

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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**DETERMINING EIGENFORMS OF PIEZO
ACTUATORS USED IN HIGH-PRECISION
MICRO ROBOTS**

Summary of Doctoral Dissertation
Technological Sciences, Informatics Engineering (07T)

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

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**PRECIZINIŲ MIKROROBOTŲ
PJEZOKEITIKLIŲ SAVŲJŲ FORMŲ
ATPAŽINIMO PROBLEMA**

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General Characteristic of the Dissertation

Relevance and problem of the research. Rapid development of world-wide industry and production encourages to intensify scientific research and create effective technologies that determine the quality of new products. Many technologies are ever closely tied to high-precision fast systems of minute geometric dimensions characterized by high resonance frequencies as well as automated control. Piezoelectric vibroengines, robotic production lines and high-precision microrobots are considered ever more frequently.

The key part of this vibration equipment, the piezomechanical movement actuator, essentially determines the dynamic characteristics of the entire system. Piezoactuators, compared to other movement actuators (electromagnetic, pneumatic, hydraulic), are characterized by the highest precision (0.01 μm), the shortest reaction time (0.01 ms) and the least geometric parameters (< 0.1 cm).

It is natural that while analyzing complex systems, such as high-precision microrobots, they are modelled and investigated numerically. The modelling process is automated and standardized to a full extent possible. Usually, for numerical research in high-precision microrobots the finite element method is used. The FEM is also employed in many software packages used nowadays.

To excite the frequency that corresponds to one of the eigenforms of a piezoceramic actuator, the geometric parameters are changed. It has been noted in researching multidimensional piezoactuators that piezoactuators of the same geometrical form but of different dimensions have different distributions of eigenforms in the frequency spectrum, i.e., the changed positions of eigenforms in their sequence. This happens because eigenfrequencies of systems are placed in the ascending order according to the algorithm for eigenvalues used in standard software packages. Since vibration equipment usually works in one of its eigenfrequencies, as the sequence of eigenforms changes the solution usually does not converge, and numerical analysis becomes meaningless. Such rule for sorting frequencies is disadvantageous when numerical analysis needs to be automated. The situation is further complicated by the fact that the frequencies of different oscillations overlap. Therefore, non-standard solutions need to be employed.

Aim of the research. The aim of this work is to create a mechanism for determining eigenforms of piezoactuators for high-precision microrobots.

Tasks of the research. To reach the aim, these tasks had to be solved:

1. To analyze the research on high-precision microrobots with multidimensional piezoactuators.
2. To research the dependency of the distribution of eigenfrequencies of tabular piezoactuators for high-precision microrobots on geometric parameters.
3. To formulate an algorithm for determining oscillation eigenforms.

Scientific novelty

1. A new definition of domination coefficients has been proposed.
2. An algorithm for determining eigenforms has been formed, which enables to automate numerical analysis of multidimensional piezoactuators.

Methodology of the research. Analytical and numerical research methods for multidimensional piezoactuators are used in the work. Theoretical analysis is performed using the linear oscillation theory. The finite element method is used for numerical modelling. The calculations have been performed with the programs created by the author and the finite element method software package ANSYS 10.

Practical value. The improvement, with the help of domination coefficients, in the scheme of calculations for the FEM software used in modelling the dynamics of piezoactuators in high-precision microrobots.

Scope of the scientific work. The dissertation “Determining Eigenforms of Piezoactuators Used in High-Precision Microrobots” is composed of the introduction, three chapters and the conclusions. The total volume of the dissertation is 116 pages.

The introduction encompasses the topicality of the research, its scientific novelty, the aim and tasks of the work, its practical value and the approbation in international conferences and seminars.

In the first chapter characteristics, constructions, electrode configurations of multidimensional piezoactuators and the influence of excitation zones on the oscillation field are examined; also, scientific piezoactuator research and the related problems are reviewed.

In the second chapter the problems of modelling and control of piezoactuators used in high-precision microrobots that arise when applying the finite element method are examined. The results of analytic calculations that prove the changes in an eigenform sequence are supplied.

A new definition of domination coefficients is introduced. An improved algorithm for determining rational geometric parameters of piezoactuators for high-precision microrobots is described.

In the third chapter the detailed practical examples of applying domination coefficient as well as recommendations and suggestions for modelling the dynamics of piezoactuators in high-precision microrobots are provided. Also, the results of numerical analysis indicating the interdependency of geometric parameters and domination coefficients are discussed.

The conclusions on the research performed and results received are provided.

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1. The Analysis of the Research in High-Precision Microrobots with Multidimensional Piezoactuators.

In this chapter the factors determining the type and characteristics of oscillations in piezoactuators for high-precision microrobots are examined: qualities of piezoceramics, geometrical parameters of piezoactuators, fixation conditions, size and direction of polarization as well as topology and geometrical form of electrodes. The main groups of piezoactuators, each of which determine its field of application, tasks and problems, are also reviewed.

Because of peculiar qualities of piezoceramics that guarantee rapidity, precision, the ability to operate at very high frequencies and very small dimensions of vibration equipment designed, the field of application of piezoceramic actuators is very wide. Hence the analysis of theoretical research also spans many scientific fields, such as informatics, electronics, automation, machine design, electrical engineering, medicine and biology.

