An Inertial Piezoelectric Drive with an Electrodynamic Actuator

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Abstract—In this paper, we study the performance of inertial linear-rotary piezoelectric drives under conditions that impede starting: lowered voltage, long idle time, high axial load, and the use of polymer materials. The application of an electrodynamic actuator for solving this problem is considered. The design of the passive actuator consisting of a magnet and a metal rod, as well as the actuator alignment procedure, is presented. Based on a system of electromechanical analogies, a model of an inertial drive with an electrodynamic actuator is described. This model was used to study a drive with an actuator, and the results of the study are presented. The actuator is shown to have two operation modes depending on the rotation direction of the drive. The features of the drive operation in these modes are described. In addition, the model showed that the actuator efficiency significantly decreases at small deformations of the piezoelectric element. In an active electrodynamic actuator, a magnet and a solenoidal coil are used to additionally affect the piezoelectric elements of the drive. The operation features of the active actuator are considered. A prototype of an inertial piezoelectric linear-rotary drive with an electrodynamic actuator is described, and the results of its tests and recommendations on the use of active and passive actuators are provided.

Inertial piezoelectric drives [1—3] of nanodisplacement are used in high-precision positioning systems with low load capacity. In the general case, this drive is a piezoelectric element loaded with a kinematic friction pair (the running gear) from one end and an inertial element from the other. The drive is controlled by asymmetrical sawtooth signals. During the slow (fractions-units of seconds) front of the control signal, gradual deformation of the piezoelectric element and displacement of the inertial elements occur. In this case, the kinematic pair is motionless. After a fast (fraction-units of milliseconds) cutoff of the control signal, the inertial elements cannot also quickly return to their initial position and so movement begins and displacement of the kinematic pair of the drive occurs.

Despite the simplicity of the design and high level of accuracy of movements, inertial drives have a number of disadvantages [2] limiting their application:

—high control voltages; and

—difficulty in being reactivated after long stops (the absence of movement under the effect of control signals).

A high voltage is necessary in inertial drives for the formation of deformations and shear forces providing element displacement of the kinematic pair of the drive [4]. At an insufficient amplitude of the control

signal, an increase in the axial load, and kinematic pair contamination, the drive's startup is significantly complicated and the value of the step motion becomes unstable. Difficulty in activation also occurs if one or both of the elements of the kinematic pair are made of plastic. In this case, a significant difference arises between the friction coefficients of rest and sliding (up to four times in dynamics and up to ten for a prolonged rest of the kinematic pair [5, 6]). This is due to the fact that the preliminary displacement of the polymer (as well as the lubricant if available) is larger than that of metals, while the energy spent on deformation differs from the energy stored in the deformed volume [4, 7].

