559. Simulation of vibrational piezoelectric actuators of the micro-robot using the finite element method

V. T. Minchenia[1], D. A. Stepanenko[1], CK. Zimmerman[3], R. Bansevičius[4], A. Bubulis[4], P. Kundu[2], I. A. Gishkeliuk[2]
[1] Belarusian National Technical University (BNTU),
220027, Minsk, Nezovisimosti avenue 65,
E-mail: *vlad_minch@mail.ru*
[2] The International Institute on Radio Ecology of A. D. Saharova,
220027, Minsk, Dolgabrodskaja street 23
[3] The Ilmenau University of Technology, PF 100565, D-98684, Ilmenau
[4] Kaunas University of Technology, Lithuania

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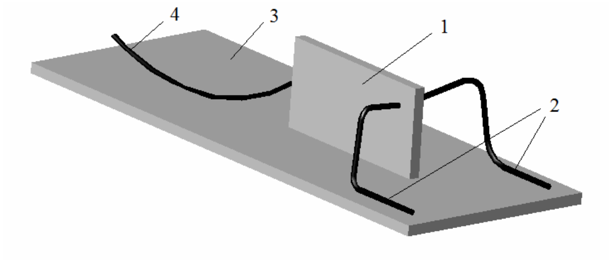
Abstract. This paper describes a micro-robot with the vibrational piezoelectric actuator that was developed and tested using finite element method. Dependency of the robot motion speed on vibration frequency and coefficient of friction of the actuating elements and bearing surface has been investigated. The principle for motion control of the robot has been described and potential domains for its application have been discussed.

Keywords: vibration, piezoelectric actuators, micro-robot, finite element method.

Introduction.

Recently, vibrational piezoelectric actuators-based (VPA-based) moving systems have become highly prevalent in fields of engineering and medicine as such actuators feature an extremely high coefficient of efficiency, low energy consumption, and can be easily miniaturized [9]. The following represent the main domains for application of VPAs: development of precision systems for micro- and nano-positioning of different objects, development of mobile micro-robots and micro-automated devices intended for different technological task-solving. The object of current research paper – a single VPA element-based micro-robot. Fig. 1 illustrates conceptual diagram of the robot structure as well as images of the actual prototype.

The robot under consideration consists of bimorph piezoelectric component 1, that generates bending vibrations, and spatially curved cane segments 2 (actuating elements or “legs”), attached to the lateral surface of the piezoelectric element that transform its vibrations depending on amplitude and direction. In result of transformation of vibrations depending on direction, ends of “legs” that interact with the bearing surface 3, shall represent a complex trajectory, i.e., elliptical, while ensuring movement and relocation of the robot in relation to the bearing surface. Increase in vibration amplitude of the actuating elements allows for increasing speed of such movement. In order to add more steadiness to its operation, it is additionally provided with the bearing element 4 (“tail”). Control of robot movement is accomplished through asymmetry in its “legs” operation, i.e., through assigning different geometric parameters. Due to asymmetry in its operation, “legs” of the robot will have different resonant frequencies, and will generate near-resonant vibrations with different amplitudes. Direction of the robot movement will change depending on the ratio of these amplitudes.



a)

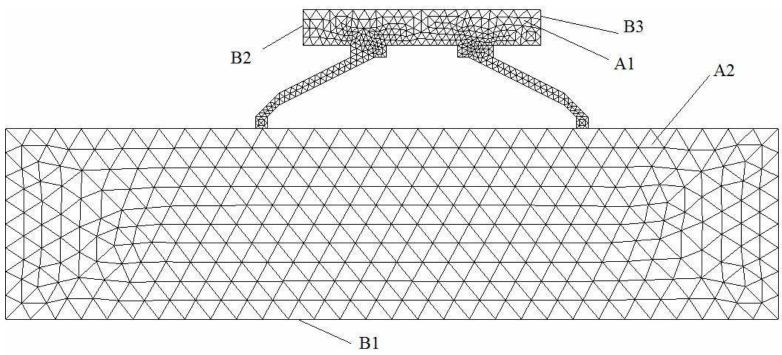
b)