Although the piezoeffect was discovered in 1880, only after 80 years a real possibility to build piezomechanical devices appeared. At the time intense research in piezoceramic movement actuators also started. The initiators of the research were scientist from the USA, Russia (then the USSR) and Lithuania. They created the fundamental theory of vibromechanics, mathematical models of vibration devices and new numerical methods. Japanese scientists contributed greatly to building piezomechanical systems and commercializing them (150–200 patents a year).

In 1963 the Russian scientist M. E. Archangelskiy first formulated theoretical principles for changing oscillations of no rigid rods into rotational or rectilinear movements of a contact body.

In 1964 the Ukrainian scientist V. V. Lavrinenko on the basis of theoretical research built a vibration engine of rotational movement using a piezoceramic element.

In 1971 scientists from KTU and the scientific society “Vibrotechnika” build the first functioning samples of piezoelectric mechanisms. The research on piezoactuator oscillations performed by the scientists from “Vibrotechnika” and its founder and long-time leader academician K. Ragulskis influenced the fundamental theory of vibromechanics. Academicians R. Bansevičius and K. Ragulskis researched the principles of functioning and design of vibration engines, their theory and schemes with the application of various piezoactuator constructions.

I. Gasiunas, A. Žukas and P. Vasiljevas proposed many theoretical and practical improvements for transforming nonrigid body oscillations into rectilinear or rotational movement of an outlet segment.

R. Barauskas and G. Kulvietis first started to apply numerical methods to piezoactuator research. They proposed an algorithm for calculating eigen frequencies of piezoactuators depending on the placement of electrodes. Using the FEM they formed mathematical models of vibration engines when the contact is continuous or discrete. They optimized the geometric parameters of piezoactuators with wavelike engines maximizing the average rotational speed of the rotor and minimizing the nonuniformity coefficient of rotor rotation. However, such optimization of geometric parameters used much computing resources. Additionally, this algorithm had disadvantages, since due to changes in the sequence of piezoactuator eigen forms, the objective function sometimes changed in jumps, and the solution sometimes did not converge.

K. Ragulskis, R. Bansevičius, A. Busilas and S. Seržentas researched piezoelectrical scanning devices. R. Barauskas and V. Ostaševičius analysed nonrigid vibroimpact systems and their optimization problems.

V. Bubulis and K. Ragulskis researched vibrobatches for fluid and powdery materials based on the principles of pulsing cameras, running and stationary waves, vibroimpacts and other.

G. Markauskaitė and R. Kurila examined wavelike vibration engines with ring-form piezoactuators.

Japanese scientists built vibroengines and nozzles.

K. Uchino, Y. Sashida and S. Ueha were the first Japanese scientists who built and analyzed impulse and ultrasound vibroengines.

Interesting experiments were performed at the company Meico Co. (Japan). There a micromobile machine was build using piezoceramic plates for exciting mechanical oscillations. Bending oscillations excited in plates are transferred to pinlike “legs” and thus the whole construction moves on the

surface. Scientists from Gifu (Japan) also performed similar experiments, having created a “spider”, a micromobile piezoceramic system.

Scientists at Tohoku University in Japan researched oscillations of a piezoceramic cylinder and methods for their control. The piezocylinder was analyzed as an actuator and a sensor. The modal expansion method was applied to numerical analysis that helped to determine state equations for the piezocylinder.

Scientists from Nippodenso Co. (Japan) researched flexible polymorphic actuators made of 10–20 piezoceramic discs used in scanning devices.

H. S. Tzou (Japan) performed theoretical and numerical research on piezoelectric shell elements and analyzed possibilities for their application.

Multidimensional piezoactuators, their constructions and piezoelectric devices have been researched by scientists from Bristol and Loughborough Technological Universities (Great Britain), Changchun Institute of Optics and Precise Mechanics (China), University of Pennsylvania (USA) and others.

Summarizing the analysis of the theoretical research it can be stated that due to special qualities of piezoceramics the field of application for piezoceramic actuators is very wide. At the time much attention is being paid to the piezoceramics produced in industry, so new possibilities for creating fast and precise vibration devices of small dimensions appear. Much contribution to the fundamental theory of vibromechanics has been made by US, Russian and Lithuanian scientists. Although the range of theoretical research is very wide, the change in eigenform sequence observed while solving optimization problems remains insufficiently researched being at the same time an important issue. The Norwegian scientist Anker J. C. states in a paper that the question how to determine if an eigenfrequency is chosen correctly while modelling with FEM and the solution converges is still open (Anker J. C. 2004). Meanwhile Avitabile P. stresses that the change in eigenforms is observed and indicates the following reasons: the selection of the coordinate system, the grid influence and the application of different numerical methods (Avitabile P. 2008). However, the authors do not examine possible solutions. At the same time an ever increasing application of piezomechanical system in development for commercial markets has been observed. It is evident that the attempts to automate modelling vibration devices are being made. And the mechanism for determining eigenforms proposed in the dissertation that simplifies the modelling of piezoactuators for high-precision microrobots and enables the automation of numerical research.