An increase in the number of piezoelectric elements and a change in the shape and duty cycle of the control signals allow the drive's startup to be somewhat simplified. However, it is more promising to use additional structural elements, for example, sources of electrodynamic effects [8] on the moving parts of the drive. A design of a drive with such a source (an actuator) is shown in Fig. 1a. The drive consists of screw *1*, nut *2*, fastening element *3* mounted rigidly on the screw, bimorph piezoelectric element *4*, and inertial element *5*. A permanent magnet can be used as the inertial element. The drive's actuator consists of coaxially located magnet *5*, glass guide *6*, and metal rod *7*. The magnet is rigidly fixed to bimorph element *4* and
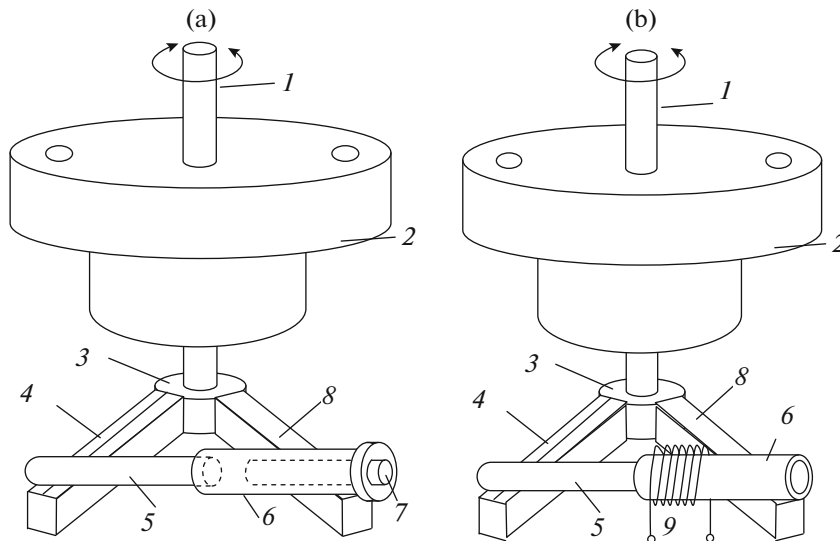
Fig. 1. Inertial drive device: (a) circuit with a passive electrodynamic actuator and (b) circuit with an active electrodynamic actuator.
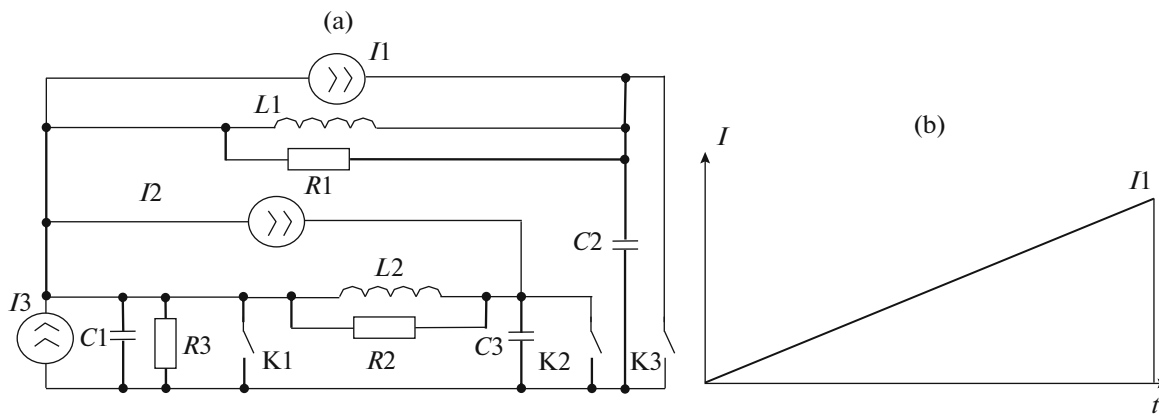

Fig. 2. Inertial drive: (a) equivalent circuit and (b) shape of the control signal.

moves freely in guide *6*, which is mounted on auxiliary holder *8* connected to fastening element *3*. To achieve maximal efficiency of the actuator avoiding the magnet and rod adhesion, it is necessary to adjust initial distance x_0 before using the drive. For this purpose, rod *7* (Fig. 1b) can be fabricated, for example, in the form of a stud with a nut, while the screw end can be equipped with a nonmagnetic gasket. In this case, the adjustment procedure will be to reduce distance x_0 to the value at which deformation of the piezoelectric element begins.

The effect of the magnetic actuator at a qualitative level was evaluated using a drive model that is based on equivalent circuits of a bending piezoelectric element and a load at its ends that were constructed according to a system of electromechanical analogies (speed, angular velocity—voltage; force, angular momen-tum—current; mass, body inertia moment—capacity; compliance, angular compliance—inductance; mechanical mobility, friction conductivity—resis-tance). The drive model with two piezoelectric elements is shown in Fig. 2a. Inductance $L1$ and $L2$ are used to represent the angular compliance of the piezo-electric elements ($L1 = L2$), and resistors $R1$ and $R2$ are used to represent their mechanical conductivity ($R1 = R2$). The load of the piezoelectric elements is the inertia moment of fastening element $C1$ and the inertia moments of inertial elements $C2$ and $C3$ ($C2 = C3$), as well as the mechanical friction conductivity in screw—nut pair $R3$. Sources $I1$ and $I2$ serve for the for-mation of sawtooth control signals (Fig. 2b). In addi-tion to the control action, source $I2$ includes action of the electrodynamic actuator I_{EM}:

