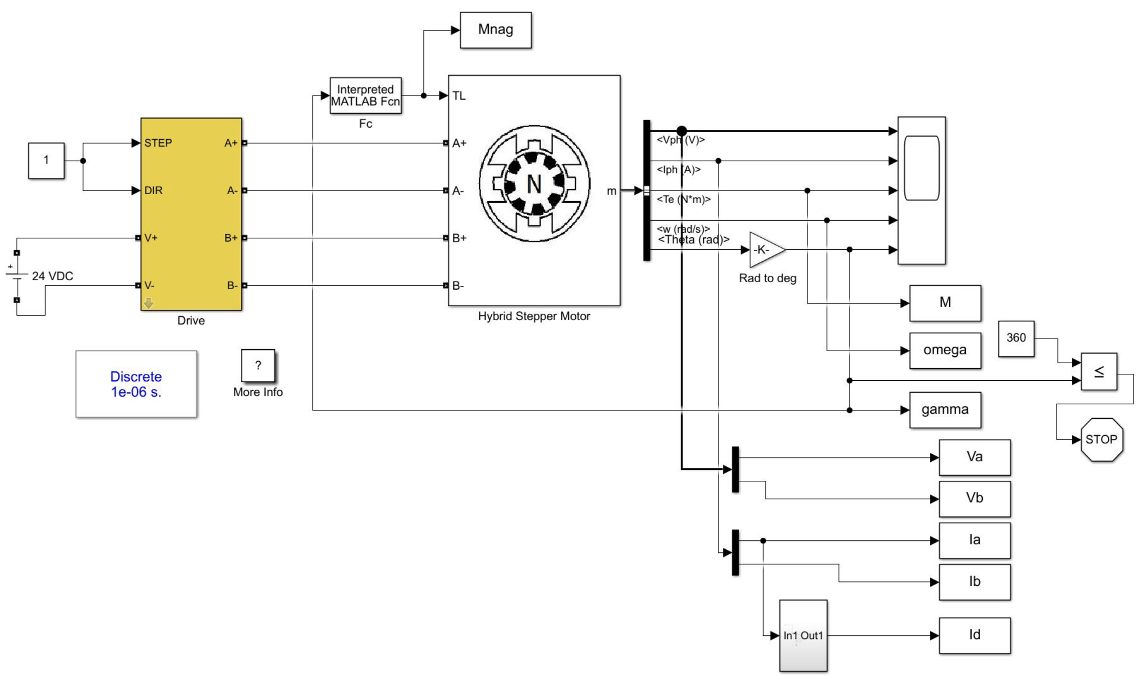

Fig. 2. Simulation model of a stepper drive of a rotary platform

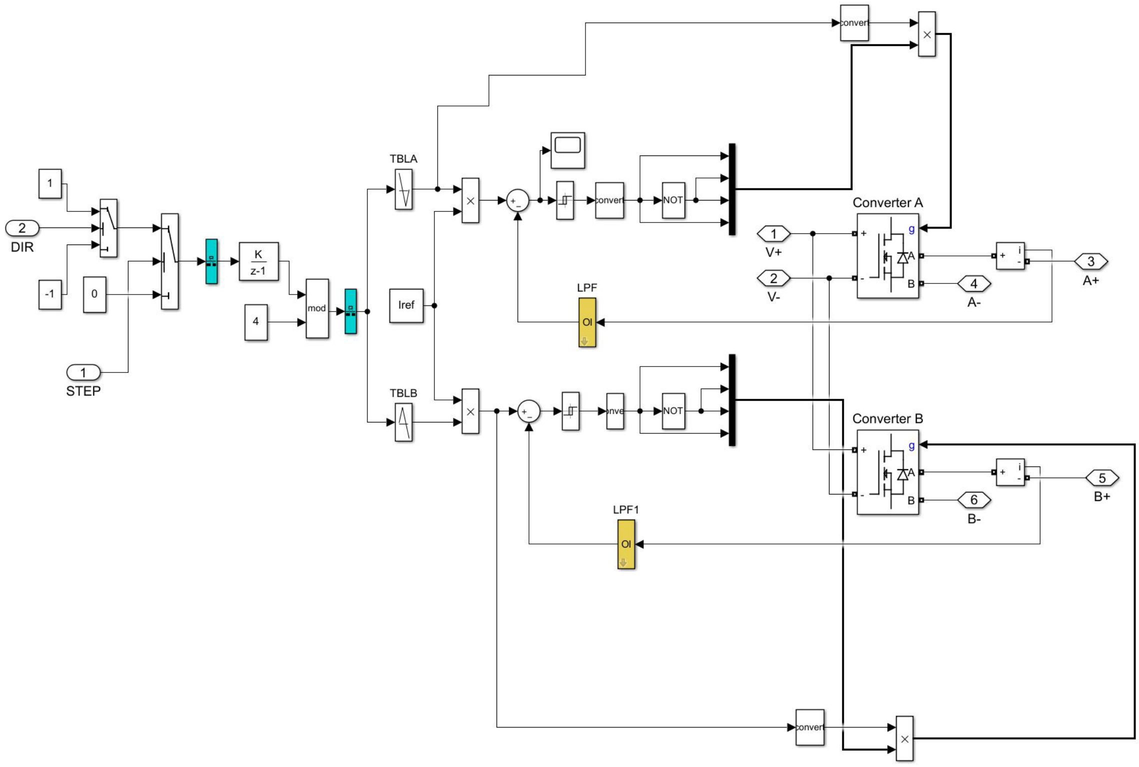

Fig. 3. Simulation model of the power supply and control subsystem (Drive) of the rotary platform stepper drive

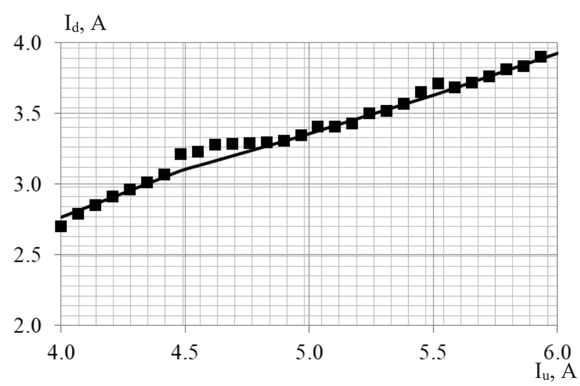

Fig. 4. The effective value of the phase current I_d, from the setpoint current I_u at a rotation frequency of 45 rpm: black line – determined by the results of modeling; marker – determined by the results of measurements on the experimental sample

According to the results of the research, the maximum deviation of the results was determined to be 3.55%, which ensures the adequacy of the developed model.

3. Results and Discussion

The operation of the stepper drive for rotating the platform was studied using the example of a rotation frequency of 45 rpm and a setpoint current of 5 A. At other values of the control parameters, the physical processes have a similar appearance.

During the research, it was found that the process of the drive operation can be conditionally divided into engine start-up, which is accompanied by the drive operation in the current limitation mode, which is from 0.012 to 0.027 s (Fig. 5), depending on the setpoint currents and the specified rotation frequency, and operation in the nominal mode. Such processes correspond to the processes of operation of stepper drives described in works [7, 8].