2. The Research in Dynamics of Piezoactuators for High-Precision Microrobots

The finite element method is one of the most popular and effective engineering methods for modeling and analysing complex structures. In the general case, eigenfrequencies and forms of piezoactuators for high-precision microrobots disregarding damping can be determined by solving a system of matrix equations for its eigenvalues:

$$\begin{aligned} [M] \{\ddot{\delta}\} + [K] \{\delta\} - [T] \{\varphi\} &= \{0\} \\ [T]^T \{\delta\} + [S] \{\varphi\} &= \{0\} \end{aligned} \quad (1)$$

where $[K]$, $[T]$, $[S]$, $[M]$ are the matrix of element stiffness, electromechanical and capacity as well as the matrix for construction masses, respectively; $\{\delta\}$, $\{\varphi\}$ – the vectors of nodes displacements and potentials, respectively.

After restructuring equation system (1), an eigenvalue equation becomes:

$$([K^*] - \omega^2 [M]) \{u\} = \{0\} \quad (2)$$

where the expression of matrix $[K^*]$ depends on the values of the vector of nodal potentials.

To employ the qualities of piezoactuators for high-precision microrobots more effectively optimal geometric parameters of piezoactuators have to be found. Problems of optimizing geometric parameters usually are of high volume so it is advisable to solve them in parts. Thus several new smaller problems are formulated. One of them is the problem of determining rational geometric parameters for multidimensional piezoactuators. While formulating the problem of rational geometric parameters, problem optimisation criteria are set, limitations chosen, numerical solution methods are defined, etc. While looking for rational geometric parameters, we will use only the results of the analysis of multidimensional piezoactuator eigenvalues. In Fig. 1 the usual scheme for determining rational geometric parameters is provided. The optimisation loop is started with the selection of geometrical parameters of piezoceramic actuators. Then eigenvalues are calculated, and the integration of dynamic equations for a piezoactuator is performed. At the level of optimisation criteria it is checked whether the results satisfy these criteria. If so, the loop is terminated, if not, it is continued. The principle of functioning of piezoactuators for high-precision microrobots is based on the excitation of

higher resonance frequencies. Numerical analysis of such piezoactuators is usually tied to a particular eigenform. During numerical analysis as only geometric parameters of actuators change, the problem of the change in the sequence of eigenforms arises, and that means that an unsuitable eigenvalue can be chosen on the level of the scheme for determining rational geometric parameters. Since vibration equipment usually functions in one of its eigenfrequencies, as the sequence of eigenforms changes the solution usually does not converge, and numerical analysis becomes meaningless.

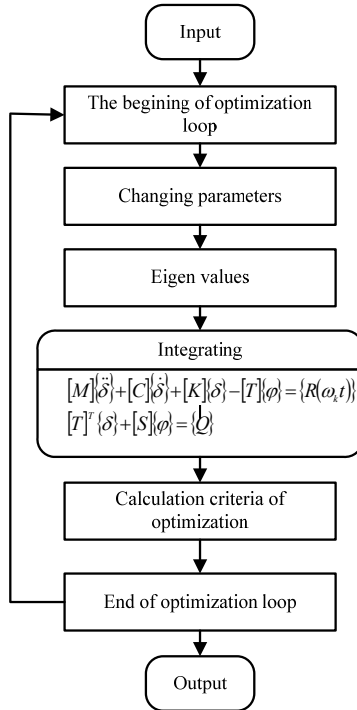


Fig. 1. The scheme for determining rational geometric parameters

Usually, for numerical analysis of piezoactuators software such as ANSYS 10 is used. By the algorithm of eigenvalue problem eigenfrequencies for systems are sorted in the ascending order; thereby the sequences of eigenforms change. This rule for sorting frequencies is disadvantageous when numerical analysis of multidimensional piezoactuators needs to be automated. This problem is also important for optimization, since calculations are tied both to eigenfrequencies and eigenforms. If the eigenfrequency is chosen incorrectly,

the piezoactuator will not function, so it is very important to numerically determine eigenforms and place them inside the eigenform matrix of the construction model.

Genadijus Kulvietis noted this problem, and in 1993 proposed to solve it by introducing domination coefficients. The author proposes for a given construction to calculate eigenfrequencies and forms of the construction. Then for the n^{th} eigenfrequency the following sum can be formed:

$$S_k^n = \sum_{i=1}^r (A_{ik}^n)^2, \quad r = \frac{l}{k} \quad (3)$$

where k – the number of degrees of freedom in a node, l – the number of nodes (degrees of freedom) in the model, r – the size of the form vector for the k^{th} coordinate, A_{ik}^n – the value of the eigenform vector for the i^{th} element. Then the ratio is formed:

$$m_{jk}^n = \frac{S_j^n}{S_k^n}, \quad j \neq k \quad (4)$$

where m_{jk}^n – the oscillation domination coefficient. The sum S_k^n corresponds to the oscillation energy of the n^{th} eigenfrequency in the k^{th} direction, and the ratio m_{jk}^n – the ratio of oscillation energies of the n^{th} eigenfrequency in the coordinate directions of j and k .

