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The ring type piezoelectric actuator generating elliptical movement

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1. Introduction

Piezoelectric actuators have advanced features if compared to others and are widely used for different commercial applications [1-4].

The demand for new type displacement transducers that can achieve high resolution and accuracy of the driving object increases nowadays [5-7].

A lot of design and operating principles are investigated to transform mechanical vibrations of piezoceramic elements into elliptical movement of the contact zone of an actuator [8, 9].

Elliptical movement of piezoelectric actuators fall under two types – rotary and linear. Rotary type actuators are one of the most popular because of high torque at low speed, high holding torque, quick response and simple construction. Linear type traveling wave actuators feature these advantages as well but development of these actuators is a complex problem [10-12].

Summarizing the following, the following types of piezoelectric actuators can be specified: traveling wave, standing wave, hybrid transducer, and multi-mode vibrations actuators. [7, 13, 14].

The ring shaped piezoelectric actuator generating elliptical movement is presented and analyzed in this paper.

2. The influence of geometric parameters on domination coefficients

Usually, for numerical analysis of piezoactuators the software such as ANSYS 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 related 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 [15].

Calculation of eigenfrequencies and forms for a given construction (Fig. 1) is proposed in this paper.

Then for the n^{th} eigenfrequency the following sum can be formed:

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

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

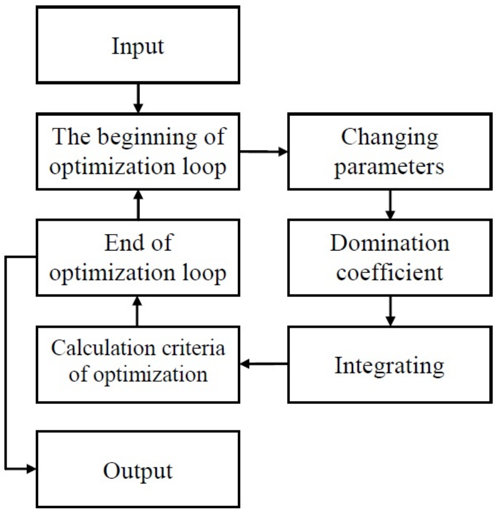


Fig. 1 The scheme for determining rational geometric parameters

Then the ratio is formed:

$$m_{jk}^n = \frac{S_j^n}{S_k^n}, \quad j \neq k, \tag{2}$$

where m_{jk}^n is 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 is 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:

Not normalized. Because of this the range of the domination coefficients calculated varies from 0 to infinity.

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 [16, 17]:

$$S_k^n = \sum_{i=1}^{r} \left(A_{ik}^n\right)^2, \tag{3}$$

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

Then the ratio is calculated [8]:

$$m_j^n = \frac{S_j^n}{\sum_{i=1}^{k} S_i^n}, \tag{4}$$

where m_j^n is the oscillation domination coefficient corresponds to the n^{th} eigenform. The index j of domination coefficients indicates 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 (4) 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 eigenform, 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 (Fig. 1), 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 the problems of piezoactuators dynamics 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 [18].

3. Design and results of numerical modeling

Numerical modeling of piezoelectric actuator was performed to validate actuator design and operating principle through the modal analysis.

Modal analysis of piezoelectric actuator was performed to find proper resonance frequency. Material damping was assumed in the finite element model [19].

Finite element model software ANSYS 11.0 was employed for simulation and finite element model was built.

Principle scheme of the analysed piezoelectric actuator is provided in Fig. 2.

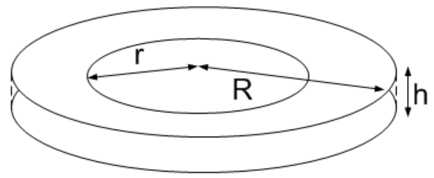


Fig. 2 Principle scheme of ring shaped piezoelectric actuator, where R – outer radius, r – inner radius, h – height

PZT-8 piezoceramics was used for the ring. The polarization vector is directed along the width of the ring. The detailed properties of this material are provided in Table 1.

Table 1

Properties of the material used for modelling

Material property	Piezoceramics PZT-8
Jung modulus, N/m^2	8.2764 x 10^{10}
Puason coefficient	0.33
Density, kg/m^3	7600
Dielectric permittivity x10^3F/m	ε_{11}=1.2; ε_{22}=1.2; ε_{33}=1.1
Piezoelectric matrix x10^{-3}C/m^2	e_{13}=-13.6; e_{23}=-13.6;
	e_{33}=27.1; e_{42}=37.0;
	E =37.0

Geometric parameters of the ring are chosen in such a way that the eigenfrequency of the 2nd flexional form is as high as possible, since in this way its rapidity is guaranteed.