$$I2 = I1 + I_{EM}.$$

The I_{EM} value is determined by the following expression:

$$I_{EM} = \frac{k}{(x_0 - x)^2}, \qquad (1)$$

where x_0 is the distance between the end surfaces of magnet *5* and rod *7* (Fig. 1a) at an undeformed bimorph element, x is the deformation of the bimorph element, and k is the interaction coefficient:

$$k \leq F_{ad} l_{PE} x_{res}^2,$$

where x_{res} is the minimal magnet-rod distance in the actuator, F_{ad} is the magnet adhesion force, and l_{PE} is the length of the piezoelectric element.

Current source *I*3 in the equivalent circuit (Fig. 2) of the drive simulates a stepwise change in the dry friction force depending on the speed of the screw:

$$I3 = M_{s.f.} \operatorname{sgn}(V(C1)),$$

where $M_{s.f.}$ is the moment of sliding friction obeying Amonton's law and $V(C1)$ is the voltage on capacitor $C1$. The key K1 sets the phases of relative rest and displacement of elements of a kinematic pair. The key K1 is closed when the following conditions are met:

$$V(C1) = 0,$$

$$|i(L1) + i(L2)| \leq M_{s.f.}.$$

The key K1 is opened if the condition is not met:

$$|i(L1) + i(L2)| > i_0, \qquad (2)$$

where $i_0 = M_{r.f.}$ is the moment of rest friction. The keys K2 and K3 simulate the restriction of the magnet-rod distance and are closed when the following condition is met:

$$(x_0 - x) \leq x_{res}.$$

Studies of the inertial drive that were performed using the presented model showed the following. Depending on the deformation direction of the piezoelectric element (direction of actuator rotation), two interaction modes of the actuator elements are possible. The first mode occurs when the actuator elements approach each other at the front end of the control signal, while the second mode occurs when the actuator elements approach each other during the cutoff formation. In the first mode, the actuator increases the deformation of the piezoelectric element and, therefore, the stepwise movement and the duration of the transients increase. In the second mode, the actuator additionally acts on the end of the piezoelectric element during the cutting of the control signal, which promotes the fulfillment of condition (2).

