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УДК 621.3
DOI: 10.37128/2306-8744-2025-1-13

CONCEPT OF CONSTRUCTION OF A MICROPROCESSOR-BASED CONTROL SYSTEM FOR A PIEZOELECTRIC MOTOR

The development of a universal concept for building a microprocessor control system for a piezoelectric motor is extremely important due to the high demands on accuracy and efficiency in controlling such devices. Piezoelectric motors are used in many fields, including microactuators, precise positioning systems, medical devices, and nanotechnology. To ensure stable and accurate operation of these devices, high-tech control systems are required, capable of implementing complex algorithms for precise performance in various conditions.

Despite their advantages, such as high speed and small size, these motors have specific control requirements due to various factors such as vibrations, temperature fluctuations, or nonlinearity of characteristics. Creating a universal control system allows for adapting the technology to various operating conditions and ensuring efficient operation across different fields.

Moreover, the versatility of the concept enables the creation of systems that can operate under changing parameters or in integration with other technologies, which is important for enhancing the reliability and stability of the systems. The development of such systems is especially crucial for micro- and nanotechnologies, where precision and control are decisive factors. This enables the use of piezoelectric motors in new innovative industries, which in turn increases the competitiveness of such technologies on the market.

The article proposes a mathematical model of a piezoelectric motor that accurately describes its response to control signals. It suggests a concept for building a microprocessor control system for a piezoelectric motor, taking into account the limitations on the range of regulating influences and providing for the implementation of a multidimensional method of speed control.

Keywords: *piezoelectric motor, control system, rotation speed, positioning, microprocessor system.*

Introduction. In instrumentation, automation, and robotics, high-precision adjustable drives for linear and rotational motion are required, operating in the micrometer range with accuracy from hundredths of a micrometer to tens of micrometers. Traditional rotary micro-motors, however, typically have insufficient positioning capabilities, and motors with mechatronic converters for converting rotational motion to linear motion fail to provide the required high precision and speed [1]. The most efficient solution for these purposes is the use of piezoelectric actuators [2].

The use of piezoelectric motors (PEM) is extremely relevant due to their unique properties, which open up new possibilities for technological advancements. One of the main advantages of piezoelectric motors is their ability to be miniaturized, allowing them to be used in compact devices such as microrobots or medical instruments [3]. With their high precision and quick response, these motors are employed in systems where exact positioning is needed, such as in microscopes or optical systems.

Moreover, piezoelectric motors are distinguished by their low energy consumption, making them ideal for portable devices with limited energy availability. This feature is especially important in fields like mobile electronics or medical implants [2, 4]. Since piezoelectric materials have no moving parts, they are highly reliable and durable, significantly extending the lifespan of devices.

Due to their adaptability, piezoelectric motors are becoming a key component of modern technologies such as robotics, the Internet of Things (IoT), and integrated control systems. Their characteristics make it possible to use these motors in challenging conditions where traditional motors may be ineffective, particularly in extreme temperatures or vacuum environments. This makes them particularly relevant for industries such as aerospace, aviation, and automotive. Given these advantages, piezoelectric motors are a promising technology for a wide range of applications in the modern world. Therefore, the development of a concept for building modern microprocessor control systems for these motors is a pressing scientific and practical task.

Analysis of Recent Research and Publications. In PEM, the conversion of electrical energy into mechanical energy occurs due to the inverse piezoelectric effect, and the deformation will be equal to [4]:

$$S_x = \frac{\Delta x}{x} = \frac{\partial \xi}{\partial x} = d_{ij} E_x \Big|_{T_x=0} = g_{ij} D_x \Big|_{T_x=0}. \qquad (1)$$

It has become traditional to use linear PEM for positioning drives, where relatively large displacement ranges (up to 10^{-3} m) and high stop accuracy (up to $5 \cdot 10^{-9}$ m) are required [5]. Broadband "adaptive" optics and scanning devices in video equipment are also areas where linear PEMs are widely used [6]. Linear PEMs are structurally quite diverse. The simplest linear designs are tubular and stacked PEM configurations. In stacked PEMs, the actuators are assembled from individual piezoelectric elements (PEs) in the form of rods, discs, or washers, with the number of PEs in a single stack reaching up to 50 or more [7]. The use of a stacked PEM configuration is determined by the need to reduce the control voltage Uy. The allowable electric field strength of piezoceramics is limited to a certain level, so to decrease Uy, the thickness of the PEs must be reduced. The stack is formed by bonding the single-polarity surfaces of individual PEs (usually with metal foil) of 1 mm thickness and connecting them mechanically in series and electrically in parallel [8]. A simplified design of a linear stacked PEM is shown in Fig. 1.

