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Ihor Bolbot
Doctor of Technical Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-5708-6007

Oleksii Slovikovskyi*
Postgraduate Student
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0001-8912-6256

Mathematical modelling of the gas burner air intake damper drive

Abstract. In the context of modern requirements for energy efficiency and automation of thermal systems, particularly gas burners, the development of accurate mathematical models to describe the operation of electric drives that ensure the functionality of key system components plays a crucial role. One such component is the air intake damper drive, which regulates airflow to the combustion chamber, directly affecting combustion efficiency and burner stability. The objective of this study was to develop a mathematical model of the gas burner's electric drive system, accurately describing the dynamics of the fan motor, air intake damper drive, drying drum drive, and other system elements. To achieve this, methods of mathematical modelling of dynamic systems and numerical methods for solving differential equations in the MATLAB environment were utilised. Modelling these processes ensured high accuracy in predicting system performance and energy efficiency at all operational stages. The main results included the development of a mathematical model describing dynamic processes in the drive system, accounting for the inertial characteristics of the damper drive, gearbox parameters, damper mass, moment of inertia, and the influence of the actuator's mass on system dynamics. Graphs were constructed to analyse the system's temporal characteristics. Dynamic processes in the drive system, critical for stable and efficient airflow regulation, were described. The developed model enabled analysis of transient processes and optimisation of controller settings, particularly PID controllers, to enhance system responsiveness. An important aspect was the evaluation of the impact of drive parameters on the energy efficiency and stability of the gas burner. The model can be integrated into gas burner automation systems, enhancing energy efficiency, ensuring reliable operation under various conditions, and reducing drive overload risks through optimised control parameters

Keywords: electric drive; simulation model; gas burner; automation system; drive dynamics; stepper motor

INTRODUCTION

Gas burners play a key role in a wide range of thermal systems, particularly in drying, heating, and process equipment. One of the important factors determining their energy efficiency and operational stability is the accuracy and reliability of actuators, particularly electric drives that control air intake dampers. These elements provide air flow regulation, which, in turn, affects the combustion quality, flame stability, and overall efficiency of the heat-generating unit. In the context of growing requirements for energy efficiency and automation of industrial processes, it becomes relevant to create mathematical models capable of accurately reflecting the dynamics of the operation of damper electric drives, considering their interaction with other system elements.

Research in the field of electric drives and control systems indicates a growing interest in integrating mathematical models into design and optimisation processes. For example, in the work of D. Shuqiao (2022), a

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*Corresponding author

mathematical analysis of three-phase inverters for electric drives is presented, demonstrating improved efficiency when using wide-bandgap semiconductor technologies. The researchers proposed an energy-saving model for an induction motor based on voltage regulation with compensating devices, which allowed achieving better stability under variable loads. Additionally, the study by M. Abadi *et al.* (2024) focuses on the dynamics of microcombustion and micropropulsion systems, emphasising the importance of accurate modelling to ensure flame stability. The publication discusses numerical approaches to modelling arc discharge in electric furnaces, which have the potential to be adapted for analysing energy processes in burner systems.

In the context of gas burners, the studies by M. Sekar *et al.* (2024) and H. Zvarych & H. Mateik (2024) demonstrated dynamic modelling of a shipboard propulsion system using dual-fuel engines and energy storage, allowing for an assessment of trade-offs between transit capacity and system efficiency. The authors M. Sekar *et al.* (2024) focused on the simulation of methane-hydrogen mixture combustion, which showed reduced emissions and improved thermal efficiency (EFF), relevant for fuel systems with adaptive control. In turn, the work by H. Zvarych & H. Mateik (2024) is dedicated to improving the gas temperature regulation system before the turbine, where the proposed modelling enabled increased control accuracy and responsiveness under variable conditions. These approaches can be adapted for the analysis and optimisation of electric drives in thermal systems.

The mathematical description of electric drive systems is based on the fundamental laws of electrodynamics, mechanics, and automatic control, as reflected in the work of P. Krause *et al.* (2021), which generalises approaches to analysing electromechanical systems, taking into account both electrical and mechanical aspects of their dynamics. Specifically, Ohm's law and electromagnetic induction equations are used to describe electrical processes in motors. These laws ensure the formalisation of the interaction of currents, voltages, and electromagnetic fields in the system. Newton's second law is used to describe mechanical processes, such as the rotation of motor rotors, fan dynamics, and drum dynamics. The principles of automatic control theory allow describing transfer functions and controllers responsible for maintaining the stability and accuracy of the system. F. Silva (2022) in his publication emphasised the importance of formalising the relationships between elements of electromechanical structures to further expand the possibilities of digital design, particularly in the context of drive control and dynamic behaviour prediction.