Fig. 1. VPA-based micro-robot: a) diagram of structure; b) photo image of the actual device: 1 – bimorph piezoelectric component, 2 – curved cane segments, 3 – bearing surface, 4 – bearing element

Similar principle of mobile robot control is described in paper [2]. In order to ensure high speed of the robot relocation in relation to the bearing surface and enable the robot to move on rough bearing surface, it uses the actuating elements that are realized in the form of lever-type four-link chains with the flexible hinges and ensure increase in vibrations amplitude. Actuating elements are made with different specific vibration frequencies, which in turn allows for controlling direction of the robot relocation with respect to the bearing surface by changing vibration frequencies. VPA operation involves two unimorphic piezoelectric elements. A phase-shift appears between vibrations of piezoelectric elements which allows generation of elliptical trajectory of the movement of actuating elements ends that are interacting with the bearing surface.

The main disadvantage of the robot is a complex structure of its actuating elements that in turn limits its miniaturization chances. Another widely known structure of the micro-robot involves robot control by means of external vibration field [3]. The robot is present on the vibrating surface and has bearing elements with different resonant frequencies resulting in vibration of bearing elements at different amplitudes, the ratio of which defines direction of the robot movement.

In the context of selecting the optimal parameters for the structure of the robot under consideration, and development of algorithms for its movement control, its mathematical and computerized simulation is of high interest. Given the fact that simulation of robot operation represents an extremely complex task involving recording of phenomena such as piezoelectric effect, contact interaction of actuating elements with bearing surface, as well as transformation and amplification of vibrations in a body by actuating elements, the finite element method was selected for the purpose of simulation as it represents a flexible tool applicable for the research of complex technical systems, and is successfully implemented in several computer programmes available on the market, for example *ANSYS Multiphysics* and *COMSOL Multiphysics* [8,10].



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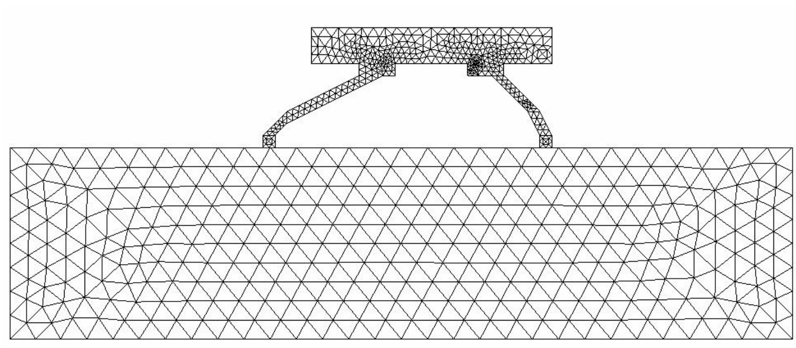

b)

Fig. 2. Effects of vibration frequency and coefficient of friction on micro-robot movement speed were examined

Simulation methodology

Since research of 3D finite element model of the robot under consideration requires significant computational time, a 2D model was analyzed as the first approximation (Fig. 2).

Simulation was performed by using module of *Structural Mechanics* in *COMSOL Multiphysics*. Body and actuating elements of the robot under consideration were introduced as area A1, and bearing surface – as area A2. The lower border-line B1 of the area A2 was fixed at all the possible levels of its looseness in order to avoid potential movement of it as a solid body. Lateral border-lines B2 and B3 of the area A1 were subjected to periodically varying forces $F_1(t)$ and $F_2(t)$ that cause deformation in the robot body while simulating a piezoelectric effect. Two different types of a model were analyzed. In the model of type 1 (Fig. 2a), the area A1 featured symmetric geometry, whereas force action was asymmetric in nature, and conformed with the following laws of force variation in time:

$$F_1(t) = F_0 \sin(2\pi f t)\phi(\sin((2\pi f t)), \quad (1)$$

$$F_2(t) = F_0\sin(2\pi ft)(1-\phi(\sin((2\pi ft))), \quad (2)$$

where F_0 – amplitude of the force action, f – frequency of the force action, t – temporary variable, $\phi(\cdot)$ – Heaviside unit step function.