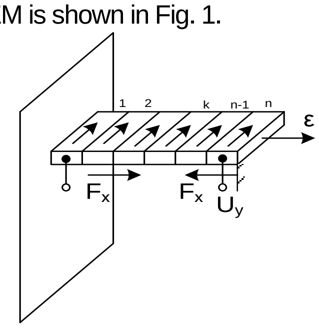

Fig. 1. Simplified design of a linear stacked PEM in the form of parallelepipeds with electrodes on the side faces

The goal of the research is to develop a universal concept for building control systems for piezoelectric motors based on modern microprocessor-based components, which has significantly simplified and accelerated the implementation of such technology in micromechanical systems for various purposes.

Development of a mathematical model of PEM. PEM is kinematically linked to various mechanisms that create displacement. To increase mechanical strength and rigidity, piezoelectric elements (PEs) in PEM designs are compressed against each other using pre-stressed elastic elements (rubber rings, springs) [5]. The hysteresis dependence of the displacement of the moving part of the PEM on the electrical and mechanical stresses is shown in Fig. 2.

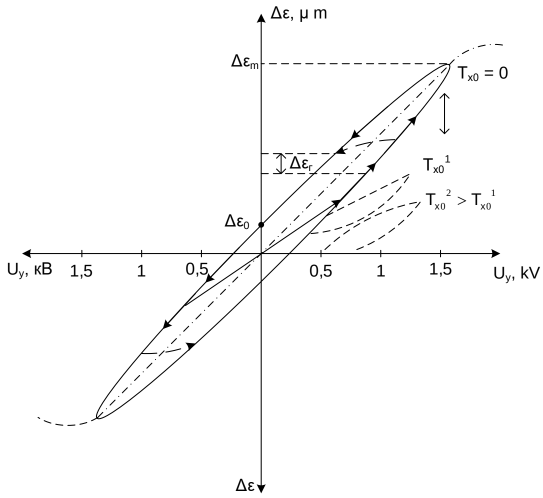

Fig. 2. Hysteresis dependence of displacement on electrical and mechanical stresses

In the quasi-static linear regime, the static characteristic of the PEM can be approximately described by the expression [9]:

$$\Delta\xi_{xp} = k_{1xp} n d_{ij} U_y - k_{2xp} F_x / Y_x^E, \qquad (2)$$

or by making a number of simplifications with acceptable accuracy:

$$\Delta\xi_x \approx k_{1x} n d_{ij} U_y. \qquad (3)$$

In this case, the equation of the inverse piezoelectric effect in the general case has the form [5]:

$$S_x = d_{ij} E_x + s_{ij}^E T_x. \qquad (4)$$

where the indices x and ij are determined by the polarization method of the PE.

In general, when the angle changes, the static characteristic is nonlinear and exhibits hysteresis loops (Fig. 2). The values of the static characteristic are nonlinear variable parameters, with maximum values at the initial (linear) section of the characteristic, which can be approximately described by one of the known analytical expressions for hysteresis loops, for example, in the form of (longitudinal polarization):

$$\Delta\xi\Big|_{T_3=0} \approx k_1 U_y + k_2 U_y^3 + k_3 U_y^5 - \\ -k_4 U_{ym} (1 - U_y^2 / U_{ym}^2)^{n/2} sign \frac{dU_y}{dt}. \qquad (5)$$

In this case, the transfer function of the PED, as a harmonically linearized link, will generally have the following form:

$$W_H = \frac{\xi_{x1}}{U_y} = q(U_{ym}, \omega) + jq^{`}(U_{ym}, \omega) = \\ = A_q(U_{ym}, \omega)\,\mathrm{e}^{j\varphi_q(U_{ym}, \omega)}. \qquad (6)$$

When U_y changes according to the harmonic law, the first harmonic of complex nonlinear oscillations arising at the output of the DER, taking into account (6), will have the form:

$$\xi_x = W_H U_y = qU_y + \frac{q^{`}}{\omega}\frac{dU_y}{dt} = \\ = A_q U_{ym}\sin(\omega t + \varphi_q). \qquad (7)$$

Development of the concept of a microprocessor-based PEM control system. The PEM is a multidimensional, multivariable control object. In such drives, the use of frequency control is limited by narrow boundaries of change, as it leads to a deterioration in PEM characteristics (underutilization of power, speed, and the emergence of acoustic noise). The operating frequency corresponding to the desired speed is usually chosen near the resonance frequency, and the range of change of the operating frequencies is significantly limited (up to 1-1.5%) [9].