The first iteration of calculations of piezoelectric actuator was performed to find proper resonance frequency and in order to determine the same eigenform of elliptical movement with diferent inner radius.

During analysis the ring dimensions have been changed. Geometric parameter‘s proportions used in the finite element model for modal analysis (Fig. 3) are provided in Table 2.

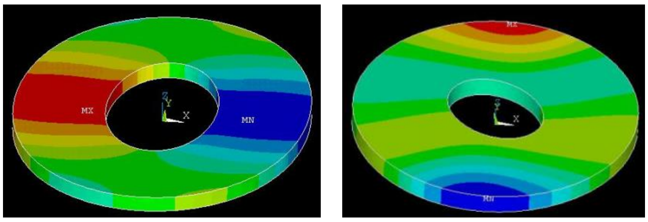


Fig. 3 Ring shaped actuators' 2nd flexional form: *a* - model 2 (best crossply movement; 18091Hz; *Sφ* (crossply) 0.871767); *b* - model 5 (best rotative movement; 88491Hz; *Sτ* (rotative) 0.831918)

Table 2

The detailed measurement of geometric parameters of the piezoceramic ring

Measured parameters of ring actuator	Model 1	Model 2	Model 3	Model 4	Model 5
Outer radius *R*, m	0.0150	0.0200	0.0150	0.0200	0.0150
Inner radius *r*, m	0.0100	0.0080	0.0075	0.0063	0.0050
Height *h*, m	0.0020	0.0020	0.0020	0.0020	0.0020

Domination coefficients and eigenfrequencies have been also calculated, considering when crossply and rotative movement is the optimal, e.g. geometrical parameters based on dominance coefficients were optimized. It was examined at what frequency rotation of the ring is the best and at what frequency it is the most flexible.

A more detailed analysis of domination coefficients (according to which better flexibility was examined) is provided in Tables 3, 4 and Figs. 4, 5.

Table 3

The domination coefficients of crossply movement

Model	*Sτ* (rotative)	*Sφ* (crossply)	*Sz* (long)
1	0.131347	0.868609	0.000045
2	0.128142	0.871767	0.000091
3	0.139465	0.860425	0.000109
4	0.324006	0.675855	0.000139
5	0.162175	0.837622	0.000203

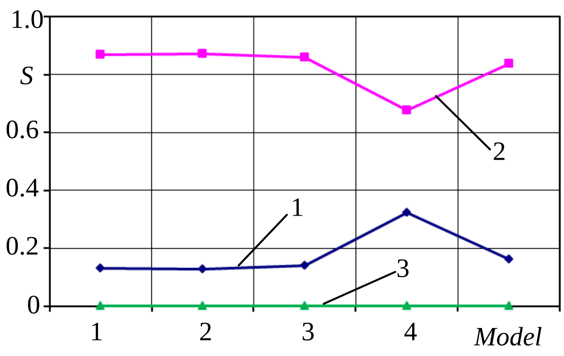


Fig. 4 The influence of geometric parameters on domination coefficients of crossply movement: *1* - *Sτ* (rotative), *2* - *Sφ* (crossply), *3* - *Sz* (long)

Table 4

The domination coefficients of rotative movement

Model	*Sτ* (rotative)	*Sφ* (crossply)	*Sz* (long)
1	0.772685	0.225999	0.001316
2	0.765639	0.233801	0.000561
3	0.791188	0.207722	0.001090
4	0.821089	0.178561	0.000351
5	0.831918	0.167350	0.000732

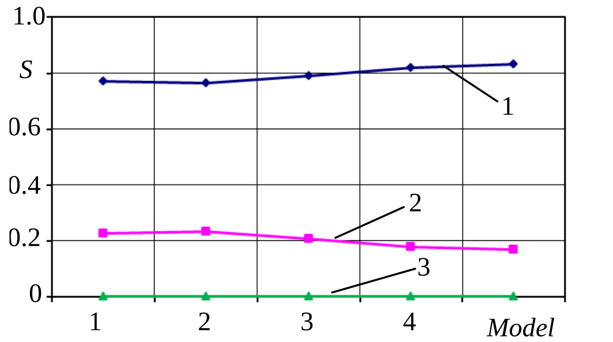


Fig. 5 The influence of geometric parameters on domination coefficients of rotative movement: *1* - *Sτ* (rotative), *2* - *Sφ* (crossply), *3* - *Sz* (long)

A more detailed analysis of model eigenfrequencies (by crossply and rotative movements) is provided in Table 5 and Fig. 6.

Table 5

The eigenfrequencies (by crossply and rotative movements)

Model	1	2	3	4	5
Sφ (crossply) Frequency *f*, Hz	12161	18091	20548	24118	30728
Sτ (rotative) Frequency *f*, Hz	89599	67579	90757	66160	88491

FEM represented below reflect the best crossply and rotation movement.

