Gravimetric Sensitivity of Acoustic Waves in Piezoelectric Plates

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As is well known, deposition of the film of finite thickness on wave guide surface causes the change in velocity of acoustic waves propagating in wave guide. This so called gravimetric effect allows developing various biological and chemical sensors, which use change in mass of the active film due to presence of analyzed substance. Today there exist a number of papers offering to use different types of acoustic waves for development of the aforementioned sensors. However the comparative analysis of known results, which is necessary for the choice of the optimal wave type in specific situation is extremely difficult. It may be explained by the fact that authors use different final expressions for calculating gravimetric sensitivity and various simplifying approaches. This paper is devoted to the theoretical investigation of the influence of the massloading on acoustic waves of zero order in plates of lithium tantalate. As massloading we used metal and dielectric layers with finite thickness. The obtained results were compared with gravimetric sensitivity for Rayleigh and SH surface acoustic waves (SAW) in the same materials. Investigation showed that in general case the gravimetric sensitivity has complicated frequency dependence and depends on plate thickness and massloading material. In our opinion gravimetric sensitivity normalized on frequency is more informative parameter because in most cases it has weak frequency dependence for low values of massloading thickness. It has been also shown that acoustic waves of zero order in piezoelectric plates are more sensitive to massloading than Rayleigh and SH SAW.

1 Introduction

As is known [1–6], the deposition of a film of a finite thickness on the surface of an acoustic line changes the velocity of the acoustic wave propagating along the surface of the line. This is the so-called gravimetric effect, which can be used to develop various biomedical and chemical sensors measuring mass variations of an active film in the presence of the analyzed substance. The important characteristic that allows estimation of the efficiency of similar devices is gravimetric sensitivity S_m of the acoustic wave to the mass load on the surface of the acoustic line, which is determined as:

$$S_m = (\Delta V/V)/\rho_s, \quad (1)$$

where $\Delta V/V$ is the fractional change in velocity and ρ_s is the load mass per unit area [4]. In this case, the influence of the mass load on the characteristics of the wave is analyzed, as a rule, using the perturbation theory, whose principles are described in [7]. This theory assumes that the layer is thin compared to the wavelength and insignificantly affects the characteristics of the wave.

At present a great number of papers (see, for example, [1–6]) are known which propose the use of various types of acoustic waves, such as the Rayleigh surface acoustic waves (SAWs), shear horizontal SAW (SH SAWs), pseudosurface waves, flexural waves in plates, etc., for the development of the above sensors. In these papers the gravimetric sensitivity of such waves are theoretically and experimentally studied and a good agreement of theory and experiment is found. However, the comparative analysis of the obtained results, which is required for selection of the wave mode optimal in each particular situation, is extremely complicated because the authors use different final expressions for the gravimetric sensitivity and different simplifying assumptions. This practice results in inconsistency of basic conclusions. For example, it is shown in [1, 2, 4, 6] that sensitivity S_m is independent of the load material and frequency and is only determined by the material of the acoustic line and the wave mode. At the same time, it has been noticed that parameter S_m depends on the load material and the frequency, and the frequency dependence can be either quadratic [3] or linear [1]. This fact complicates the comparison because different publications give data for different frequencies. The authors also use different approaches to the estimation of the limits of applicability of the aforementioned perturbation theory. For example, it is shown in [1] that this theory gives equivalent results for loads with thicknesses on an order of wavelength λ, whereas in [2], it is mentioned that, starting from a thickness of 0.2λ, the influence of the mass load is reduced, and, in this case, it is necessary to take into account the modules of elasticity of the layer. In addition, in most papers [2–4] it is necessary to know the vibrational velocity of particles (or their displacement) on the surface of the piezoelectric in order to calculate S_m. This requirement is a complicated problem in itself.

However, it should be noted that the analysis of the known studies indicates that it is promising to use acoustic waves in piezoelectric plates for the development of gravimetric sensors. In regard to this point, it is of interest is to theoretically analyze the influence of the mass load made of various materials on characteristics of zeroth-order waves in the piezoelectric plates and to compare the gravimetric sensitivity of these waves with the corresponding parameters of widely used Rayleigh and SH SAWs.

This work theoretically analyzes the influence of the mass load on characteristics of the zeroth-order acoustic waves propagating in a piezoelectric plate. Lithium tantalate is used as a substrate. As the the mass load we used the metal layers excluding the influence of electric boundary conditions and dielectric nonpiezoelectric layers. Characteristics of these waves were compared with similar characteristics of Raleigh and SH SAWs.