The use of amplitude control for the PEM speed also has certain limitations, caused by the specific features of the PEM operation (variability and nonlinearity of parameters, etc.). In this case, conditions for maintaining the balance of amplitudes and phases in the operation of self-oscillating cascades at the required operating frequency may be disrupted, making their operation unstable and potentially leading to noise (such as squeaks).

As a result, there is low accuracy in speed stabilization, especially under strong oscillations. Some mismatch of resonance frequencies, which can be significant in transient modes, also affects the accuracy.

The emergence of noise is related to the fact that changes in the self-oscillating circuit can capture a frequency band larger than the band of silent PEM operation. This leads to fluctuations in the instantaneous speed of the PEM (up to 5% or more of the average speed) and potential excitation of the PEM at the frequency of a parasitic vibration mode [3].

These disadvantages can be partially eliminated by complicating the autooperator circuits, for example, by including various filters in the feedback loop, tuned to the operating resonance frequency, phase-shifting active and passive circuits, or devices that perform the corresponding functions of oscillatory circuits, electromagnetic high-frequency transformers, and piezoelectric elements (PE). Therefore, the use of the amplitude control method in devices with PEMs is limited. In PEM designs where friction force is little dependent on speed (PEMs in sliding mode), the amplitude control method is also not used, as the rotor speed practically becomes independent of the supply voltage. The amplitude method can be used independently only for more stable PEMs (for example, PEMs with protruding spacers) or when working with reduced accuracy, shaft power, efficiency requirements, and under the influence of weak disturbances [3].

The phase control method for PEM speed does not have independent significance and is typically used in conjunction with other methods, i.e., when implementing dual and multidimensional speed control methods in PEM devices [3].

In this context, the implementation of output (end) stages (power modules) in PEM control devices is of great interest. Power modules are typically frequency and amplitude-controlled power amplifiers (PAs). The power amplifier can be made using single-ended, push-pull (half-bridge), or full-bridge circuits. The output of the PA is typically connected in the general case through a corrective link to the input of the PEM directly (without a transformer output) or through a step-up transformer. A power module can be designed using a PA with a single-ended output with an autotransformer oscillatory circuit for impulse excitation, increasing the voltage by 2.5-3 times. A twofold increase is achieved in full-bridge PA circuits, with voltage increase up to approximately 300-400 V. It is advisable to use transformers made with ferrite cores [10]. Since, according to (7), the control characteristic of the PED is linear, the speed of rotation (displacement of the moving part) of the motor, considering the above-mentioned limitations on the control range, will be directly proportional to the voltage applied to the excitation winding by the control system. In this case, the output voltage of the DAC, as the main power block of the control system, depends on the reference voltage source, the resolution of the DAC, and the number supplied to it:

$$U_{вих\ ЦАП} = \frac{N_{вх} \cdot U_{оп}}{2^n}. \qquad (8)$$

where n – DAC bit resolution;
$N_{вх}$ – input code;
$U_{оп}$ – DAC reference voltage.

Let's consider the features of the DAC operation using the example of a standard IC type K572PA1A. This chip is designed to convert a 10-bit direct parallel binary code, presented at the digital inputs, into a current at the analog output, which is proportional to the value of the code and/or the reference voltage. The circuit is implemented using CMOS technology with polysilicon gates.

The DAC K572PA1 consists of a precision resistor matrix of the R–2R type, inverters to control current switches, and two-position current switches, which are made using CMOS transistors.

For the circuit to operate in a voltage output mode, an external reference voltage source and an operational amplifier with a negative feedback loop are connected to the DAC K572PA1. This ensures current addition mode.

The values of the main parameters of the integrated circuit (IC) primarily depend on the accuracy of implementing the relationships $R_{o.c}/R = 1$ and $R/2R = 0.5$ for all branches of the resistor matrix. Therefore, the resistors are designed as geometrically identical regions, which are oriented in the same direction relative to the crystal axes. The reference material used is a thin polysilicon film with high resistance stability, which is grown on the surface of the crystal using vacuum deposition. The current-switch transistors are designed in such a way that their resistance in the open state is sufficiently low and inversely proportional to the through current.

When operating the DAC K572PA1, a number of its specific properties related to its CMOS technology should be taken into account. The current consumed by the chip from the power supply depends on the digital signal levels at the input. At certain signal levels between logical 0 and 1, the current consumption is maximal and can exceed the rated value by several times.

