

# Simulation of Surface Oscillation of Ultrasound Sensor Based on Piezoelectric Semiconductor Transducer

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**Abstract.** In the article theoretical and experimental studies of the surface deformation of piezoelectric sensors are carried out. Round membrane was used as a model of piezoelectric sensors. Experimental studies were conducted on mass-produced sensors and self-made sensor. Good match fluctuations in membrane model with fixed edges real sensors is shown.

## 1. Introduction

The ultrasonic testing based on excitation of piezoelectric sensors by electric pulse, which converts the electric pulse to the ultrasonic signal and passes one in the researched object. Ultrasonic signal interacts with a testing object, echo signal receive and one is analyzed [1-4]. When an electrical signal arrives to piezoelectric sensors, piezoelectric plate fluctuations occur synchronously over the entire surface, that follow from the inverse piezoelectric effect equation [5, 6]:

$$U = s \sigma + d E + \sigma T ,$$

where  $U$  – mechanical deformation,  $s$  – mechanical compliance,  $\sigma$  – mechanical stress,  $E$  – electrical field strength,  $d$  – piezoelectric constant,  $T$  – temperature.

It is considered that all changes of acoustic signal happen only in the testing object. However, when the sensor is manufactured, flat side of a piezoelectric plate fixes by a box or another construction unit [7]. Therefore, a piezoelectric plate deformation has intricate form (shape). Study of natural oscillations of piezoelectric plates were devoted to a work [8–10]. But one did not take into account the influence of degree of fixing flat side of a piezoelectric plate in the manufacture of the sensor. The purpose of this work is to study fluctuations of surface sensor in mode excitation, which must be taken into account when analyzing the reflected echo-signal.

## 2. Theoretical aspects of phantom head designing

The behavior of the sensor is studied during of shock excitation (this mode uses the most frequently). The analogue sensor oscillations can be fluctuations circular membranes, the edges of which either rigidly fixed or on the edge of the membrane acting elastic force proportional to the deviation of the



membrane. Options considered to correspond to the boundary conditions of the problem of the membrane oscillation [11]. An equation of free oscillations of the membrane with fixed edges is:

$$U(r,t)_{tt} = c^2 \Delta U, \quad (1)$$

at initial conditions:

$$U(r,t)|_{t=0} = A, \quad U(r,t)_t|_{t=0} = 0,$$

and the boundary condition:

$$U(r,t)|_{r=b} = 0,$$

where  $A$  is the residual amplitude after shock excitation,  $U(r,t)_t$  – first derivative of oscillations amplitude with time,  $r$  – current radius coordinate,  $b$  – the radius of the membrane,  $U(r,t)_{tt}$  – the second derivative of oscillations amplitude with time,  $c$  – the speed of propagation of flexural vibrations,  $\Delta U$  – Laplace operator.

For the free vibrations of the membrane with elastic fastening edges only boundary conditions are changed:

$$G \cdot U(r,t)_r|_{r=b} = K \cdot U(r,t)|_{r=b} \Rightarrow U(r,t)_r + H \cdot U(r,t)|_{r=b} = 0,$$

where  $G$  is the shear modulus,  $G \cdot U(r,t)_r$  – elastic force,  $U(r,t)_r$  – the first derivative of oscillations amplitude with radius.

Focus on task with a stiff pinning the edges of the membrane:

$$U(r,t)_{tt} = c^2 \cdot [U(r,t)_{rr} + \frac{1}{r} \cdot U(r,t)_r],$$

The solution to the equation is:

$$U(r,t) = 2 \cdot A \cdot b \cdot \sum_{k=1}^{\infty} \frac{1}{\alpha_k^2} \cdot J_1(\alpha_k) \cdot J_0(\alpha_k \cdot \frac{r}{b}) \cdot \cos(\frac{\alpha_k \cdot c}{b} \cdot t), \quad (2)$$

