Influence of electrodes shape to the vibrations of a piezoelectric disk

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Introduction

Vibrations of piezoelectric disks with solid electrodes are well discussed [1-4]. These piezodisks have simple a shape and can be analyzed using analytical [1] or computational models [2-4]. Piezodisks with solid electrodes are offered by many manufacturers of piezoceramics. These electrodes cover both parallel surfaces of a disk. Therefore, piezoelements of a disk shape are widely used in ultrasonic transducers [5]. On the other hand, mechanical and electrical characteristics of a piezoelement depend not only on its shape but also on configuration of electrodes.

Non-uniform electrodes are used in piezotransducers for excitation of a non-uniform electric field [6, 7]. The reason of use of such electrodes is broad frequency band of transducer. Some cases of piezodisk are discussed in [8]. On the other hand, non-uniform electrodes can be used because it is practical for connection of excitation, shielding and mechanical mounting (Fig. 1).

However, characteristics of piezoelements with this shape of electrodes are insufficiently discussed in available papers. Some attempt of analysis was made in [9], but this analysis was performed at frequencies of radial modes only. Therefore, more detailed investigation is necessary.

The present study covers estimation of influence of a top electrode diameter to the electrical and mechanical characteristics of a unloaded piezodisk. Configuration of the grounded bottom electrode is estimated also. The goal is evaluation of efficiency of use of such electrodes for excitation of thickness-extensional mode in a piezoelectric disk. Practical recommendation for the electrode shape and the diameter are proposed in the conclusions of this study.

Model of piezoelectric disk

Simulations of a piezodisk were performed using the finite elements method (FEM) package ANSYS [10]. Axisymmetric two-dimensional models of a disk were analyzed in frequency and time domains. The models were built for the disk with solid electrodes (Fig. 2 a) and three combinations of non-uniform electrodes (Fig. 2 b-d). The last one was the model of a disk, which is rather practical design (Fig. 1).

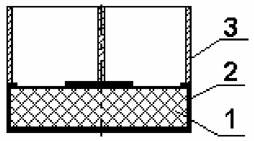


Fig.1. **Piezotransducer with non-uniforms electrodes and coaxial connection of excitation: 1 – piezoelement, 2 – electrodes, 3 – coaxial case of transducer**

FEM analysis in the frequency domain gives charge on nodes which are coupled by the electrode. It is performed by coupling voltage degree of freedom of the ANSYS element PLANE13. The impedance magnitude of piezoelement can be found using equations [3]

$$Y(\omega) = \omega \int_A Q_{mi} = \omega \sum_n Q_{mi} \text{ ,} \qquad (1)$$

$$Z(\omega) = 1/Y(\omega) \text{ ,} \qquad (2)$$

where Y is the admittance, ω is the frequency, A is the area of electrodes, n is the number of nodes in electrode and Q_{mi} is the calculated charge on nodes. Eq. 1 gives a correct admittance when the excitation voltage is 1V.

The piezoelectric disk of the diameter D=16 mm and the thickness t=1.6 mm was used in this study. The radius of the top electrode $R_{el}=d/2$ varied in the range $(0.1R...R)$, where $R=D/2$ is the radius of a piezodisk. The exception is model of the disk where lateral surfaces are coated by the electrode (Fig. 2 c-d). There R_{el} was slightly less than R in order to avoid electrical connection between the top and bottom electrodes. The bottom electrode was extended by $0.1R$ (0.8 mm) on the top of the disk in the last model (Fig.2 d). This electrode was used as a ground (0V) in all models.

Elastic, piezoelectric and dielectric constants of the piezoceramic CTS-19 were used in simulations [11].

The radius of a disk was divided into 50 elements and the thickness into 10 elements. This mesh grid corresponds to 20 elements per wavelength at the frequency of thickness mode at 1.2 MHz. FEM calculation errors of frequency and impedance magnitudes are less than 0.5-0.6%. These errors were estimated in [12].