These coefficients have to be called partial domination coefficients since they estimate energy only in two coordinate directions. The domination coefficients discussed above have the following shortcomings:

1. Not normalized. Because of this the range of the domination coefficients calculated varies from 0 to infinity.
2. In the case of three dimensions, six domination coefficients result. Such a number of coefficients aggravate analysis.

To solve this problem the following algorithm is proposed: find the sum of the amplitude squares of piezoactuator oscillations in all directions of the degrees of freedom for a point, i.e., the full system energy in all directions:

$$S_k^n = \sum_{i=1}^r (A_{ik}^n)^2 \quad (5)$$

where n – the eigen frequency for a system, k – the number of degrees of freedom in a node, A_{ik}^n – the value of the eigenform vector for the i^{th} element.

Then the ratio is calculated:

$$m_j^n = \frac{S_j^n}{\sum_{i=1}^k S_i^n} \quad (6)$$

where m_j^n – the oscillation domination coefficient corresponds to the n^{th} eigenform. The index j of domination coefficients indicate, in which direction the energy under investigation is the largest. j can assume such values: 1 corresponds to the x coordinate, 2 – y , and 3 – z , etc. Having calculated domination coefficients in all directions of degrees of freedom and having compared them to each other, we can determine the dominant oscillation type. The domination coefficients calculated according to formula (6) are normalized, so their limits vary from 0 to 1. It is very convenient for analyzing the influence of various parameters on domination coefficients.

To clearly determine the eigenform and its place in the eigenform matrix of the construction model, it is not enough to calculate only the oscillation domination coefficients. Domination coefficients only help to differentiate eigenforms by dominating oscillations, for example, radial, tangential, axial, etc.

Because of this an additional criterion is introduced into the process of determining eigen form, individual for each eigenform, i.e., the number of nodal points or nodal lines for the form. That depends on the dimensionality of the eigenform. During calculations the number of nodal points of beam-like and two-dimensional piezoactuators is determined by the number of sign changes in oscillation amplitude for the full length of the piezoactuator in the directions of coordinate axes.

Summarizing the algorithm for determining eigenforms of piezoactuator oscillations, we can note that it is composed of two integral stages: calculating domination coefficients and determining the number of nodal points or lines of the eigenform. This algorithm is not tightly bound to multidimensional piezoactuators, so it can be successfully applied in analysing oscillations of any constructions. When solving dynamics problems of piezoactuators for high precision microrobots where repeated calculations with higher eigenfrequencies are involved, it is proposed to modify the general algorithm introducing the stage of determining eigenforms with the help of domination coefficients.

3. The Dynamics of Piezoactuators for High-Precision Microrobots with Two Degrees of Freedom

The case is analysed when a piezoactuator shaped as a two-dimensional plate is rigidly fixed on the side (see Fig .2).

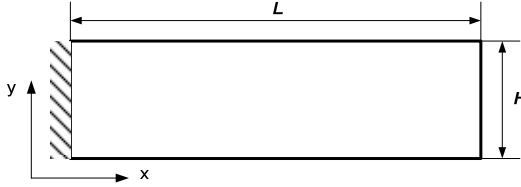


Fig. 2. A model of a two-dimensional piezoactuator

The piezoceramic plate is made of PZT-8 piezoceramic material. Material properties are provided in Table 1, and are marked with Number 1.

Table 1. The properties of the material used for modeling

Material property	Piezoceramics PZT-8 (1)	Steel (2)
Jung modulus N/m^2	8.5×10^{10}	204×10^9
Puason coefficient	0.39	0.3
Density kg/m^3	7600	7800
Dielectric permittivity, $\times 10^{-9} \text{F/m}$	$\epsilon_{11} = 15.937; \epsilon_{33} = 15.937$	
Piezoelectric matrix C/m^2	$e_{13} = -3.09; e_{33} = 16.0; e_{52} = 11.64$	
Elasticity matrix, $\times 10^{10} \text{N/m}^2$	$c_{11} = 14.68; c_{12} = 8.108; c_{13} = 8.105; c_{33} = 13.17; c_{44} = 3.29; c_{66} = 3.14$	

Geometric dimensions of a piezoactuator plate have been varied during numerical analysis as shown in Table 2.

Table 2. Dimensions of a piezoactuator

Name	Piezoceramic plate
Length (L), m	0.02
Height (H), m	0.004 – 0.01

Numerical piezoactuator analysis was performed using the 4-node finite element (Plane42), which is included in the finite element library of ANSYS 10 and belongs to the coupled field element group.

Having performed the numerical analysis and modeling the system under investigation, the problem of eigenvalues is usually solved. The problem of piezoactuator eigenvalues was solved with Block Lanczos solution. Further the first 10 eigenfrequencies and forms were analysed. For solving the problem we will use domination coefficient described in more detail in Chapter 2. The system considered has two degrees of freedom. Thus, for each particular case two domination coefficients are calculated according to formula (6), m_{12} and m_{21} . Calculation results with the following parameters of a piezoactuator when the ratio of length and height is $l/h=2$ are supplied in Table 6. The domination coefficients calculated are compared to each other. In the column Form, the minus sign (-) is placed if $m_{12} > m_{21}$, and the multiplication sign (*) is placed if $m_{12} < m_{21}$. Letter n marks the serial number of the eigenform.