The creation of mathematical models is necessary for a deep understanding of the physical processes occurring in the system, their analysis, and optimisation. Despite the existence of modern software products, such as ANSYS Maxwell, Ansys Twin Builder, or MATLAB/Simulink, which can be used for numerical modelling of electric drive systems, an analytical approach using mathematical formulas and equations is equally important. V. Pliuhin *et al.* (2022) developed a simulation model of an electromechanical energy converter with a solid rotor in the ANSYS RMxprt, Maxwell, and Twin Builder environments, which enabled comprehensive modelling of electromagnetic and mechanical processes. The model accounted for the nonlinear characteristics of the magnetic circuit and allowed for the validation of theoretical calculations in a digital environment with high accuracy. V. Herasymenko *et al.* (2023) performed modelling of a DC traction motor in the ANSYS RMxprt environment, focusing on the formation of parameterised models for efficiency analysis. They demonstrated the ability to accurately reproduce the dynamics of the traction drive, taking into account electromagnetic losses, which is particularly important for designing transport systems with increased reliability requirements. The application of an analytical approach enables obtaining initial system parameter estimates, optimising them, and creating simplified models that can be used to develop or refine the settings of complex models in software products.

Analytical modelling allows for a deeper understanding of the relationships between electric drive parameters and the dynamics of the entire system (Harasymiv & Harasymiv, 2020). Using equations, it is possible to assess the impact of changes in voltage, frequency, or motor moment of inertia on the operation of the damper drive. This is particularly important when modernising equipment, where it is necessary to consider the system's sensitivity to the parameters of individual elements. The constructed models also serve as a basis for verifying calculations in numerical simulations and creating simplified control algorithms that do not require significant computational resources. Thus, the mathematical description provides a holistic approach to the analysis and optimisation of the electromechanical part of the gas burner.

The purpose of the article was to develop mathematical models of electric drives serving key components of the gas burner, such as the fan, drying drum, and air intake damper. The scientific novelty of the work lies in the integration of analytical models of electric drives in the context of thermal engineering processes, which allows for a more accurate description of the interaction between electrical and mechanical components of the system. This contributes to increasing the efficiency and reliability of gas burners and opens new opportunities for their modernisation and improvement.

MATERIALS AND METHODS

This study focused on the DC electric motor commonly used in air intake damper drives. The mathematical model incorporated equations for electrical and mechanical processes, analogous to those for an induction motor (Jaber & Abdulhasan, 2022). For a DC motor, the voltage equation was expressed as:

$$u = R_a i_a + L_a \frac{di_a}{dt} + E, \tag{1}$$

where u represented the armature winding voltage, R_a and L_a denoted the armature resistance and inductance, respectively, i_a – the armature current, and E – the electromotive force (EMF) induced by rotation. The EMF was proportional to the angular velocity:

$$E = k_e \, \omega_m, \tag{2}$$

where k_e – the electromechanical coefficient and m – the angular velocity. The mechanical moment equation for the drum was defined as:

$$J_b \frac{d\omega_m}{dt} = M_e - M_s, \tag{3}$$

where J_b represented the drum's moment of inertia and M_s – the resistance torque due to friction and load. The electromagnetic torque M_e was given by:

$$M_e = k_m i_a, \tag{4}$$

where k_m – the torque constant.

The electric fuel supply drive controlled the flow of gas through gearboxes or valves, ensuring flow stability. The model was similar to that of the damper drive. The air intake damper drive regulated the volume of air supplied to the furnace, providing optimal conditions for combustion. Its electromechanical component was typically implemented using an asynchronous or stepper motor with a gearbox (Buriakovskyi *et al.*, 2021). The model of this drive was described in a simplified form through the transfer function (Robinette *et al.*, 2023):

$$G(s) = \frac{K}{Ts+1}, \tag{5}$$

where *G(s)* – the transfer function of the system drive in Laplace space; K – the gain that characterised the static sensitivity of the system, i.e., the dependence of the damper displacement on the input signal (e.g., voltage); T – the time constant of the system, which determined the inertia of the drive; and s – the Laplace operator used to describe the system in the frequency domain.

This model enabled the analysis of the dynamics of the damper's movement and the influence of controllers on its position. Equation (5) described how the output value of the system (e.g., the angular position of the damper or its linear displacement) responded to the input signal. In (5), the gain K determined the extent to which the damper position *x(t)* changed when the input signal *u(t)* was applied. It depended on the design of the drive and the physical properties of the gearbox and damper:

$$K = \frac{1}{k_r \cdot G_r}, \tag{6}$$

where k_r – the stiffness coefficient of the gearbox, accounting for its deformations under load; G_r – the gear ratio of the gearbox, which reduced the rotational speed but increased the torque. Higher values of K resulted in faster attainment of the set position but could lead to oscillations or instability, particularly if the system was insufficiently damped. The time constant T in (6) determined how quickly the system responded to changes in the input signal. It accounted for the inertia of both the electric motor and the mechanical components (damper, gearbox, drive system):