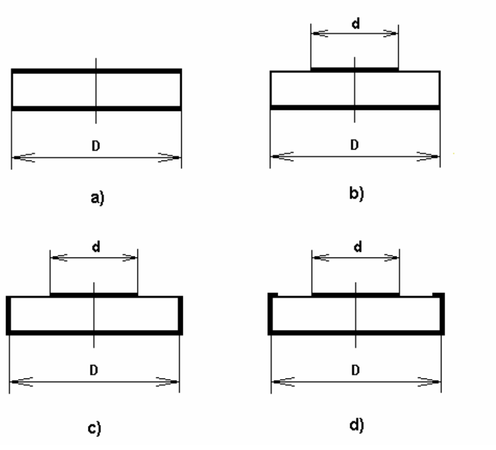
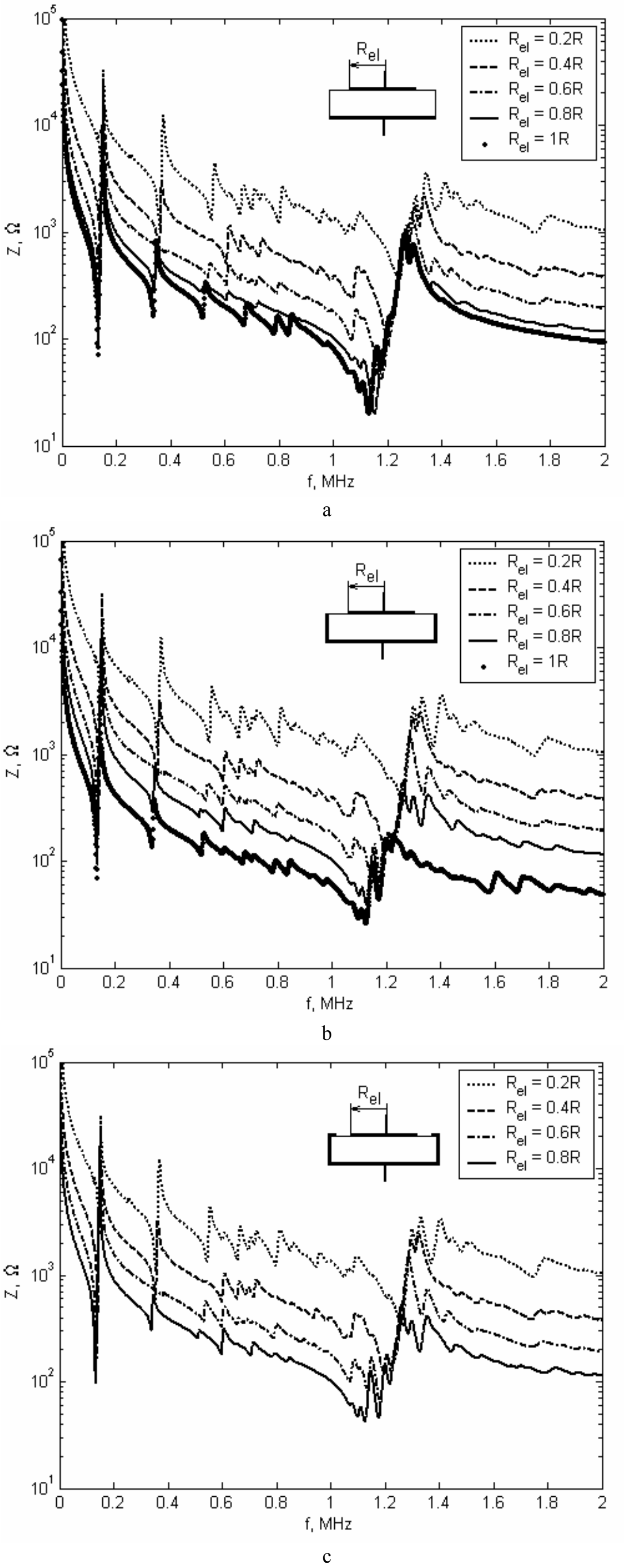


Fig.2. **Configuration of non-uniform electrodes: a) solid electrodes, b) partial upper electrode, c) partial upper electrode and metallization on bottom and lateral surface, d) the same as (c) with the bottom electrode extended to the top of piezoelement**

Results of analysis in frequency domain

Results of simulation of impedance magnitude characteristics are presented in Fig. 3. It is evident, that difference between characteristics of the models with a lateral surface coated by electrodes (Fig. 2. c-d) is very small (Fig.3 b-c).



a

b

c

Fig.3. **Influence of the top electrode radius to the impedance magnitude characteristics of piezoelectric disks: a) solid bottom electrode, b) bottom electrode extended on lateral surface, c) bottom electrode on lateral and top surfaces**

A general point for all three models is that change of the radius of a top electrode has significant influence on the magnitude of impedance. The less is R_{el}, the higher is the magnitude. It is valid for all types of simulated piezoelements (Fig.3 a-c). The origin of this effect is evident decrease of the piezoelement capacity C_0.

The frequency shift of a thickness mode to the higher frequencies can be observed when the radius of a top electrode is decreased. This shift can be explained keeping in mind the equivalent network of a piezoelement. The capacitors of the equivalent network C_0 and C_1 are conditioned by electrodes area. Decrease of this area means decrease of capacities and increase of serial and parallel resonance frequencies.