Table 3. The values of domination coefficients for two-dimensional piezoactuators, when the ratio of length and height is $l/h=2$

n	Frequency, Hz	m_{12}^n	m_{21}^n	Form
1	12583	0.067	0.932	*
2	46613	0.981	0.018	-
3	47148	0.282	0.717	*
4	99579	0.359	0.640	*

As the height of a piezoactuator changes at the constant length, the summary of domination coefficient comparison is supplied in Table 4. The research determined that as the ratio of length and width of two-dimensional piezoactuators stays within the interval of $0.5 < l/h < 3.5$, a usual sequence of eigenforms is observed, in other cases the second and third forms switch places (Fig. 3).

Table 4. The results of comparing domination coefficients for two-dimensional piezoactuators

n	l/h ratio						
	0,5	1	2	2,5	3	4	5
1	*	*	*	*	*	*	*
2	*	-	-	*	*	*	*
3	-	*	*	-	-	-	-
4	-	*	*	*	*	*	*

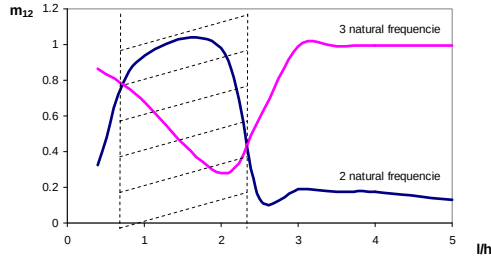


Fig. 3. The dependence of the domination coefficient values of two-dimensional piezoactuators on the l/h ratio

More results are supplied in the dissertation.

Another case investigated is a two-dimensional piezoceramic plate with a concentrated mass attached at the end, which composes $1/50$ of the total body mass. First, the amplitude of the plate with the mass ($a=b$) was calculated (Fig. 4).

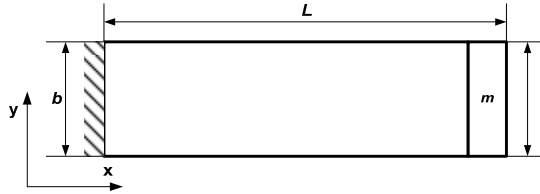


Fig. 4. A model of a two-dimensional piezoactuator with a concentrated mass attached at the end

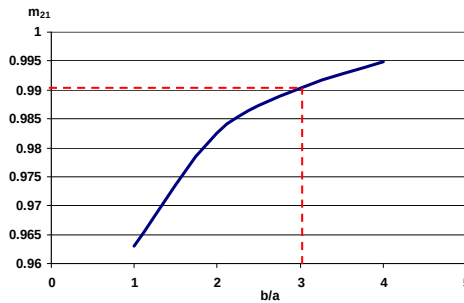


Fig. 5. The influence of the dimensions of a free end of the plate on domination coefficients

The length of the plate was $L=0.005 \text{ m}$ and the width $b=0.02 \text{ m}$. During analysis the dimensions of a free end of the plate were changed, and the

amplitudes of the contact point for each construction considered were noted Fig. 5 (a). We notice that the largest oscillation amplitude is when a free end of the plate is $b/a = 4$. As the dimension of a free end is $b/3$, the amplitude of the contact point is close to the oscillation amplitude of a plate of the same width, but the frequency is 600 Hz higher.

Having calculated domination coefficients we can claim that at the ratio of the dimensions of the free and fixed ends of the plate of $b/a=3$, we have the first flexional form. We can conclude that the concentrated mass added and the decreasing of the ratio b/a is similar to lengthening of the plate. And that means that as the ratio b/a increases, flexional oscillations keep growing.

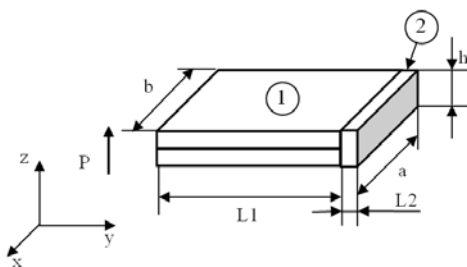


Fig. 6. The scheme of a laser gate: P – the vector of polarisation, b and a – width of the fixed and free ends of the plate, respectively, h– height, L1 and L2 – lengths of the piezoceramic plate (1) and mass (2), respectively

The model of a laser gate is composed of two glued piezoceramic plates of rectangular shape, marked with number 1 (see Fig. 6) – made of PZT-8 (<http://www.ferroperm-piezo.com>) piezoceramic material; the polarization vector is directed along the width of the plate. At their end the mass from steel is glued (Fig. 6), marked with number 2. The detailed properties of these materials are provided in Table 4.

The electrode throughout the whole area of the glued piezoceramic plates is grounded. The upper and lower surfaces of the plate are covered in electrodes that are connected to the 100 V voltage, see Fig. 7. Such electrode placement is used for exciting the first flexional form in the piezoactuator.