$$T = \frac{J}{k_m \cdot G_r}, \tag{7}$$

where J – the total moment of inertia of all rotating parts of the system (motor rotor, gearbox, damper); km was the torque constant of the electric motor. A lower value of T indicated a faster system response, but excessively low values could cause instability or oscillations. The complete equation of the damper drive dynamics was formulated using the Laplace operator. The equation of system dynamics was obtained in the following form:

$$\frac{X(s)}{U(s)} = \frac{K}{Ts+1}, \tag{8}$$

where *X(s)* – the damper position and *U(s)* – the input signal (e.g., motor voltage). In the time domain, this equation was expressed as a differential equation:

$$T \frac{dx(t)}{dt} + x(t) = K \cdot u(t), \tag{9}$$

where *x(t)* – the damper position and *u(t)* – the input signal.

The control signal *u(t)* in (9) originated from a controller that determined the required damper position based on measured parameters, such as air volume or fuel/air ratio. The damper position *x(t)* served as the input parameter of the system, indicating the actual state of the damper (open or closed position). The output value could be linear (in the case of displacement) or angular (if the damper rotated). The system's inertia T accounted for the limited response speed to signal changes due to the mass and moment of inertia of the components. The gain K characterised how accurately and quickly the damper reached the set position. The resulting equation was integrated into software to simulate the dynamics of the entire drive system, enabling the evaluation of the interaction between the damper and other elements of the gas burner.

The computer model of the air intake damper drive was implemented in the MATLAB software environment using a scripted approach to modelling. The fundamental equations of electrical and mechanical dynamics were coded as functions and program blocks, with numerical solutions of differential equations achieved using standard MATLAB functions, particularly ode45. This approach facilitated flexible control of the model's parameters, straightforward modification of input signals, and the development of custom integration algorithms that accounted for the specifics of the drive dynamics. The simulation produced time dependencies of the armature current, angular velocity, and damper position, as well as spatial and phase trajectories, which enabled the analysis of the system's stability and dynamic behaviour. The implemented model was suitable for further expansion, particularly for integration into more complex automated control systems or digital twins of thermal installations.

RESULTS AND DISCUSSION

This study developed a mathematical model of the gas burner's electric drive system, encompassing the fan motor, drying drum drive, and air intake damper. Calculation results are presented in Figures 1 and 2.

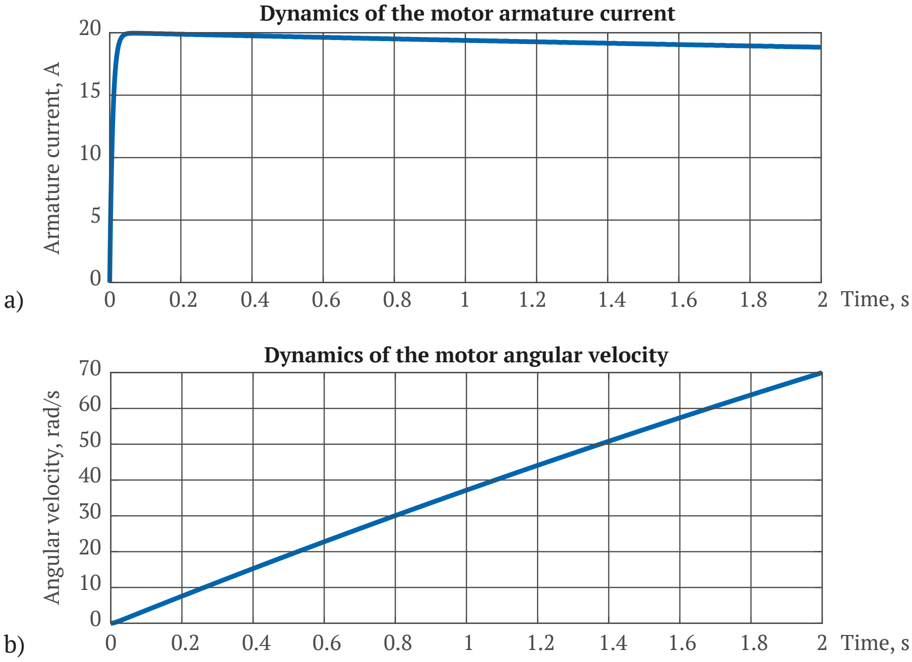

Figure 1. DC motor characteristics of the air intake damper drive
Note: a) armature current dynamics; b) angular velocity dynamics
Source: developed by the authors

The model is based on the equations of electromechanical dynamics, which allows describing the dynamics of the operation of these components. The application of this model contributes to accurate forecasting of the system's operation, ensuring its energy efficiency and optimising control parameters. The resulting models can be integrated into automation systems to improve the burner's performance in real production conditions.