It can be noted, that characteristics of the impedance of a piezoelement with a small radius of the top electrode ($R_{el}=0.2R$) have new peaks which are not noticeable when the electrode radius is large (Fig.3). The modal analysis shows that these peaks are related to a bending mode of disk (Fig. 4). The left side of each mode shape in Fig. 4 represents axis of the disk. The frequency of the bending mode is related to the diameter of a disk but not to the diameter of an electrode (Table 1). No significant differences in the frequency were observed comparing all three models.

Table 1. **Frequencies of bending mode**

Harmonic		1	2	3	4	5
fr, kHz	$R_{el}=0.1R$	36.65	130.8	252.9	386.2	519.9
	$R_{el}=0.5R$	36.65	130.6	251.8	384.0	517.2
	$R_{el}=0.9R$	36.63	130.4	251.2	382.5	514.1

Impedance magnitude characteristics give only approximated view of mechanical aspect of vibration. Therefore analysis of mechanical vibrations of a piezoelement was done. The magnitude of a normal displacement at the center and the edge of a disk can definitely illustrate influence of the electrode radius (Fig. 5). Modes and harmonics can be observed as sharp peaks in this curve.

Decrease of R_{el} by 20% has significant influence to the vibration of a disk. The bending mode and harmonics are excited in this disk and it is clearly visible in Fig. 5. Impedance characteristics are not so sensitive to this change of the electrode. Significant raise of the displacement of a disk centre can be observed at the frequencies above the thickness-extensional mode (Fig. 5a).

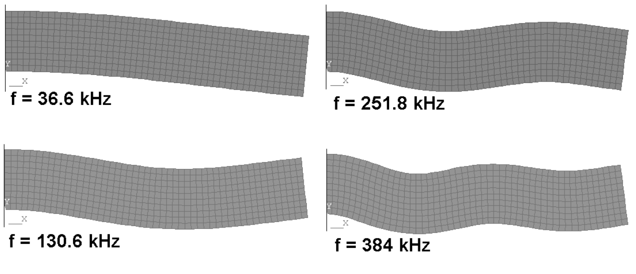
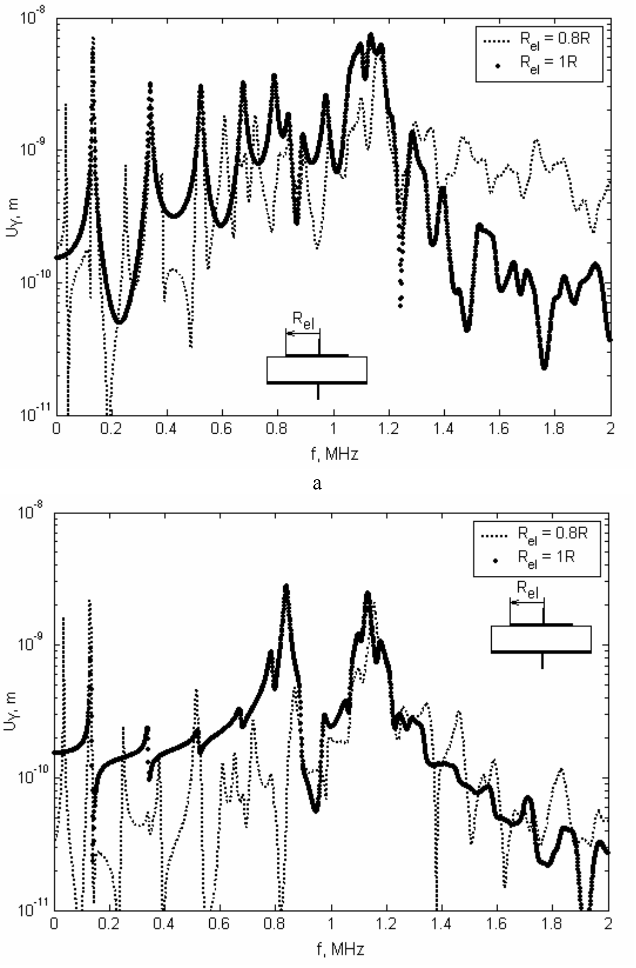


Fig.4. **Harmonics of bending mode in a piezoelectric disk**

Another effect of non-uniform electrodes is disappearance of edge mode. This mode is described in [2] and it is related to vibration of a disk edge. The edge mode exists in a disk with solid electrodes ($R_{el}=R$) at the frequency ~840 kHz (Fig. 5 b). This mode is not excited when the radius of the electrode is less than the radius of a disk.



a

b

Fig.5. **Influence of electrode radius to the displacement of a disk center (a) and edge (b).**

Analysis of vibration in the time domain

Analysis of a frequency response does not give full representation of processes in a piezodisk. Therefore, analysis in the time domain was done. The response of a piezodisk to the voltage pulse was calculated. The disk was excited by a short pulse of a negative voltage (τ=0.1 µs, U=-1V). The time increment 0.02 µs was used in this simulation. The piezodisk with a top electrode radius R_{el}=0.5R and the electrode on bottom and lateral surfaces was used in this analysis (Fig. 2 c).