When operating the DAC, the following sequence of applying electrical modes is recommended: ground potential, supply voltage, reference voltage, and voltage on the digital inputs. The voltage removal sequence is the reverse of the application sequence. If the levels of the digital signals do not exceed 5.5 V, the sequence of mode application can be arbitrary.

To ensure the function of unipolar conversion of the code into voltage at the output, the circuit shown in Fig. 3 is proposed.

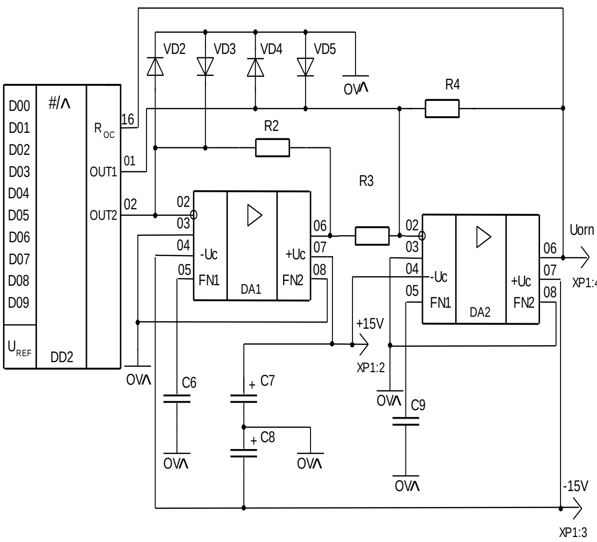

Fig. 3. DAC connection diagram

According to the schematic (Fig. 3), the output voltage is formed in the range from 0 to 36 V. To ensure that the accuracy and speed characteristics of the DAC are not degraded, it is necessary to correctly choose the external operational amplifiers (OPs). It is recommended that the OP's offset voltage does not exceed 5 mV, and the settling time should not be greater than 2-5 µs. In this circuit, the OP K154UD3 is used, which has an offset of 8 mV and a settling time of 0.5 µs.

To protect the converter from interference in the OP's power circuits, capacitors are used. To protect the DAC outputs from accidental negative voltage, it is advisable to ground them or connect them through Schottky diode limiters (KD514A).

The main element of the overall system control circuit is the microprocessor. For the required functions, the microprocessor K1816VE751 is chosen, which is a complete analog of the well-known microprocessor K1816VE51, with the distinction that it has an extended capability for direct control of a non-volatile memory device (EPROM) [11]. The package pinout is of the MK51 microcontroller type.

The MK51 requires a single power supply source of +5 V. Through four programmable input/output ports, the MK51 interacts with the environment in the TTL logic standard with three-state output.

The MK51 package has two pins for connecting a quartz resonator, four pins for signals that control the operating mode of the MK, and eight lines of port 3, which can be programmed by the user to perform specialized (alternative) functions for information exchange with the environment.

When the power supply is turned on, the state of the processor's data memory (RAM) and control registers is undefined. Random values can be stored in the registers. Therefore, the program written in the program memory can start from any location, as the Program Counter (PC) contains an arbitrary value. As a result, it is necessary to organize an automatic reset of the processor when power is supplied.

The reset of the microchip is performed by the RST signal (with a high voltage level being active) if the processor is supplied with an external synchronization signal or connected to a quartz resonator. The RST input is the input of an internal Schmitt trigger.

To ensure that the processor is reliably reset, the duration of the high-level signal at the RST input must be at least two machine cycles (24 clock periods of the synchronization frequency). At a synchronization frequency of 12 MHz, the external reset signal must last at least 2 µs. Upon receiving the external reset signal, the microprocessor generates an internal signal.

The external reset signal is asynchronous relative to the processor's internal synchronization. The state of the RST output is checked during the S5P2 phase of each machine cycle. After the reset signal is applied to RST, the processor continues operating for a period of time between 19 and 31 clock cycles (forming ALE, PME, etc.). After a "0" signal is applied to the RST input, between 1 and 2 machine cycles pass before the formation of ALE, PME.

Upon receiving the reset signal, the internal algorithm of the microprocessor performs the following actions: it sets the program counter (PC) and all special function registers (except for the port latch registers P0-P3, stack pointer SP, and SBUF register) to zero; the stack pointer takes the value of 07H; it disables all interrupt sources, timer/counter operation, and serial port operation; selects bank 0 of RAM; prepares ports P0-P3 for data reception; configures the ALE and PME outputs as inputs for external synchronization; in the special function registers PCON, IP, and IE, reserved bits take arbitrary values, and all other bits are reset to zero; random values are written to the SBUF registers; and the port latches for ports P0-P2 are set.