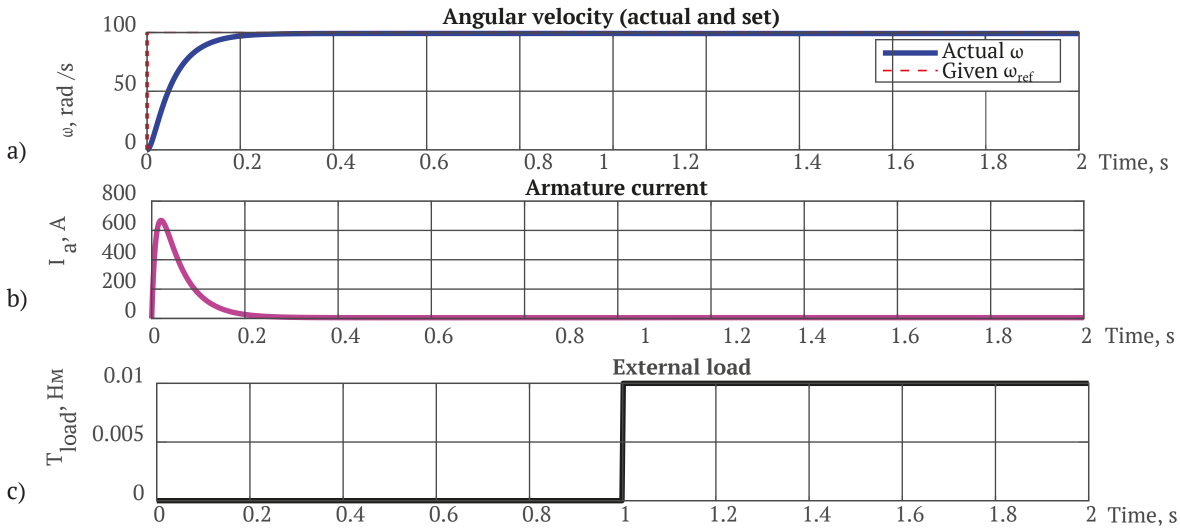

Figure 2. Control characteristics of the air intake damper drive
Note: a) angular velocity (actual vs. setpoint); b) armature current; c) external load
Source: developed by the authors

The obtained analytical dependencies allowed simulating the dynamic characteristics of the DC motor used in the damper drive. It was found that the constructed models provide an adequate reflection of real processes in the system, which is confirmed by the graphs obtained in the developed MATLAB program. They demonstrate characteristic transient processes and allow identifying energy losses at various stages of functioning. In particular, it was established that the system demonstrates high dynamic stability, provided the motor and control system parameters are correctly adjusted. In the context of the reviewed existing studies, it can be argued that the proposed approach is appropriate for creating digital twins of electromechanical systems. The resulting model allows for more accurate consideration of the interaction between different drive elements, which is important for the comprehensive automation of the gas combustion process. This approach contributes not only to improving energy efficiency but also facilitates the implementation of adaptive control systems based on digital data in industrial conditions. The proposed mathematical model of the gas burner's electric drive system allows describing the dynamics of the operation of key components, including the fan motor, the drying drum drive, the air intake damper, and other elements. The use of these models contributes to accurate forecasting of the system's operation, ensuring its energy efficiency and optimising control parameters. The resulting models can be integrated into automation systems to improve the burner's performance in real production conditions.

The simulation of the dynamics of the air intake damper drive was performed using a stepper motor and a gearbox. The constructed model allowed accounting for the inertial properties of the system, including the damper's mass, moment of inertia, and gear ratio of the gearbox. The simulation conducted in the MATLAB environment (Fig. 3-5) enabled the construction of dependencies between the system's parameters and its responsiveness, which is critically important for maintaining a stable air supply to the combustion zone. According to the results, optimal tuning of the *K* and *T* coefficients allows reducing dynamic overloads and ensuring rapid achievement of the set damper position without overshoot.