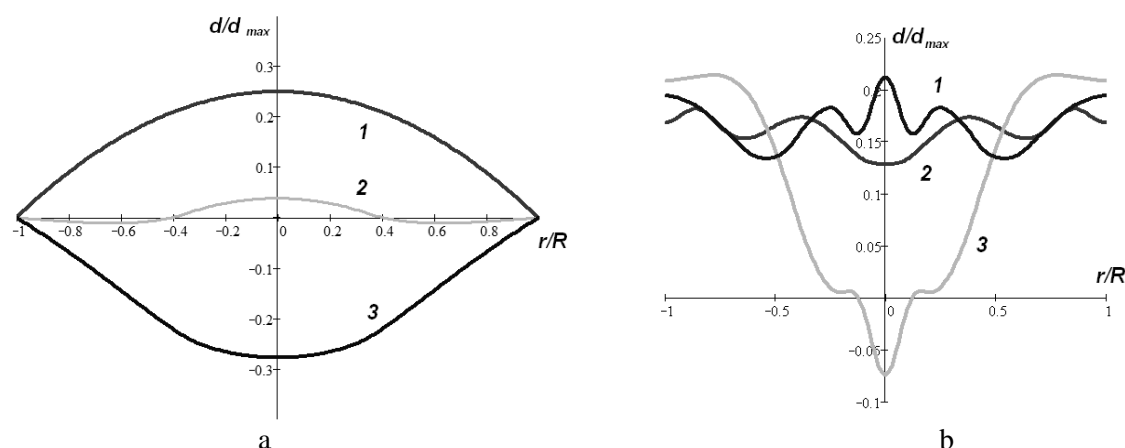
where  $\alpha_k$  - the positive roots of the equation  $J_0(x) = 0$

Table 1 shows the values of the first of six roots of the equation  $J_0(x) = 0$  for stiff  $\alpha_k$  and elastic  $\beta_k$  pin of the membrane edge.

**Table 1.** The first of six values of the roots.

№ root	1	2	3	4	5	6
$\alpha_k$	2.40	5.52	8.65	11.79	14.02	18.10
$\beta_k$	3.832	7.016	10.173	13.324	16.471	19.616

Using the obtained values of the roots calculations of longitudinal amplitude oscillations of the surface of the membrane were carried out. The results of the calculations for expression (2) are presented figure 1.



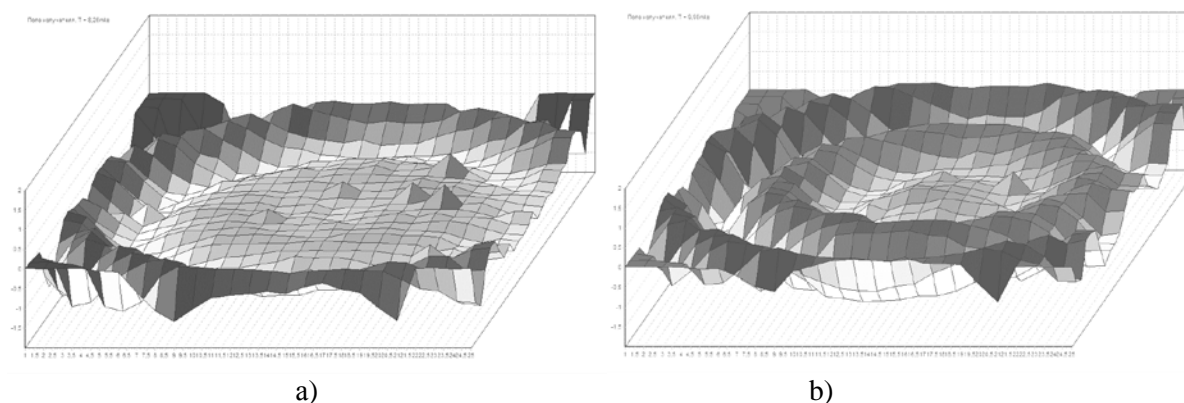
**Figure 1.** Membrane fluctuations: a– edge stiff fixed, b– edge elastic fixed; 1–start of the excitation, 2 – on time  $\pi/2$ , 3– on time  $\pi$ .