The 2nd iteration of calculations of piezoelectric actuator was performed to find proper resonance frequency and in order determine the same eigenform of elliptical movement with diferent outer radius.

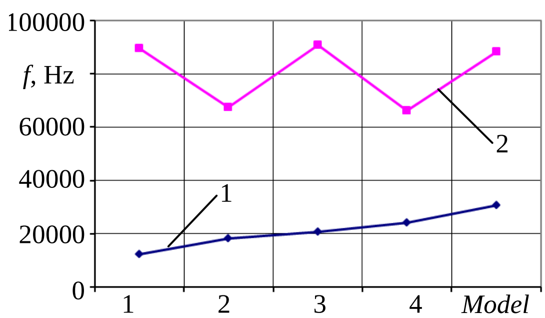
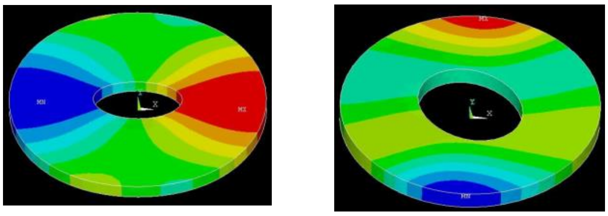


Fig. 6 The influence of geometric parameters on eigenfrequencies (f) (by crossply and rotative movements): *1* - *Sτ* (rotative), *2* - *Sφ* (crossply)

During analysis in the 2nd iteration of calculations dimensions of the ring have been changed. Geometric parameter's proportions used in the finite element model for modal analysis (Fig. 7) are provided in Table 6.



a b

Fig. 7 Ring shaped actuators' 2nd flexional form in the 2nd iteration of calculations: *a* - model 3 (best crossply movement; 29191 Hz; *Sφ* (crossply) 0.890225); *b* - model 2 (best rotative movement; 107425 Hz; *Sτ* (rotative) 0.835137)

Table 6

The detailed measurement of geometric parameters of the piezoceramis ring in the 2nd iteration of calculations

Measured parameters of ring actuator	Model 1	Model 2	Model 3
Outer radius *R*, m	0.0100	0.0125	0.0175
Inner radius *r*, m	0.0050	0.0050	0.0050
Height *h*, m	0.0020	0.0020	0.0020

During analysis in the 2nd iteration domination coefficients and eigenfrequencies have been also calculated, considering when crossply and rotative movement is most optimal, namely were optimized geometrical parameters based on domination coefficients. It was examined at what frequency the rotation of the ring is the best and at what frequency it is the most flexible.

A more detailed analysis of domination coefficients (according to which better flexibility was examined) is provided in Tables 7, 8 and Figures 8, 9.

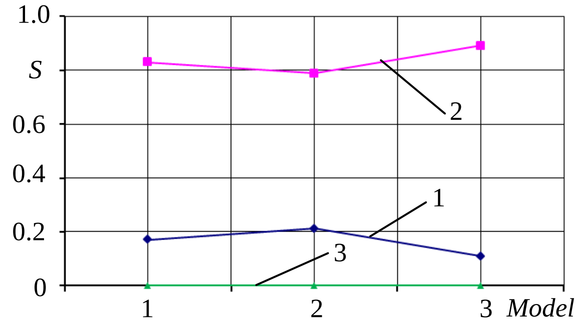


Fig. 8 The influence of geometric parameters on domination coefficients in crossply movement in the 2nd iteration of calculations: *1* - *Sτ* (rotative), *2* - *Sφ* (crossply), *3* - *Sz* (long)

Table 7

The domination coefficients of crossply movement in the 2nd iteration of calculations

Model	*Sτ* (rotative)	*Sφ* (crossply)	*Sz* (long)
1	0.170595	0.829186	0.000219
2	0.211616	0.788173	0.000211
3	0.109596	0.890225	0.000179

Table 8

The domination coefficients of rotative movement in the 2nd iteration of calculations

Model	*Sτ* (rotative)	*Sφ* (crossply)	*Sz* (long)
1	0.718499	0.278451	0.00305
2	0.835137	0.163658	0.001204
3	0.706132	0.293226	0.000642

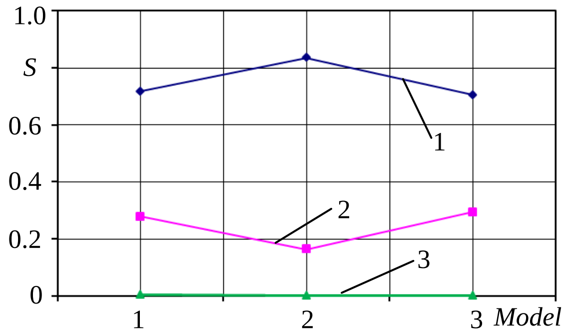


Fig. 9 The influence of geometric parameters on domination coefficients of rotative movement in the 2nd iteration of calculations: *1* - *Sτ* (rotative), *2* - *Sφ* (crossply), *3* - *Sz* (long)

A more detailed analysis of model eigenfrequencies (by crossply and rotative movements) is provided in Table 9 and Fig. 10.