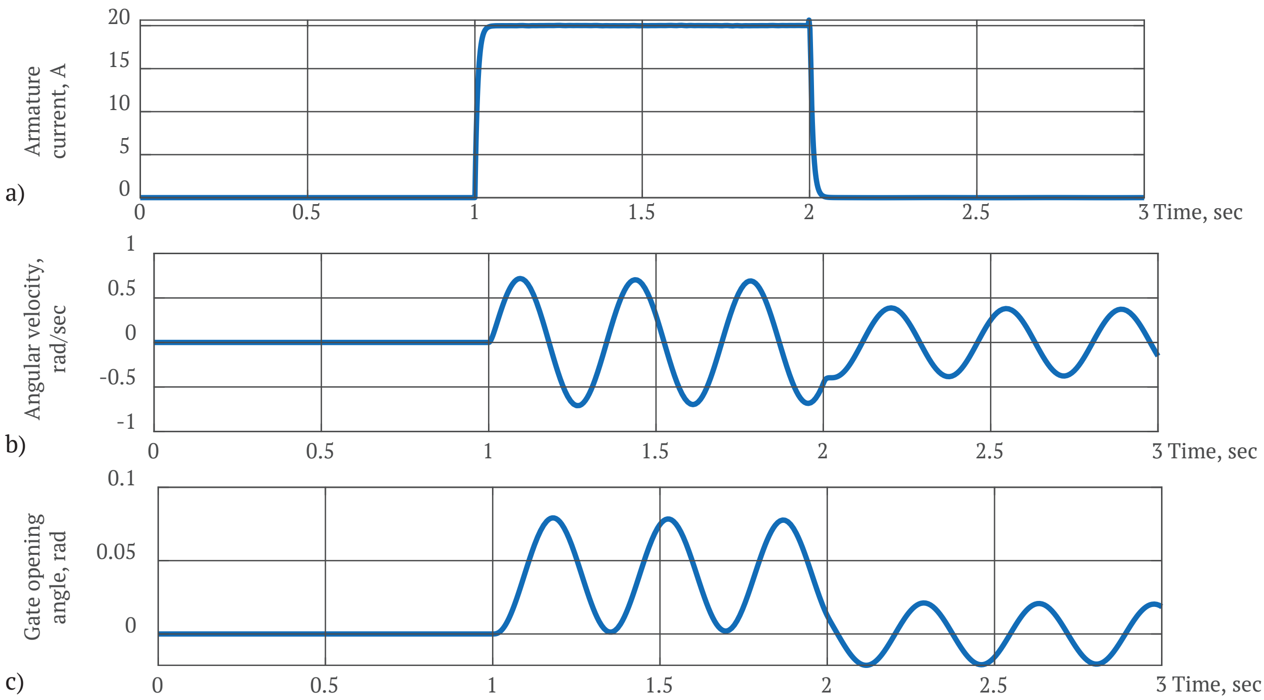

Figure 3. Simulation results of the air intake damper drive
Note: a) dynamics of the motor current; b) dynamics of the angular velocity; c) dynamics of the damper opening
Source: developed by the authors