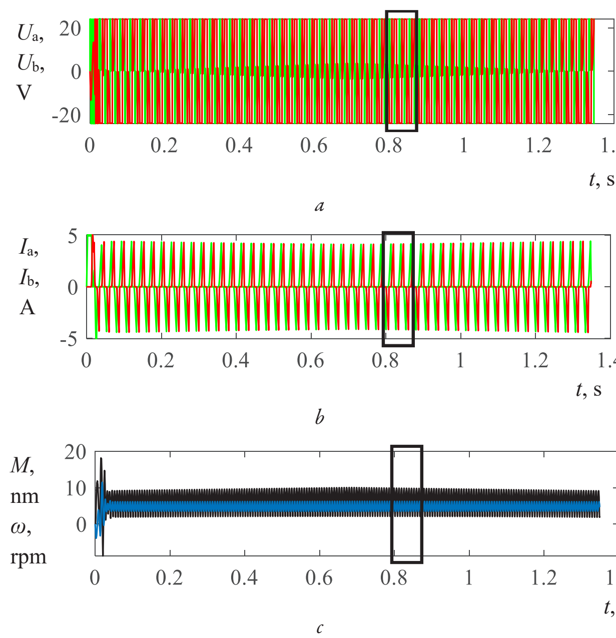

Fig. 5. Simulation results of the operation of the stepper drive for rotating the mortar platform at a rotation frequency of 45 rpm and a set current of 5 A when the platform rotates from 0 to 4°: *a* – phase voltages (V); *b* – phase currents (A); *c* – torque on the motor shaft (N · m) and rotation frequency (rpm). Red lines – phase A, green phase B

The change in load during rotation does not have a significant impact on the physical processes of operation and affects only the effective value of the motor phase current, which is close to the results considered for the drives in the work [9].

The operation process of the stepper drive is accompanied by the supply of voltage from bridge single-phase inverters to the phases of the stepper motor (Fig. 5), which are shifted relative to each other by half

ISSN-L 2664-9969; E-ISSN 2706-5448

a phase. The voltage has a rectangular shape with a significant decrease in the first half of the phase, which is due to the action of the electromotive force induced in the phase (Fig. 6, *a*). The phase current has a triangular shape, which is due to the gradual increase and decrease of the current along exponential curves (Fig. 6, *b*). During engine operation, the maximum electromagnetic moment is realized, which is equal to 18.87 N · m (Fig. 5, *c*).

For further studies, according to the results of modeling, the amplitudes of the variable components of the moment on the shaft of the stepper motor were found. At a rotation frequency of 45 rpm and a set current of 5 A, it is 7.715 N · m (Fig. 5, *c*). The oscillograms of the processes correspond to the results obtained, which are considered in the works [7, 8].

A set of numerical experiments on the simulation model shown in Fig. 2 and Fig. 3, to determine the influence of control parameters, in particular the set current and the specified motor rotation frequency, were carried out by determining the dependence of the effective value of the motor phase current (Fig. 7), the amplitude of the variable component of the torque (vibration torque) on its shaft (Fig. 8) and the maximum torque on the motor shaft (Fig. 9).

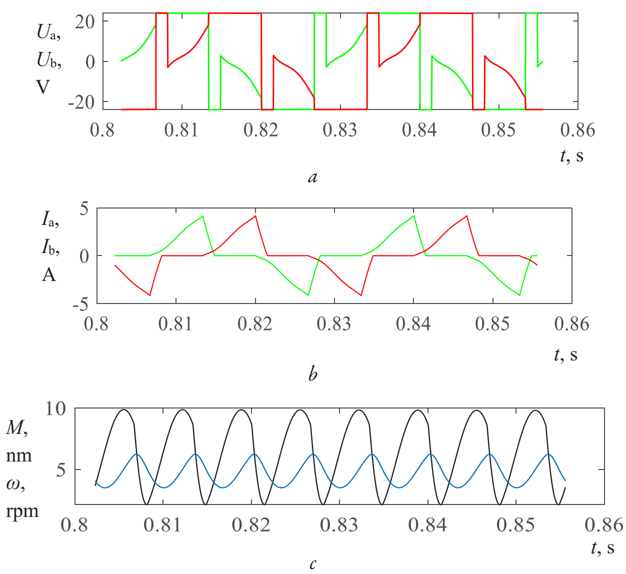

Fig. 6. Simulation results of the operation of the stepper drive for rotating the mortar platform at a rotation frequency of 45 rpm and a set current of 5 A in the time interval from 0.8 to 0.86 s, which are shown in Fig. 5 in the black rectangle: *a* – phase voltages, V; *b* – phase currents, A; *c* – torque on the motor shaft, N · m and rotation frequency, rpm. Red lines – phase A, green lines – phase B