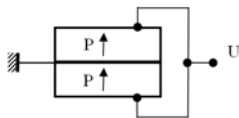


Fig. 7. The scheme of electrode placement

Geometric parameters of a laser gate have to be chosen in such a way that the eigenfrequency of the first flexional form be as high as possible, since this way its rapidity is guaranteed. Also, during analysis the oscillation amplitude A has to remain unchanged or change insignificantly. The resulting construction would satisfy system's technical characteristics and be rational from a technological standpoint.

During analysis the dimensions of a free end of the plate have been changed. For each case considered an eigenvalue problem have been solved and harmonic analysis performed; the amplitudes for the contact point, and the system eigenfrequencies have been calculated for each construction considered. Domination coefficients have been also calculated. A more detailed analysis is provided below. Part of the values of domination coefficients are provided in Table 9.

Table 5. Domination coefficients and the results of harmonic analysis

Width a , m	Frequency, Hz	Amplitude, μm	m_{312}	m_{213}	m_{123}
0.01	385	0.021	0.99	8.52×10^{-7}	0.000656
0.005	412	0.0126	0.91	1.06×10^{-7}	0.000584
0.0034	410	0.021	0.99	2.2×10^{-7}	0.000513

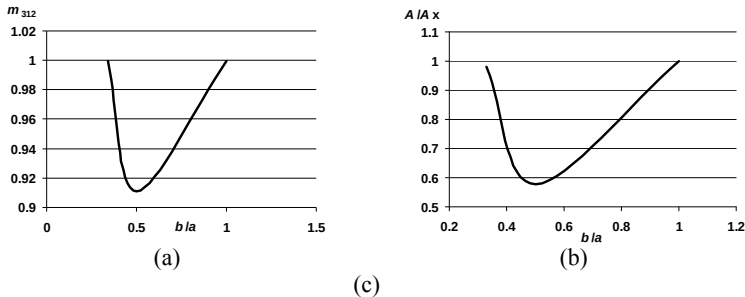


Fig. 8. The influence of geometric parameters on: domination coefficients (a), oscillation amplitude (b)

As can be seen from Table 5, the largest domination coefficients are in the z direction, and that means that flexional oscillations dominate. Having compared the influence of geometric parameters on domination coefficients and oscillation amplitude (Fig. 8 (a) and (b)), we can claim that with the help of domination coefficients we can determine the point where the vibration amplitude is the largest.

Summarizing the results provided in Table 9 we can conclude: the height of the plate according to requirements is 0.002, and the resulting amplitude is 0.0021 μm , when the free end of the plate is $a=0.0034$. So we can conclude that such displacement is sufficient to open the laser gate. Also, with changed geometry the eigenfrequency of vibration has increased to 25 Hz, the necessary condition for guaranteeing rapidity. The construction achieved satisfies system's technical characteristics and is rational from a technological standpoint.

General Conclusions

1. Having performed the analysis of the research on piezoactuators for high-precision microrobots, it has been determined that the problem of the change in eigenfrequencies and eigenforms is little researched and an important one.
2. Having analyzed the dynamics of piezoactuators for high-precision microrobots, the change in eigenform sequence has been determined. The change in eigenform sequence is observed while performing analytic calculations and applying numerical methods.
3. A new proposed definition for domination coefficients is more advantageous. The domination coefficients received are normalized so their range is between 0 and 1. That is very convenient while investigating the influence of chosen parameters on domination coefficients. The number of coefficients under the new definition is twice smaller, and that simplifies analysis.
4. A new definition of domination coefficients enables to choose the required eigenfrequency and thus decrease the number of repetitions in the optimization cycle.

About the author

Inga Tumasonienė was born on 10 February 1975 in Joniškis. In 1998 received a five-year first degree in Physics/Astronomy and Informatics with a minor in secondary school pedagogy from Vilnius Pedagogical University. In 2000 received a Master's in Natural Sciences. During 2004–2008 studied in a doctoral programme of Informatics Engineering at Vilnius Gediminas Technical University. Since 2004 works as a lecturer at the Department of Information Technologies in VGTU. Married, has two daughters.

List of published papers on the topic of the dissertation

In the reviewed scientific periodical publications:

1. Kulvietiene, R.; Kulvietis, G.; Tumasoniene, I. 2006. A symbolic-numeric vibrations analysis of systems with many degrees of freedom; *Strojniški Vestnik journal of mechanical engineering* 52 (5): 309–316. ISSN 0039-2480 (Thomson ISI Web of Science).
2. Tumasoniene, I.; Kulvietis, G.; Mazeika, D.; Bansevicius, R. 2007. The eigenvalue problem and its relevance to the optimal configuration of electrodes for ultrasound actuators, *Journal of sound and vibration* 308: 683–691. ISSN 0022-460X (Thomson ISI Web of Science).
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4. Kulvietis, G.; Mazeika, D.; Tumasoniene, I. 2006. Eigenfrequency identification for optimization of multicomponent ultrasonic actuators, *WSEAS transactions on systems* 3(5): 558-564. ISSN 1109-2777.
5. Kulvietis, G.; Tumasoniene, I.; Mazeika, D. 2006. The design of the multicomponent ultrasonic actuators on the basis of mode – frequency analysis, *WSEAS transactions on systems*, 5(5): 558–564. ISSN 1109-2777.