In the model of type 2 (Fig. 2b), the area A1 featured asymmetric geometry, and force action was symmetric in nature, i.e.:

$$F_1(t) = -F_2(t) = F_0\sin(2\pi ft). \quad (3)$$

Solution of the dynamic task was reduced to the solution of sequence of static problems, for the purpose of which a temporal discretization was performed, and at every level of discretization, consistent with the step of loading, a static load was applied to the model, consistent with the value of initial dynamic load at the beginning of the interval. Since magnitude of load at every step of loading was dependent on the parameter representing a temporal variable, a parametric segregated solver was used for the solution. Obtained results of task solution for every step of loading were used as initial conditions for obtaining solution in the next step. Mathematically, reduction of the dynamic task to the sequence of static tasks is adequate to elimination of inert members from (in) equations of equilibrium.

Results and discussion of findings

Based on results of computation, graphs were produced representing a temporal dependency of the actuating elements of the robot in a direction of axis *Ox* that was parallel to the border-line B1 of the area A2. Fig. 3 offers an example of such graphical representation for the coefficient of friction μ=0.2 and vibration frequency $f = 10^4/2\pi$Hz. Computation was made for the model of type 2 (Fig. 2b).

Upper curve represents displacement of the contact surface of the right (short) leg of the robot, whereas lower curve – displacement of the contact surface of the left (long) leg of the robot. As it is obvious from graphical schemes, displacement of actuating elements occurs in anti-phase. Analogous results were observed for the model of type 1 (Fig. 2a), however in the case of models with symmetric geometry and symmetric force action, displacement was not observed. All of this leads to conclusion that in order to make the robot move, it is necessary to create asymmetry of any kind, for example asymmetry in force or geometry. In order to determine speed of the robot movement, results of computation were subjected to numerical differentiation using *MathCad* that resulted in periodical function of temporal variable with the nonzero average value. This average value was considered to represent speed of robot movement. Dependencies of robot movement speed on the coefficient of friction μ (Fig.4) and vibration frequency f have also been examined.

Graph presented in Fig. 4 was obtained for the vibration frequency of $f = 10^4/2\pi$Hz. Its analysis revealed that dependence of robot motion speed on the coefficient of friction possesses an extreme character achieving maximum at $\mu \approx 0.2$. According to the results of simulation, dependence of movement speed on the vibration frequency possesses a linear character. In real physical experiments, a resonant character of dependence of robot movement speed on the vibration frequency is commonly observed [1]. The disagreement between findings of our simulation and real experiment might be explained by the fact that inert members have been eliminated from equations of equilibrium of the system, whereas resonant frequencies of the system are dependent upon its inertial features (density of the material). Consequently, reduction of the dynamic task to the sequence of static tasks resulted in loss of information regarding resonant features of the system and associated phenomena. Inability of the model to take into account resonant phenomena might also explain rather low robot movement speeds, obtained in a result of computation. In the future, a transient analysis might be used in order to make model take into consideration resonant phenomena, including inertial effects. Simulation using different software (for example, *ANSYS Multiphysics* that proved to be sufficiently successful in simulation of VPA) is also possible.