### 3. Experimental research

To verify the correctness of the calculations experimental research of deformation of the surface of self-made and mass-produced sensors were carry out.

For this purpose test stand has been used [12], which allows you to move point receiver on the surface of the emitter with the specified step. Minimum scan step is 0.1 mm. The movement control is performed by a personal computer. The resulting data set was used for the reconstruction of 3D images of the surface piezoceramic sensors using algorithms described in [13–15].

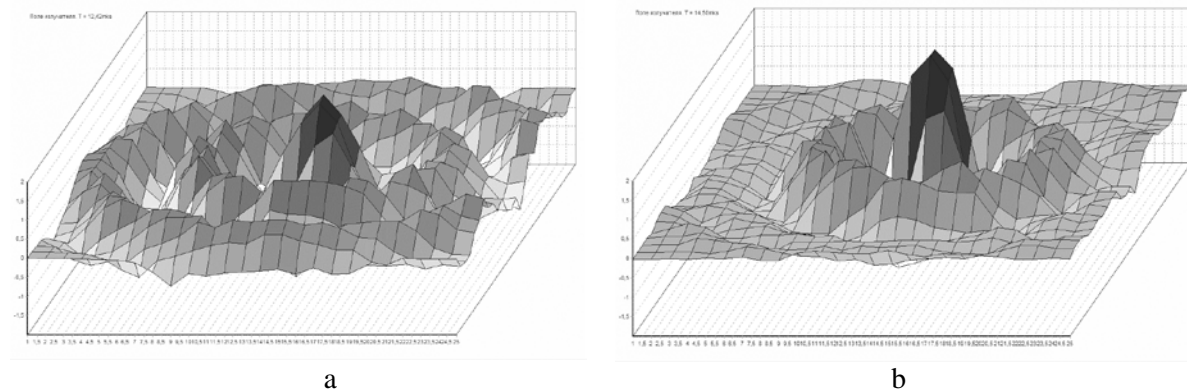
The sensor P111-1, 25-K20 company IC "Fizpribor" was researched. The results are showed in figure 2 and figure 3. The surface of the emitter shifts down during the shot (figure 2a), except the outer edge which one is bonded to the sensor box. On the edge of the converter starts to bending wave after the finish of the shot. It moving from the edge to the center of the plate (figure 2b)



**Figure 2.** 3D image deformation of the on the surface mass-produced sensor: a – the start shot, b – after the finish shot.

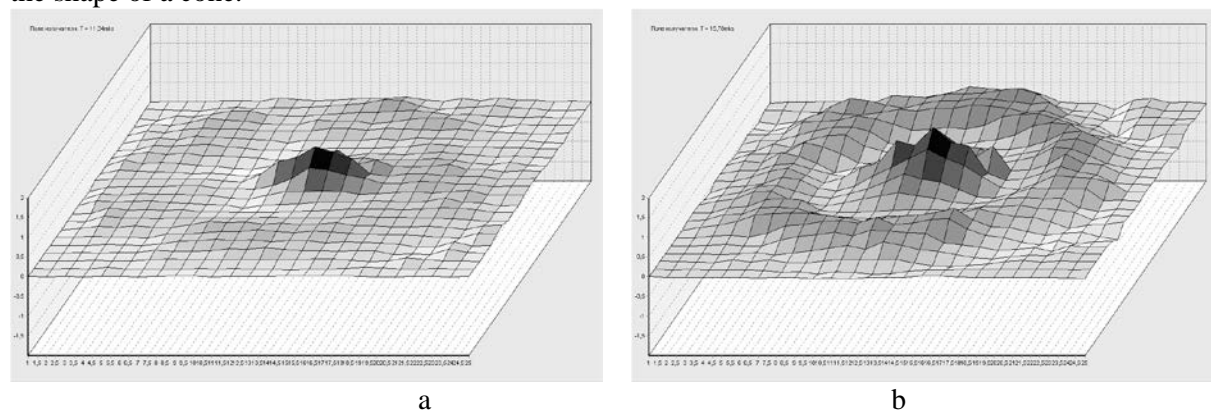
After that the second wave on the surface sensor is formed, which also moves to the center of the sensor (figure 2b). At this time the shot was finished. As a result, the interference of waves, coming from the edge of the emitter, at the center of the sensor turned out spike; it has much more amplitude than the amplitude of the waves coming from the edges (figures 3a and 3b).