The reset signal does not affect the internal data RAM. After power is turned on, the contents of the internal data RAM cells take random values.

The schematic diagram for connecting the microcontroller to implement automatic reset upon power-up is shown in Fig. 4.

For an n-MOS microcontroller, automatic reset when the power is turned on can be implemented by connecting the RST input to the power rail through a 10 μF capacitor and to the ground rail through an 8.2 kΩ resistor. For a CMOS microcontroller, this resistor is not necessary, but it will not cause any harm.

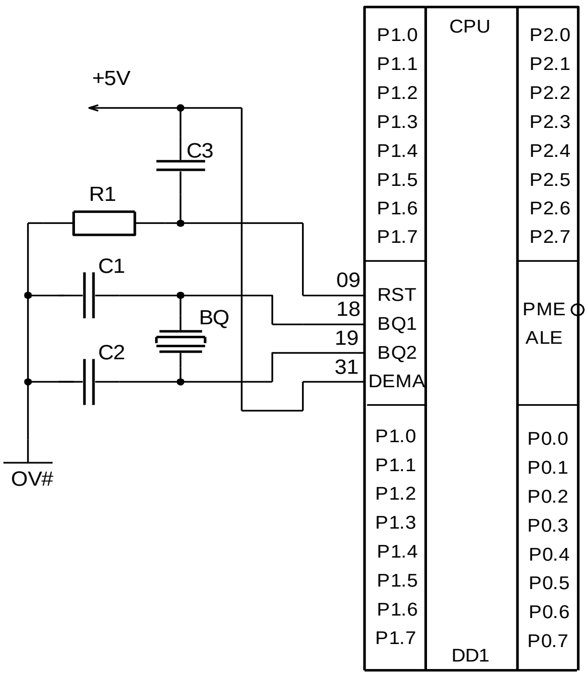

Fig. 4. Circuit diagram of automatic processor reset upon power-on

Conclusions and Directions for Further Research. The proposed mathematical model of the PEM accurately describes the response of the piezoelectric motor to control signals. An analytical expression has been derived for the first harmonic component of the total loading force on the ceramic beam, which forms the basis of the motor.

A concept for the development of a microprocessor-based control system for the piezoelectric motor has been proposed. This system takes into account the limitations on the range of control influences and provides for the implementation of a multidimensional speed control method for the PEM.

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КОНЦЕПЦІЯ ПОБУДОВИ МІКРОПРОЦЕСОРНОЇ СИСТЕМИ КЕРУВАННЯ П’ЄЗОЕЛЕКТРИЧНИМ ДВИГУНОМ

Розробка універсальної концепції побудови мікропроцесорної системи керування п’єзоелектричним двигуном є надзвичайно важливою через високі вимоги до точності та ефективності керування такими пристроями. П’єзоелектричні двигуни застосовуються в багатьох сферах, зокрема у мікроактуаторах, системах точного позиціонування, медичних приладах та нанотехнологіях. Для забезпечення стабільної та точної роботи цих пристроїв потрібні високотехнологічні системи керування, які можуть реалізувати складні алгоритми для точної роботи в різних умовах.

Такі двигуни, попри свої переваги, як висока швидкість та малий розмір, мають специфічні вимоги до управління через різноманітні фактори, як-от вібрації, температурні коливання чи нелінійність характеристик. Створення універсальної системи керування дозволяє адаптувати технології під різноманітні умови експлуатації та забезпечити ефективну роботу в різних сферах.

Крім того, універсальність концепції дає змогу створювати системи, які можуть працювати в умовах змінюваних параметрів або в інтеграції з іншими технологіями, що важливо для підвищення надійності та стійкості систем. Розвиток таких систем є особливо важливим для мікро- та нанотехнологій, де точність і контроль мають вирішальне значення. Це дозволяє застосовувати п’єзоелектричні двигуни у нових інноваційних галузях, що, в свою чергу, підвищує конкурентоспроможність таких технологій на ринку.

У статті запропонована математична модель п’єзоелектричного двигуна, що з достатньою точністю описує його реакцію на управляючі сигнали. Запропоновано концепцію побудови мікропроцесорної системи керування п’єзоелектричним двигуном, що враховує обмеження на діапазон зміни регулюючих впливів та передбачає реалізації багатовимірного способу управління швидкістю.

Ключові слова: *п’єзоелектричний двигун, система керування, швидкість обертання, позиціонування, мікропроцесорна система.*

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