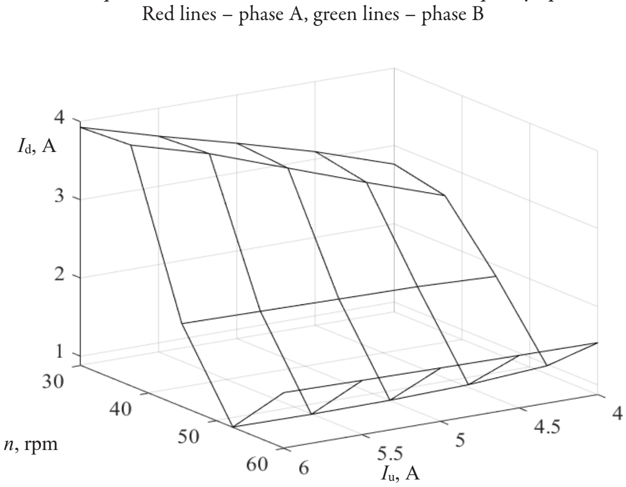

Fig. 7. Dependence of the phase current I_d on the setpoint current I_u and the speed *n*

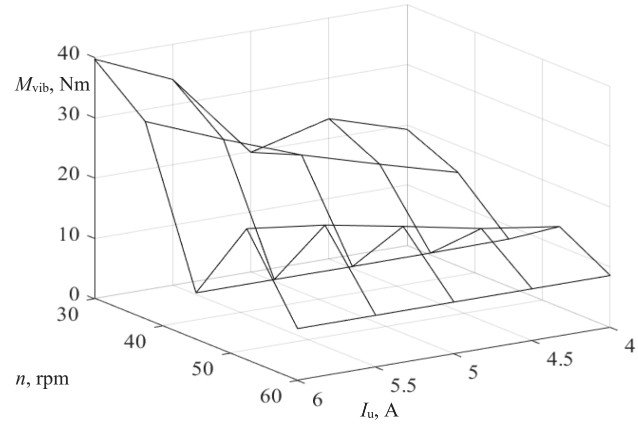

Fig. 8. Dependence of the amplitude of the vibration moment on the shaft of the stepper motor M_{vib} on the setpoint current I_u and the speed *n*

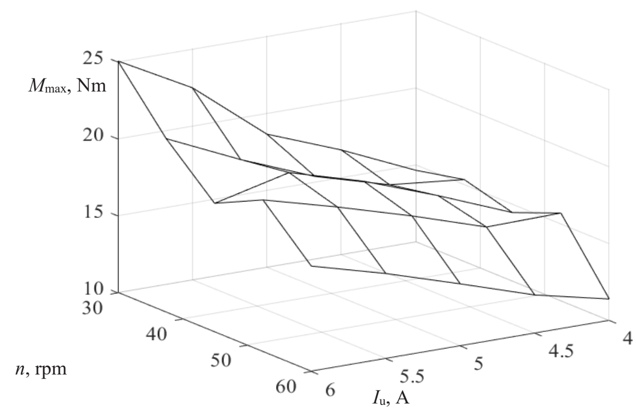

Fig. 9. Dependence of the maximum value of the moment on the shaft of the stepper motor M_{max} on the setpoint current I_u and the speed *n*

It is determined that the effective value of the phase current (Fig. 7) has a variable character. The minimum current value is observed at a rotation frequency of $n = 52.5$ rpm, and a setpoint current of $I_u = 5.5$ A and is $I_u = 0.875$ A. The obtained dependence of the effective current on the control parameters has a non-monotonic variable character, due to a change in the shape of the current during engine operation, which, in turn, significantly changes the harmonic composition of the current. The dependence of the engine vibration moment also has a variable character. However, the minimum vibration is observed at a rotation frequency of $n = 45$ rpm and the setpoint current $I_u = 5$ A and is $M_{vib} = 7.715$ N · m, and the maximum vibrations at the minimum operating frequency and the maximum setpoint current reach $M_{vib} = 39.72$ N · m.

The dependence of the maximum torque value on the stepper motor shaft has a decreasing character, due to the operation of the drive in the starting mode. The decrease in the starting torque is due, on the one hand, to a decrease in the setpoint current – the maximum motor current. On the other hand, this process is due to an increase in the electromotive force in the phase with an increase in the set speed.