In the other editions:

6. Kulvietis, G.; Mazeika, D.; Tumasoniene, I. 2005. Multi ultrasonic actuators with some degree of freedom, in *Proceedings of the WSEAS Int. Conf. on dynamical systems and control*: 609–613. CD-ROM. ISBN 960-8457-37-8.
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8. Kulvietis, G.; Tumasoniene, I.; Mazeika, D. 2006. The identification of eigenfrequencies for cylinder-shaped piezo actuators, in *Proceedings of the 5 th WSEAS international conference on applications of electrical engineering (AEE'06)*: 176–180. CD-ROM. ISBN 960-8457-42-4, ISSN 1790-5117.
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PRECIZINIŲ MIKROROBOTŲ PJEZOKEITIKLIŲ SAVŲJŲ FORMŲ ATPAŽINIMO PROBLEMA

Mokslo problemos aktualumas

Spartus pasaulinės pramonės ir gamybos vystymasis skatina intensyviai mokslinius tyrimus, kurti efektyvias technologijas, lemiančias naujos produkcijos kokybę. Daugelis technologijų vis labiau susijusios su labai mažų geometrinių matmenų, precizinėmis, greitaveikėmis, pasižyminčiomis aukštais rezonansiniais dažniais sistemomis, automatizuotu valdymu. Todėl vis dažniau žvalgomasi į pjezoelektrinius vibrovareiklius, robotizuotas gamybos linijas, precizinius mikrorobotus.

Pagrindinė šių vibracinių įrenginių dalis – pjezomechaninis judesio keitiklis – iš esmės apibrėžia dinamines visos sistemos charakteristikas. Pjezokeitikliai, palyginti su kitais judesio keitikliais (elektromagnetiniais, pneumatiniais, hidrauliniais), pasižymi didžiausiu tikslumu (0,01 μm), trumpiausiu reakcijos laiku (0,01 ms) bei mažiausiais geometriniais parametrais ($< 0,1$ cm).

Natūralu, kad analizuojamos sudėtingos sistemos, pvz., preciziniai mikrorobotai, modeliuojamos ir skaitiškai tiriamos. Modeliavimo eigą stengiamasi kuo daugiau automatizuoti ir standartizuoti. Įprastai precizinių mikrorobotų skaitiniams tyrimams taikomas baigtinių elementų metodas (BEM). BEM taikomas ir daugelyje šiuo metu naudojamų programinių paketų.

Siekiant sužadinti dažnį, kuris atitiktų vieną iš pjezokeraminio keitiklio savųjų formų, yra keičiami geometriniai parametrai. Tiriant daugiamačius pjezokeitiklius, pastebėta, kad tos pačios geometrinės formos, bet skirtingų matmenų pjezokeitiklių savosios formos dažnių spektre išsidėsto skirtingai, t. y. pasikeitusią savųjų formų vietą jų eilėje. Taip atsitinka todėl, jog pagal savųjų reikšmių uždavinio algoritmą, naudojamą standartiniuose programiniuose paketuose, sistemų savieji dažniai išdėstomi didėjimo tvarka. Kadangi vibraciniai įrenginiai paprastai dirba vienu iš savųjų dažnių, tai, pasikeitus savųjų formų sekai, uždavinio sprendinys paprastai nekonverguoja ir skaitiniai tyrimai netenka prasmės. Tokia dažnių rūšiavimo taisyklė yra nepalanki, kai norima automatizuoti skaitinius tyrimus. Situacija komplikuojasi ir todėl, kad skirtingų virpesių dažnių sritys persidengia. Todėl reikalinga ieškoti nestandartinių sprendimo būdų.

Darbo tikslas. Šio darbo tikslas – sukurti precizinių mikrorobotų pjezokeitiklių savųjų formų atpažinimo būdą.

Darbo uždaviniai. Siekiant darbo tikslo, buvo sprendžiami šie uždaviniai:

1. Apibendrinti precizinių mikrorobotų su daugiamačiais pjezokeitikliais tyrimus.
2. Atlikti precizinių mikrorobotų pjezokeitiklių dinamikos tyrimus.
3. Suformuluoti virpesių savųjų formų atpažinimo būdą.

Mokslinis naujumas

1. Pasiūlytas naujas dominavimo koeficientų apibrėžimas.
2. Sukurtas savųjų dažnių formų atpažinimo algoritmas, kuris leidžia automatizuoti daugiamačių pjezokeitiklių skaitinius tyrimus.

Praktinė vertė. BEM programinės įrangos, naudojamos precizinių mikrorobotų pjezokeitiklių dinamikai modeliuoti, skaičiavimų schemos patobulinimas naudojant dominavimo koeficientus.

Tyrimų metodika. Darbe taikomi naudojami analitiniai ir skaitiniai daugiamačių pjezokeitiklių tyrimų metodai. Teorinė analizė atliekama naudojantis tiesine virpesių teorija. Skaitiniam modeliavimui taikomas baigtinių elementų metodas. Skaičiuota naudojantis autorės sukurtomis programomis ir baigtinių elementų metodo programiniu paketu ANSYS 10.