Piezoelements shape during the first period of thickness extensional mode allows more detail understanding of vibration. The disk response shapes during period 0…1 µs after the excitation pulse are presented in Fig. 6. These shapes show evolution of vibrations.

It can be seen, that maximal displacements are in the region where both electrodes are parallel. Thickness vibration occurs in this region and magnitude of these vibrations is few times higher than in the region without top electrode. A peak of displacement is on the edge of the electrode. This peak is an origin of acoustic wave in a piezoelement. The direction of propagation of the positive peak of this acoustic wave is towards the center of a disk. A negative peak of displacement moves to the edge of a disk. Magnitude of the positive peak is higher than the magnitude of the negative peak due the focusing of acoustic wave in center of a disk.

The described process explains disappearance of edge mode, because the edge of a disk is not excited by an electric pulse. Excitation of the edge by acoustic energy of the wave is many times less.

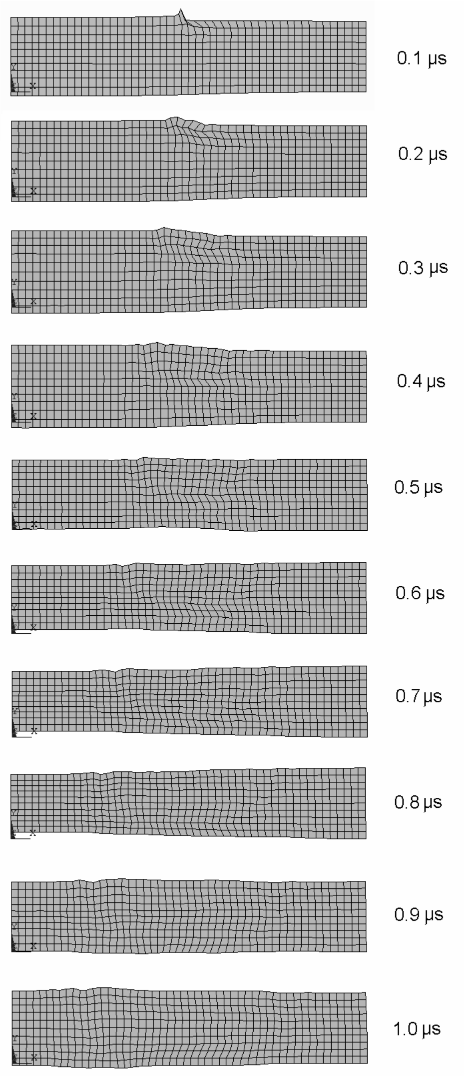


Fig. 6. **Shapes of displacement of piezodisk during the first period of the response to voltage pulse excitation**.

Conclusions and discussion

Results of the presented analysis show that vibration of a piezoelectric disk with non-uniform electrodes is more complex than vibration of the disk with solid electrodes.

Non-uniform distribution of electromagnetic field in a piezoelement is origin of bending mode. This mode takes part of energy of excitation. Therefore thickness extensional mode is not as effective as in the case of solid electrodes. Distribution of nodal displacements show that non-uniform configuration of electrodes allow effective excitation of thickness mode only in part of a piezoelement.

Therefore, raise of piezoelements' efficiency is possible when the radius of a top electrode is as maximal as possible. Thickness extensional wave is excited in maximal volume of a disk in this design. The width of a grounded electrode on the top of a disk should be enough for mounting purposes. Excessive area of this part of the electrode decreases efficiency of a piezoelement.

However, more detailed investigation is necessary for evaluation of radiation of such piezodisks into acoustic media. Simulations of field distribution and bandwidth could give a final answer on the practical aspect of such piezoelements. The acoustical focusing of wave using electrodes of ring shape could be analyzed also.

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Elektrodų formos įtaka pjezoelektrinio disko virpesiams

Reziumė

Elektrodų forma turi didelę įtaką pjezoelektrinio disko virpesių charakteristikoms. Kai viršutinis ir apatinis elektrodai yra nevienodi, kai kuriais atvejais tokį pjezoelementą montuoti ultragarsiniame keitiklyje yra patogiau. Straipsnyje nagrinėjami tokiame pjezoelemente sužadinami virpesiai. Baigtinių elementų metodu tiriama vieno iš elektrodų ploto mažinimo įtaka pjezoelemento impedanso modulio dažninėms charakteristikoms bei jo paviršiaus virpesiams. Pastebėta, jog pjezoelemente sužadinamos pašalinės lankstymosi modos. Ištirtos šio proceso laikinės priklausomybės.

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