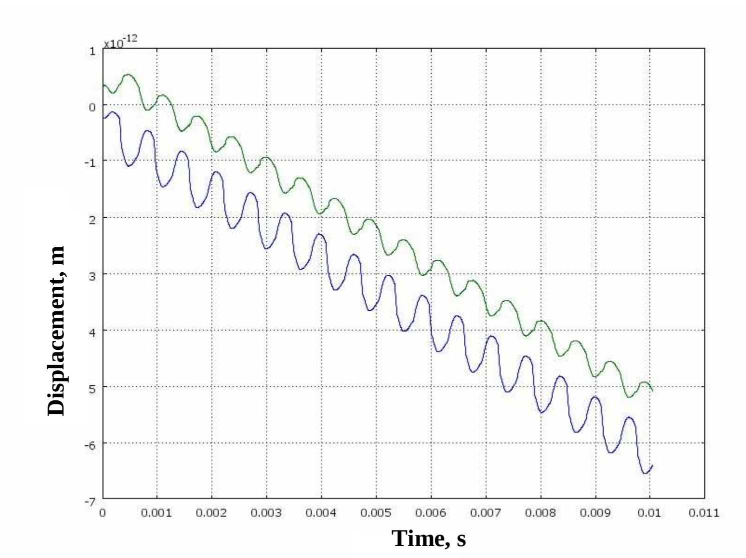

Fig. 3. Temporal variation of displacement of robot actuating elements

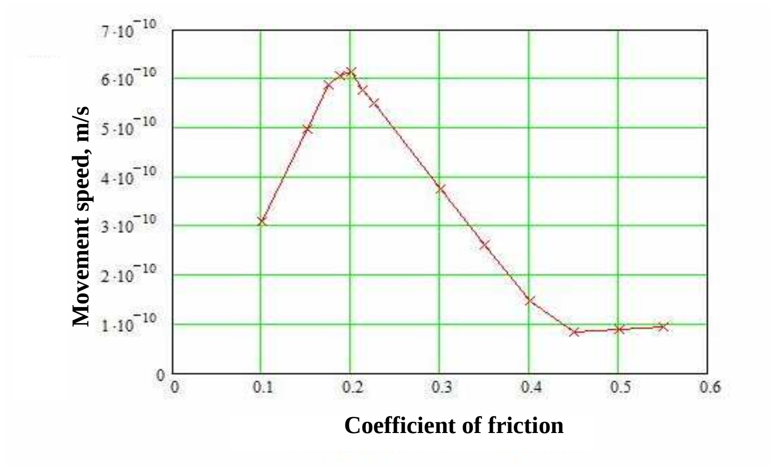

Fig. 4. Dependence of robot movement speed on the coefficient of friction

Curves represented in Fig. 3 are in agreement with the data obtained through experimental research of linear VPA [5]. They obviously demonstrate robot relocation to have a step-wise character. Even in the case when speed of movement is low (from tenths to tens of nm/s, in the model under consideration) VPA represent a high practical interest, for example in the field of precision positioning of objects in micro- and nano-technologies. In particular, a concept exists for developing a nano-plant on the basis of many interacting nano-robots with VPA, fitted with operating and measuring tools, for example a probe for scanning tunneling microscopy [6].

Actuating elements of the robot might be directly used as sensor elements as their resonant frequencies are dependent upon physico-mechanical features of the bearing surface that serves to perform function of acoustic load. Dependence of the resonant characteristics of vibrational framed structures on features of acoustic load is well-known and widely used for ultrasound hardometers and resonant tactile sensors for examination of resilience qualities of biological tissues [7].

Consequently, the developed model might serve as a useful tool for the research of effect of different parameters on the efficiency of VPA operation. It would be expedient to undertake further development and elaboration of this model, as well as its additional verification by introducing results obtained through experimental studies, and results of simulations using different methods and software.

Conclusions

1. A finite-element model of VPA-based micro-robot was developed by using software *COMSOL Multiphysics*.
2. Effects of vibration frequency and coefficient of friction on micro-robot movement speed were examined.
3. Based on findings and results of simulation, some disadvantages of model under consideration were revealed, namely its inability to take into consideration resonant phenomena that contributed to identification of potential course for further research and elaboration of the developed model.

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