Figure 3a shows typical graphs of inertial element movement when using a actuator (mode 1) and without one. The graphs were obtained with the following
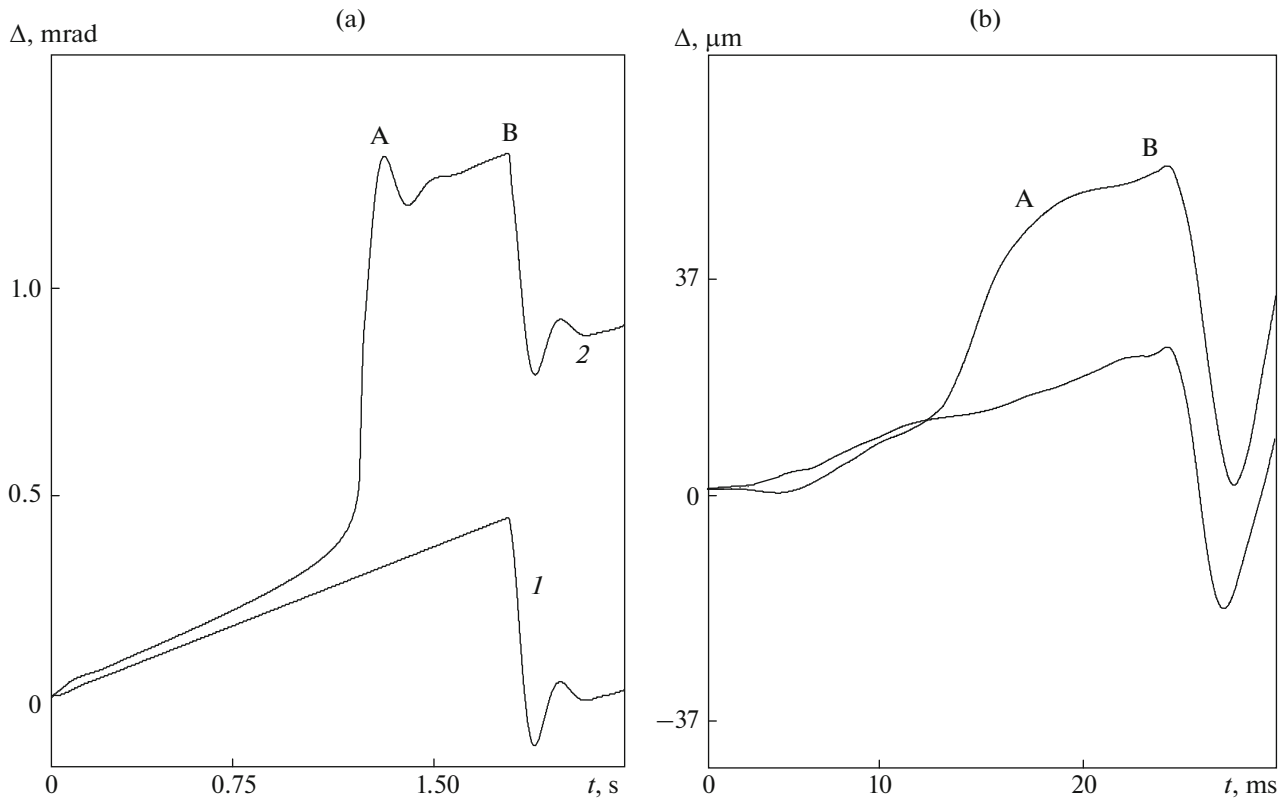
Fig. 3. Effect of the actuator on the movement of the drive ((*1*) without an actuator and (*2*) with an actuator): (a) simulation results and (b) results of measuring the tangential displacement of the end of the bimorph element.
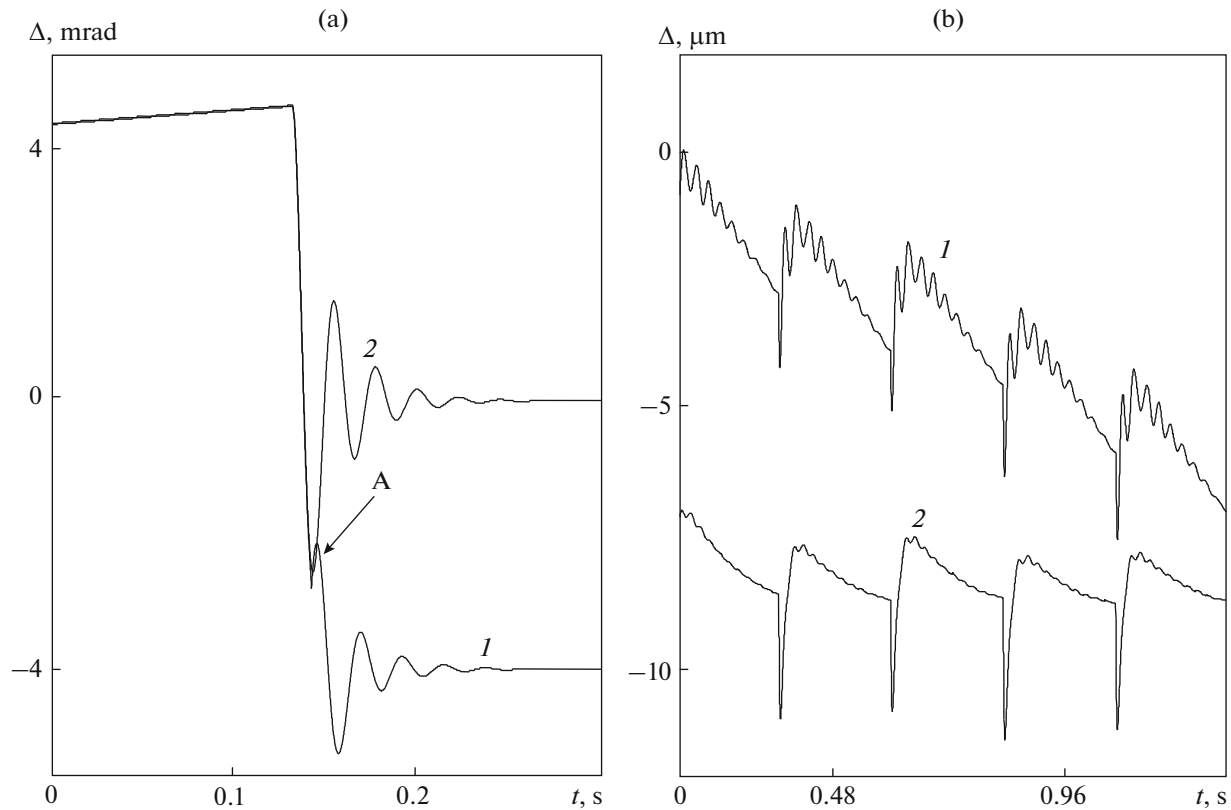
Fig. 4. Effect of the actuator on the drive movement when forming a cutoff of the control signal ((*1*) with a actuator and (*2*) without a actuator): (a) simulation results and (b) screw displacement.