Considering that scan step on the surface of the emitter was 1 mm, it is possible to estimate the geometric size of the spike, which had 6 mm diameter. A total diameter sensor is 25 mm. The spike in the center of the sensor turned out on time of 5 period. After that the process dies.



**Figure 3.** Result of interference of flexural waves on the surface mass-produced sensor: a – on time  $8\pi$ , b – on time  $10\pi$ .

The results of the study of ultrasonic field on the surface emitter self-made are presented in figure 4. Constructively sensor consists of tread, a piezoelectric plate of 25 mm diameter and a dash-pot in the shape of a cone.

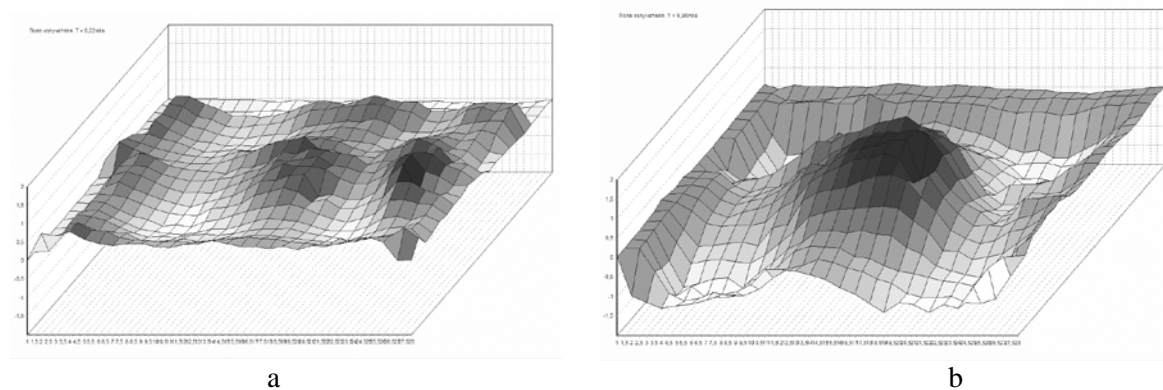


**Figure 4.** Result of interference of flexural waves self-made sensor: a – on time  $8\pi$ , b – on time  $10\pi$ .

Figure 4b shows that the frequency of flexural vibrations almost one and a half times lower and central peak has a smaller amplitude than the figure 3b. Figure 4b shows that the frequency of flexural waves a half times lower and spike has a smaller amplitude than the figure 3b. This is due to the stronger damping emitter. However, the general nature of the deformation of the surface of the emitter has remained unchanged.

The figure 5 presents the results of experimental researches of self-made sensor for which piezoelectric cell of square shape was used.

Change the shape of piezoelectric cell lead to change the deformation of the surface of the sensor.



**Figure 5.** Result of the interference of flexural waves on the surface of piezoelectric cell of the square shape: a – the spike starts to formation, b – the spike finishes to formation.

Figure 5 shows that the sensor edges are formed by two bending waves moving in mutually perpendicular directions, and the result of their interference is observed not only in the center but on the edges of the sensor at equal distance from the corners. Design of both sensors is the same, so the amplitude of deformation and frequency of flexural waves of these sensors are the same too.

#### 4. Conclusions

Comparison of theoretical and experimental studies leads to the conclusion of the adequacy of the proposed model of the sensor with fixed flat side by a box. Using the proposed model we can predict technical features of the sensor and determine the nature of the emitted signal and analyze the reflected signal with regard to the shape and duration of the echo signal. This will allow to increase the reliable estimate of testing result and to eliminate false rejection of products.

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