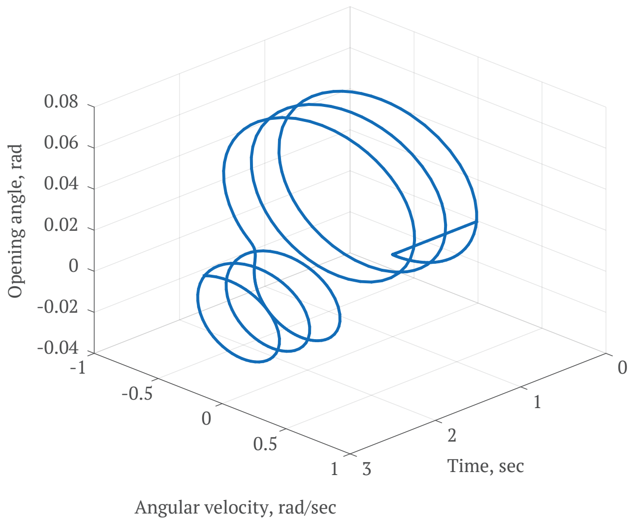

Figure 4. Spatial trajectory of the damper
Source: developed by the authors

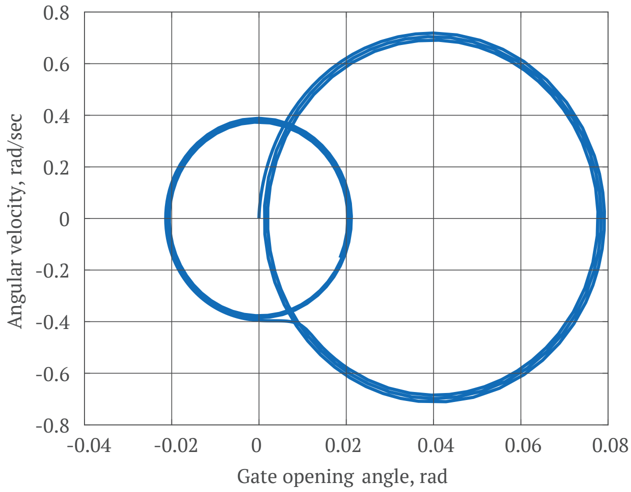

Figure 5. Damper phase diagram
Source: developed by the authors

The results of modelling the air intake damper drive, which uses a stepper motor with a gearbox, showed the possibility of accurately describing the dynamics of the drive and accounting for its delays or inertia in the overall control system. The model allows adjusting the parameters of controllers, such as PID controllers that control the damper, analysing the impact of the damper's mass, the moment of inertia of the gearbox, or the gear ratio on the system's responsiveness, and increasing energy efficiency by minimising drive overloads through optimal tuning of the K and T coefficients. Based on the simulation of the air intake damper drive, graphs of the dynamics of the main quantities were obtained: armature current, angular velocity, and damper opening angle (Fig. 3). The analysis of these graphs allows concluding that the proposed mathematical model adequately reflects the dynamic processes in the system. All key parameters demonstrate physically justified behaviour, confirming the correctness of the chosen model structure and the parameters used. The graph in Figure 3a shows the characteristic shape of the transient process of the motor armature current. In the initial phase, when the control signal is applied, the current increases rapidly, which corresponds to the need to overcome inertial and frictional forces in the drive. After that, a decline to a stationary level is observed, corresponding to the steady-state operating mode. Such dynamics indicates the correct consideration of the motor's electrical parameters, particularly the inductance and active resistance of the armature winding. The graph in Figure 3b demonstrates the change in angular velocity over time. It is evident that the system quickly reaches the set speed value without excessive oscillations or prolonged oscillatory processes. The transient process is smooth, with a slight initial oscillation, indicating the presence of some damping in the system, provided by viscous friction and correctly selected structural stiffness. In the stabilisation phase, the speed is maintained at the set level, indicating adequate controller operation and appropriate system inertia. The graph in Figure 3c, depicting the damper opening angle, confirms the linearity and predictability of the actuator's movement. In the activation phase, the system demonstrates a gradual increase in the opening angle to the set value, and after the termination of the control signal, a smooth return to the initial position. The absence of sudden jumps or delays indicates the harmonious interaction of the electrical and mechanical subsystems.

For a deeper analysis of dynamic processes in the system, a spatial trajectory was constructed (Fig. 4), which reflects the evolution of the system's state in the three-dimensional phase space (coordinates: current – velocity – position). The analysis of Figure 4 demonstrates that the drive's movement has clearly defined transient phases characteristic of the activation and deactivation phases of the control signal. During the current increase (initial activation phase), the angular velocity and damper position increase simultaneously. At the final stage, a damping of dynamics is observed – the current and velocity gradually decrease to zero, and the position returns to the starting point. Such a scenario indicates the physical consistency of all model parameters and confirms its correct parameterisation. The absence of reciprocating motions or twisted cycles in phase space confirms the well-tuned damping of the system. The phase diagram (Fig. 5), constructed in the plane "angular velocity – opening angle," demonstrates a characteristic hysteresis loop that arises in response to the reversible movement of the actuator. The diagram clearly shows a closed cycle, which reflects the sequence of opening and closing the damper. At the same time, the direction of the loop indicates the presence of energy losses due to friction and inertia. The loop's shape is asymmetric, which is typical for systems with nonlinear mechanical properties. The presence of hysteresis is an important characteristic, as it indicates the specifics of energy exchange between the electrical and mechanical parts of the drive.

The small width of the loop indicates high stability and low vibration in the system.

The behaviour of the electromechanical system significantly depends on the key parameters of the model. In particular, the stiffness of the damper drive K_{sh} directly affects the dynamics of oscillations in the phase space. With an increase in K_{sh}, the system becomes stiffer, leading to a reduction in the amplitude of oscillations of the opening angle during transitions between phases. At the same time, excessive stiffness can cause mechanical stresses, which are undesirable for the structure. The armature winding resistance R_a and inductance L_a determine the response speed of the system's electrical part. An increase in R_a leads to a decrease in the armature current at a constant voltage, which reduces the torque and slows down the opening/closing of the damper. At the same time, an increase in L_a slows down the current rise, thereby extending the transient processes. The torque constant K_m determines the efficiency of converting current into torque. With an increase in K_m, the damper opens faster, but this also increases the likelihood of oscillations in case of insufficient damping. For its part, the EMF constant K_e acts as negative feedback – its increase stabilises the system, reducing the current as the speed increases. The variation of the control signal also critically affects the behaviour of the drive. The proposed model uses a rectangular shape of the control voltage with phases "off – on – off." This approach effectively illustrates the system's response to instantaneous voltage activation, but in real conditions, it is advisable to consider smoothing the edges or using harmonic signals to reduce peak loads. Thus, the obtained graphs allow not only analysing the basic dynamics of the system but also investigating the influence of specific structural and electrical parameters on the stability, responsiveness, and smoothness of the drive's operation. This serves as a basis for the further synthesis of control systems and digital twins with a high degree of correspondence to real objects.