model parameters: $L1 = 1.5$ H, $R1 = 468$ Ω, $C2 = 0.0006$ F, $C1 = 0.00004$ F, $I3 = 0.0057$ A, $i_0 = 0.0067$ A, $R3 = 1500$ Ω, amplitude of the source $I1$ is 7.5 mA, the front duration is 1.9 s, the cutoff duration is 2 ms, $x_0 = 600$ µm, $x_{res} = 5$ µm, and $l_{PE} = 5$ cm. Figure 3a (curve *2*) shows that the movement of the end of the piezoelectric element increases in the presence of an actuator. In this case, the onset of moving the kinematic pair can begin even before the control signal is cut (section AB, Fig. 3a). This is confirmed by the measurement of the tangential displacement of the drive piezoelectric element (Fig. 3b).

The effect of the actuator during the cutoff formation (Fig. 4) consists in acting on the end of the piezoelectric element. This produces an additional moment allowing the friction force in the kinematic pair of the drive to be overcome. The corresponding region in Fig. 4a is indicated by an arrow (distinguishing model parameters for which Fig. 4a is obtained: $I1 = 6$ mA, $x_0 = -250$ µm, $I3 = 0.0037$ A, and $i_0 = 0.0057$ A). In this case, a side effect of the actuator is an insignificant increase in the oscillatory nature of the transient (Fig. 4b).

Studies of the considered drive model also allowed establishing that the actuator efficiency is significantly reduced at small deformations of the piezoelectric ele-

ments due to the narrowing of the range of the difference $(x - x_0)$, expression (1). This drawback can be eliminated by using an active actuator (Fig. 1b) with solenoidal coil *9* used instead of a metal rod. An active actuator has the following advantages:

—the actuator operates in a wider range of the relative coil-magnet distance;

—simplified adjustment of actuator elements;

—performance at small deformations (tens of microns or less) of the piezoelectric drive element; and

—the ability to control the starting effect.

It is advisable to use an active actuator when forming the front of the control signal since its inclusion in the process of cutoff formation is limited by low performance. Figure 5 presents the simulation results of the drive operation and the results of measuring displacements with an active actuator $I_{EM} = 1.5$ mA (curves *1*) and without one (curves *2*).