The obtained research results can be used in practice when creating an automated electric drive for turning a gas-detonation mortar based on a stepper motor by selecting the parameters of the setpoint current for the semiconductor converter, in accordance with the rotation speed. The conducted research can be used as the basis for the methodology for determining the control parameters of the electric drive for turning based on a stepper motor.

Further development of the research may be to conduct a planned full factorial experiment on the parameters of the setpoint current I_u

and the rotation frequency n for continuous regression dependencies on the factors of the phase current I_d, the amplitude of the vibration moment M_{vib} and the maximum value of the moment $M_{\max}$ on the stepper motor shaft.

Simulation modeling of the operating modes of the stepper drive for turning the platform was carried out when changing the setpoint current I_u from 4 A to 6 A and the motor shaft rotation frequency n from 30 to 60 rpm. At such values of currents and rotation speeds, the stepper drive operates stably without start-up stops and with increasing load.

The effective value of the motor phase current determines the thermal processes in it and the semiconductor converter. In further studies of thermal processes in the drive, the effect of the effective current on the temperature of the structural elements of the stepper motor in the modes of working out the specified parameters of the mortar guidance signal and target tracking modes will be considered.

The vibration moment determines the accuracy of working out the control signal. Minimizing this moment leads to an increase in the accuracy of the shot, which can be used in further studies in field tests of the mortar. The selection of optimal values of the setpoint current and rotation frequency for the main operating mode is possible on the basis of decision-making theory.

The obtained dependencies can be used as a basis for the methodology for determining the parameters of the stepper drive for turning the platform, allowing the determination of the conditions for using the stepper motor in combat modes. Thus, the applied aspect of using the obtained scientific result is the possibility of determining the control parameters of the stepper drive for turning the platform of a gas-detonation powderless mortar. This creates prerequisites for the transfer of the obtained technical solutions in the development of electric drives for guiding auxiliary weapons of military equipment.

The results of the conducted research can be useful in the development of guidance systems based on stepper motors.

The limitations of this study are that it does not take into account the change in the supply voltage of the battery. The nominal voltage value of 24 V was chosen during the study. However, during the operation of the drive, the charge and voltage of the battery decrease, which can become a further direction of scientific research.

4. Conclusions

1. The simulation model of the stepper drive was improved by taking into account the design parameters of the load, stepper motor and semiconductor converter, parameters of the control system and stepper motor. The model was supplemented with a load block in the form of a MATLAB function of the turning resistance, which was determined experimentally on the physical model of the drive. The parameters of the SY130ST199-6004A stepper motor were identified in the model, which were added to the Hybrid Stepper Motor block. The simulation model of the power supply and control subsystem block was also modernized by establishing the correspondence of the control pulse supply to the motor to the real semiconductor converter. These changes to the basic model made it possible to take into account the peculiarities of the operation of the turning drive when the vehicle with the platform on which it is installed tilts in field conditions.

2. According to the results of physical experiments, the reliability of the simulation model of the stepper drive of the turning platform was proven by comparative analysis of the effective value of the motor phase current, determined by the results of modeling, and measurements during operation of the physical model. The maximum deviation of the phase current is 3.55%.

3. According to the conducted set of numerical experiments on the simulation model, the dependences of the setpoint current I_u and the rotation frequency n on the phase current I_d, the amplitude of the vibration moment M_{vib} and the maximum value of the moment $M_{\max}$ on the shaft of the stepper motor were determined. It was determined that the minimum current value is observed at a rotation frequency $n = 52.5$ rpm and the setpoint current $I_u = 5.5$ A and is $I_u = 0.875$ A; the minimum of the vibration moment is observed at a rotation frequency $n = 45$ rpm and the setpoint current $I_u = 5$ A and is $M_{vib} = 7.715$ N · m, and the maximum vibrations at the minimum operating frequency and the maximum setpoint current reach $M_{vib} = 39.72$ N · m.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other nature, which could affect the research and its results presented in this article.

Financing

The work was carried out with the financial support of the National Research Foundation of Ukraine. Project registration number: 2023.04/0101 "Design of the automated aiming and control systems of the gas-detonation mortar for firing smoke grenades".

Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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