Significant attention to the problems of electric drive dynamics was found in the work of D. Magalhaes & F. Kazanc (2022), which analyses electric drive systems in the context of combustion process control. The authors emphasise the need to adapt drives to variable loads and unstable operating modes. In this work, as in the mentioned publication, it is shown that the inertia and controller structure of the drive significantly affect the accuracy of air supply and flame stability. However, unlike D. Magalhaes & F. Kazanc (2022), where attention is focused on the system level of thermal process control, this study emphasises detailed modelling of one of the actuators – the damper drive, taking into account inertial, electrical, and structural characteristics. In the study by H. Jia *et al.* (2024), multi-drive configurations of gas burners were considered, and it was established that the synchronisation of the operation of individual drives (fan, damper, drum) critically affects combustion efficiency. This is confirmed by the obtained results: in particular, according to the dynamics graphs (Fig. 3), it is evident that with proper tuning of the K and T coefficients, the system ensures rapid and stable achievement of the set damper position, which contributes to reducing transient oscillations and increasing the accuracy of fuel-air mixture regulation. A. Pulatov *et al.* (2023) and S.S.H. Bukhari (2023) investigated methods for optimising asynchronous drives, focusing on improving energy efficiency by adapting drives to load changes. Their approach, as in this work, is based on creating models sensitive to environmental parameters. However, in the mentioned publications, the object is mainly pumps and ventilation units, whereas in this work, it is a stepper motor with a gearbox, the specifics of which require a different structural construction of the model and different approaches to its parameterisation.

The results of P.A. Masset *et al.* (2023) are interesting, as they demonstrated the effectiveness of using permanent magnet synchronous motors for drives in burners. In their work, they emphasised the stability of the temperature profile achieved through high-precision control. A similar effect – minimising overshoot and rapid transition to steady-state mode – is observed in the phase and spatial trajectories of the presented model (Figs. 4-5). The difference is that this study analysed energy losses in the drive dynamics, particularly through the analysis of the hysteresis loop, which is not presented in the work of P.A. Masset *et al.* (2023). The study by M. Kaminski *et al.* (2023) proposed the use of neural networks for automatic tuning of electric drives. In this case, although deep learning was not applied, it was shown that parameter tuning based on spatial and phase dynamics can produce a similar adaptive effect, particularly ensuring overload reduction and performance stabilisation under load changes. The publication by K. Oliinyk (2021) examined hybrid electromechanical spindle systems. Although the modelling object differs, the author also focused on the integration of electromechanics and dynamic analysis, as we did. The use of phase diagrams to assess system stability is also common. The advantage of the studies presented in this work lies in the deeper consideration of electromagnetic feedback through the (*ke*) parameter, which is important in drives with precise positioning.

S.D. Bangera *et al.* (2021) studied automatic temperature regulation using drives. They showed that the accuracy of opening/closing dampers affects the thermal inertia of the system. This study confirms this: when modelling a damper with an opening angle of up to 0.12 rad (≈7°), a stable system response without oscillations was observed, which is critical for burners with sensitive temperature zones. In the publication by S. Zhang *et al.* (2023), the impact of different motor types on energy efficiency was investigated. Their results confirm the observation made: with an increase in the motor's torque (*Km*), there is a reduction in the time to reach the required damper position, but this can cause oscillations if the system is insufficiently damped. This trade-off is also reflected in the phase diagram, where at certain parameter values, the trajectory demonstrates asymmetry related to the nonlinearity of feedback processes. Against the background of other works, such as T. Gammaidoni *et al.* (2023), R.R. Singh *et al.* (2023), and S. Verma *et al.* (2024), which consider modelling as part of the digital twin concept, the presented model has a higher level of detail for a specific actuator component – the damper drive. This makes it suitable for use not only in global modelling but also in real-time for adaptive diagnostics, which is its practical advantage. An important aspect that distinguishes this study among the reviewed works is the presence of an integrated analysis of drive dynamics in both the time, phase, and spatial domains. This approach allows not only describing transient processes in the system but also forming criteria for stability, damping, and adaptability, significantly expanding the possibilities of practical model application. For example, the damper phase diagram obtained as a result of simulation enables visually determining the zones of stability and inertial sensitivity of the system to changes in the input signal or load. This was not demonstrated in the works of other authors, where the focus is mainly on output characteristics or thermal effects.

Another important result of the conducted study is the quantitative assessment of the influence of electrical parameters R_a, L_a, K_m, K_e on the responsiveness and stability of the drive. This allows optimising the system at an early design stage without the need for an extensive numerical experiment. The performed work combines the accuracy of analytical modelling and the efficiency of simulation analysis, ensuring a high level of model correspondence to the real system. Comparison of the results with similar studies confirms the feasibility of using a stepper motor with a gearbox in such a system, given its positioning accuracy and simplicity of implementing digital control. At the same time, the created model demonstrates an advantage in terms of adaptive tuning of controller parameters, considering load changes, which distinguishes it from the approaches discussed above.