An additional effect allowed increasing the deformation of the piezoelectric element (similar to the first mode of the passive actuator) and to simplify the fulfillment of conditions (2). Unlike the passive actuator, it is possible to provide the same conditions for starting the drive in both rotation directions (clockwise and counterclockwise) and combine the movement onset
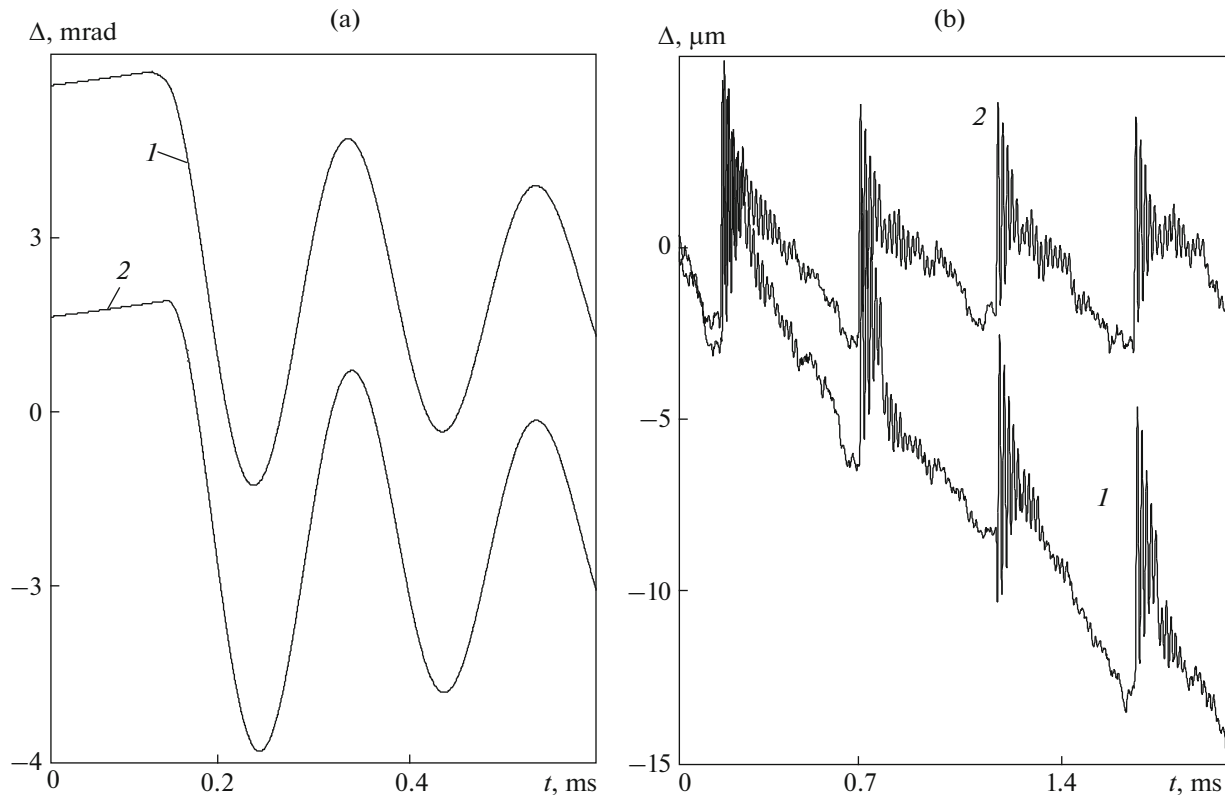
Fig. 5. Effect of the active actuator on the movement of the drive ((*1*) with an actuator and (*2*) without an actuator): (a) simulation results and (b) result of measuring screw movements.

with the beginning of the cutoff formation by controlling the current value in the solenoid.

Thus, the presence of an electrodynamic actuator simplifies the start of the inertial drive. The use of a passive actuator can be justified for actuators with bimorph piezoelectric elements having a relatively large (fraction of a millimeter) range of deformations. The active actuator may be recommended for high-precision actuators with small deformations of the piezoelectric element. In addition, the actuator allows the use of low-voltage sources of control signals and reduces the number of piezoelectric elements necessary to overcome the friction forces in the drive kinematic pair.

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Translated by A. Ivanov