Table 9

The eigenfrequencies (by crossply and rotative movements) in the 2nd iteration of calculations

Model	1	2	3
Sφ (crossply) frequency *f*, Hz	30836	31684	29191
Sτ (rotative) frequency *f*, Hz	136067	107425	75342

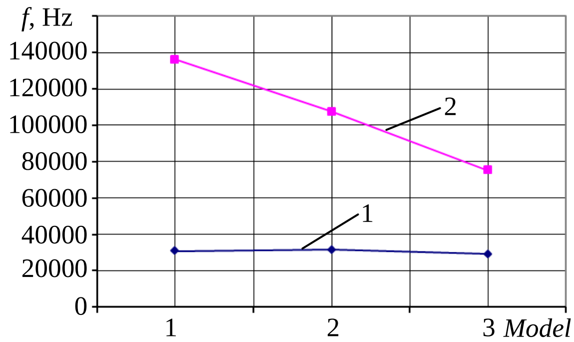


Fig. 10 The influence of geometric parameters on eigenfrequencies *f*. (by crossply and rotative movements) in the 2nd iteration of calculations: *1* - *Sτ* (rotative), *2* - *Sφ* (crossply)

FEM represented below the best reflect the crossply and rotation movement.

Having compared the influence of geometric parameters on domination coefficients and eigenfrequencies in two iterations of the calculation, it can be claimed that with the help of domination coefficients the eigenform of elliptical rotation can be partially determined.

Also, during analysis the oscillation amplitude A has to remain unchanged or change unsignificantly. The resulting construction would satisfy technical characteristics of the system and be rational from a technological standpoint.

4. Conclusions

Results of numerical modeling and simulation of piezoelectric actuator are presented and analyzed in this paper.

Numerical modeling of piezoelectric actuator was performed to validate design and operating principle of the actuator through its modal response analysis.

While changing geometrical parameters of piezoelectric actuators the variation in the modal shape sequence has been observed.

Identification of modal shapes sequence is the necessary step in order to automate numerical experiments of multicomponent piezoelectric actuators.

In practical part modal analysis is performed, eigenform determined and eigenfrequency calculated, the size of inner and outer radius represented maximum rotation and flexibility.

In two iterations of the calculation, the best result of crossply movement was obtained in model 3 with coefficient 0.890225, which was achieved with eigenfrequency of 29191Hz (Table 7).

In two iterations of calculation, the best result of rotation movement was obtained in model 2 with coefficient 0.835137, which was achieved with eigenfrequency of 107425 Hz (Table 8).

Experimental studies confirmed that elliptical rotation oscillations were obtained on the surface of the actuator.

Acknowledgement

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ELIPSINIAM JUDESIUI GAUTI ŽIEDO FORMOS PJEZOELEKTRINIS ŽADINTUVAS

R e z i u m ė

Straipsnyje pasiūlyta pjezoelektrinio žiedinio žadintuvo, skirto elipsės formos judesiui generuoti, konstrukcija, ir atlikta jos analizė. Elipsinis judesys generuojamas tam tikroje žadintuvo zonoje, jį sužadinus harmoniniais signalais su fazės perstūmimu. Pjezoelektrinio žiedinio žadintuvo savųjų dažnių ir žadinimo formų nustatymui baigtinių elementų metodu atliktas skaitinis žadintuvo modeliavimas. Gautų pjezoelektrinio žiedo formų pagrindu nustatyti tinkami jo išorinio ir vidinio skersmenų dydžiai elipsės formos judesiui gauti. Išanalizuoti skaitinio modeliavimo rezultatai.

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THE RING TYPE PIEZOELECTRICAL ACTUATOR GENERATING ELLIPTICAL MOVEMENT

S u m m a r y

A design of ring type piezoelectric actuator generatig elliptical movement is proposed and analyzed in the paper. Elliptical movement is generated at the area of the actuator applying harmonic excitation signals with different phases. Numerical modeling based on finite element method was performed in order to find resonant frequencies and modal shapes of the actuator and to calculate the size of inner and outer radius, ensuring maximum rotation and bending movements under excitation scheme. Results of numerical studies are discussed.

Keywords: piezoelectric ring, elliptical movement, finite element modeling.

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