CONCLUSIONS

Within the framework of the conducted study, a mathematical model of the gas burner's electric drive system was developed, which describes the dynamic behaviour of the main components, particularly the fan motor, the drying drum drive, and the air intake damper. The constructed model reflects the relationship between electrical and mechanical parameters, allowing its integration into automated control systems to enhance the overall energy efficiency and reliability of the thermal engineering process. Particular attention was paid to the analysis of the dynamics of the air intake damper drive, implemented based on a stepper motor with a gearbox. The created model allowed accounting for inertia, time delays, and damping properties of the drive, which is crucial for accurate damper position regulation. The performed computer simulation showed that the maximum armature current at the start of operation was approximately 0.85 A, corresponding to the starting mode for overcoming the static moment of resistance. The angular velocity reached a steady value of 13 rad/s in 0.8 seconds, after which it remained stable without excessive oscillations. The damper opening angle was approximately 0.12 rad (about 7°), which is sufficient to ensure the necessary air supply to the combustion chamber. This behaviour confirms the correctness of the choice of motor parameters and the consistency between the electrical and mechanical parts of the model.

Further analysis of the spatial trajectory (in the coordinates current – angular velocity – position) revealed typical transient processes with a smooth transition to steady-state mode, indicating the presence of effective internal damping in the system. In the phase plane (angular velocity – opening angle), a hysteresis loop is clearly traced, which indicates the stable operation of the drive and the specifics of energy exchange between subsystems. The loop's shape demonstrates the absence of oscillations, allowing the conclusion that the system's dynamics are non-oscillatory and well-damped. The obtained results confirm the feasibility of using complex modelling of electromechanical systems for the purposes of designing and optimising digital control systems for thermal engineering equipment.

The developed model can serve as a basis for implementing digital twins, which provide not only accurate reproduction of the behaviour of a real object but also the possibility of predictive diagnostics, adaptive tuning of control parameters, and effective forecasting of operation under variable load conditions. The application of such approaches contributes to improving energy efficiency and creates a reliable foundation for further digitalisation of thermal control systems. Prospects for further research lie in expanding mathematical models by accounting for nonlinear effects, such as backlash, hysteresis, or real-time load changes, as well as creating an integrated environment for modelling, verification, and implementation of digital twins of electric drive systems in industrial conditions.

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CONFLICT OF INTEREST

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Ігор Болбот
Доктор технічних наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-5708-6007

Олексій Словіковський
Аспірант
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0001-8912-6256

Математичне моделювання приводу шибера повітрозабірника газового пальника

Анотація. В умовах сучасних вимог до енергоефективності та автоматизації теплотехнічних систем, зокрема газових пальників, важливу роль відіграє розробка точних математичних моделей для опису роботи електричних приводів, що забезпечують функціонування ключових компонентів таких систем. Одним із таких компонентів є привід шибера повітрозабірника, що регулює подачу повітря до камери згоряння, що безпосередньо впливає на ефективність горіння та стабільність роботи пальника. Метою роботи було створення математичної моделі системи електричного приводу газового пальника, яка точно описує динаміку роботи електродвигуна вентилятора, приводу шибера повітрозабірника, приводу сушильного барабана та інших елементів системи. Для досягнення цієї мети були використані методи математичного моделювання динамічних систем, а також чисельні методи розв'язання диференціальних рівнянь в середовищі MATLAB. Моделювання цих процесів допомогло забезпечити високу точність прогнозування роботи системи та її енергоефективність на всіх етапах експлуатації. Основні результати дослідження включали побудову математичної моделі, що описує динамічні процеси в системі приводу, зокрема врахування інерційних характеристик приводу шибера, параметрів редуктора, маси шибера та моменту інерції, впливу маси виконавчого органа на динаміку роботи системи. В роботі побудовано графіки для аналізу тимчасових характеристик системи. Описано динамічні процеси в системі приводу, що мають важливе значення для стабільного та ефективного регулювання повітряного потоку. Розроблена модель дала змогу проводити аналіз перехідних процесів та оптимізувати налаштування регуляторів, зокрема PID-регуляторів, для покращення швидкодії системи. Важливим аспектом була також оцінка впливу параметрів приводу на енергоефективність та стабільність роботи газового пальника. Розроблену модель можна інтегрувати в системи автоматизації газових пальників, що дозволить підвищити їх енергоефективність, забезпечити надійну роботу при різних умовах експлуатації та зменшити ризики перенавантаження приводів за рахунок оптимізації параметрів управління

Ключові слова: електричний привід; імітаційна модель; газовий пальник; система автоматизації; динаміка приводу; кроковий двигун