Darbo aprobavimas

Darbo rezultatai buvo paskelbti penkiose mokslinėse konferencijose Lietuvoje ir užsienyje. Disertacijos tematika yra išspausdinti 9 moksliniai straipsniai: 2 – straipsnių rinkinyje, įtraukame į *Thomson ISI Web of Science*; 3 – žurnaluose, cituojamame *Inspec* duomenų bazėje, 3 – recenzuojamuose tarptautinių konferencijų straipsnių rinkiniuose, 1 – respublikinės konferencijos straipsnių rinkinyje.

Darbo apimtis. Disertaciją „Precizinių mikrorobotų pjezokeitiklių savųjų formų atpažinimo problema“ sudaro šie skyriai:

Įvadas.

1. Precizinių mikrorobotų su daugiamačiais pjezokeitikliais tyrimų analizė.
2. Precizinių mikrorobotų pjezokeitiklių dinamikos tyrimas.
3. Precizinių mikrorobotų su dviem laisvės laipsniais pjezokeitiklių dinamika.

Rezultatų apibendrinimas.

Bendra disertacijos apimtis – 116 puslapių.

Ivade pristatomas tyrimo aktualumas, mokslinis naujumas, darbo tikslai ir uždaviniai, praktinė tyrimo vertė, aprobavimas tarptautinėse konferencijose ir seminaruose.

Pirmajame skyriuje nagrinėjamos daugiamačių pjezokeitiklių charakteristikos, konstrukcijos, elektrodų konfigūracijos, žadinimo zonų įtaka virpesių laukui, taip pat apžvelgiami moksliniai pjezokeitiklių tyrimai bei su jais susijusios problemos.

Antrajame skyriuje nagrinėjamos precizinių mikrorobotų pjezokeitiklių modeliavimo ir valdymo problemos, kylančios taikant baigtinių elementų metodą. Pateikiami analitiniai skaičiavimų rezultatai, įrodantys savųjų formų sekos pasikeitimus. Taikomas naujas dominavimo koeficientų apibrėžimas. Aprašomas patobulintas precizinių mikrorobotų pjezokeitiklių racionalių geometrinių parametrų nustatymo algoritmas.

Trečiajame skyriuje pateikiami detalūs praktiniai dominavimo koeficientų taikymo pavyzdžiai bei rekomendacijos ir siūlymai precizinių mikrorobotų pjezokeitiklių dinamikai modeliuoti. Aptariami skaitinių tyrimų rezultatai, rodantys geometrinių matmenų ir dominavimo koeficientų priklausomybę.

Darbo pabaigoje pateikiamos išvados apie atliktus tyrimus ir gautus rezultatus.

Rezultatų apibendrinimas

1. Išanalizavus precizinių mikrorobotų pjezokeitiklių dinamiką, nustatytas savųjų formų susikeitimas. Savųjų formų sekos susikeitimas matomas analitinių skaičiavimų metu ir taikant skaitinius metodus.
2. Pasiūlytas naujas dominavimo koeficientų apibrėžimas yra pranašesnis. Gauti dominavimo koeficientai yra normuoti, todėl jų kitimo ribos yra nuo 0 iki 1. Tai labai patogu tiriant pasirinktų parametrų įtaką dominavimo koeficientams. Pagal naują apibrėžimą reikalingų koeficientų skaičius yra mažesnis, ir tai palengvina analizę.
3. Išanalizuota plokštelinio pjezokeitiklių savųjų dažnių pasiskirstymo priklausomybė nuo geometrinių parametrų. Nustatyta, kad savųjų formų sekos pasikeitimai priklauso tik nuo pjezokeitklio pločio ir ilgio santykio.
4. Naujas dominavimo koeficientų apibrėžimas leidžia parinkti reikiamą savąjį dažnį ir tokiu būdu sumažinti optimizavimo ciklo kartojimų skaičių.

Trumpos žinios apie autore

Inga Tumasonienė gimė 1975 m. vasario 10 d. Joniškėje. 1998 įgijo bendrojo lavinimo mokyklos fizikos ir astronomijos bei informatikos mokytojo kvalifikaciją VPU, 2000 m. – gamtos mokslų magistro laipsnį VPU. 2004–2008 metais Vilniaus Gedimino technikos universiteto informatikos inžinerijos mokslo krypties doktorantė. Nuo 2004 dirba lektore Vilniaus Gedimino technikos universiteto Informacinių technologijų katedroje. Ištekėjusi, augina dvi dukras.

Inga Tumasonienė

**DETERMINING EIGENFORMS OF PIEZO ACTUATORS USED IN
HIGH-PRECISION MICROROBOTS**

Summary of Doctoral Dissertation

Technological Sciences, Informatics Engineering (07T)

Inga Tumasonienė

**PRECIZINIŲ MIKROROBOTŲ PJEZOKEITIKLIŲ SAVŲJŲ FORMŲ
ATPAŽINIMO PROBLEMA**

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