2 Theoretical analysis

2.1 Initial equations, boundary conditions, and the solution method

Figure 1 show the geometry of the problem for acoustic waves in plates. A standard boundary value problem detailed in [8, 9] was solved in order to analyze the influence of the mass load on the characteristics of acoustic waves. The equation of motion for this medium, the Laplace's equation, and constitutive equations for the mechanical stress and the electric displacement with/without allowance for the piezoelectric effect were written for the piezoelectric substrate/dielectric massloading layer respectively. The equation of motion and constitutive equation for the mechanical stress were constructed for case of a

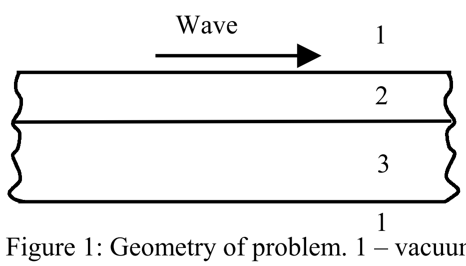

Figure 1: Geometry of problem. 1 – vacuum, 2 – massloading layer (dielectric or metal), 3 – substrate

perfectly conducting load. In vacuum, only the Laplace's equation was taken into account.

The following standard boundary conditions [8, 9] were also used: (i) the mechanical stresses at the free boundaries are equal to zero; (ii) components of the mechanical displacement and the mechanical stress are continuous at the interfaces between elastic mediums, (iii) the electric potential is zero at the perfectly conducting layers, and (iv) the electric potential and normal component of the electric displacement are continuous at the interface between dielectric mediums.

A standard matrix method of solution [8, 9] based on the representation of the desired solution as a sum of partial waves was used.

2.2 Results of the theoretical analysis of gravimetric sensitivity to perfectly conducting load

In the course of the theoretical analysis, we calculated velocities of antisymmetric (A_0), symmetric (S_0) and shear-horizontal (SH_0) waves in a thin (as compared to the wavelength) lithium tantalate plate in the presence of a mass load made of various materials. Figures 2–4 show dependencies of normalized sensitivity $S = S_m/f$ (f is the wave frequency) on normalized thickness d/h of layers of aluminum, silver, and gold for the above wave modes with different values of parameter hf. Here d is the thickness of the load layer, and h is the thickness of the piezoelectric plate. The choice of materials for the mass load was determined by their density, and the orientation of the substrate was chosen such that the piezoelectric activity of the considered wave was maximal [10]: for the A_0 wave, (128Y–X); for the S_0 wave, (X– Y+25); and for the SH_0 wave, (Y–X). The material constants of lithium tantalate and metal layers were taken from [11] and [12], respectively. As the value of an undisturbed velocity, the value of this velocity corresponding to a plate with one electrically shorted side was used. It can be seen from the figures that, in most cases, the mass load decreases velocities of acoustic waves, although opposite situations also exist. For example, the velocity of the A_0 wave propagating in the structure of the Al layer/$LiTaO_3$ plate increases with an increase in the layer thickness for all values of parameter hf (Fig. 2). Moreover, it can be seen from the analysis results that for any thickness of the substrate a load material should exist that virtually does not affect the velocity of the A_0 wave (Fig. 2). It can also be shown that gravimetric sensitivity S increases for all wave modes as density ρ_{ld} of the load material increases and normalized thickness of the plate hf decreases. In this case, the sensitivity can increase (Fig. 2), decrease (Figs. 2c, 3b, 3c, 4b, 4c), or remain unchanged (Figs. 3a, 4a). This means that the frequency dependence of

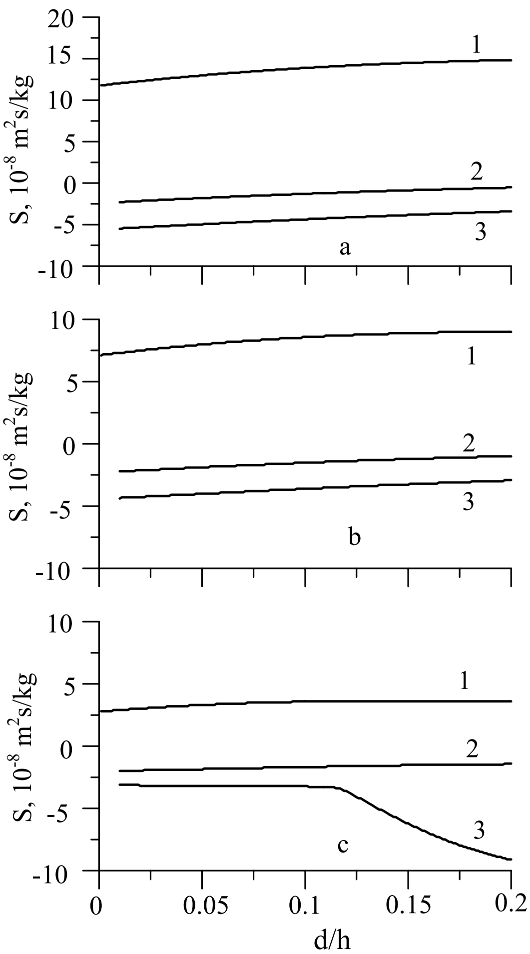

Figure 2: The normalized gravimetric sensitivity S versus normalized massloading thickness d/h for A_0 wave in 128^0Y–X $LiTaO_3$ plate at hf = 500 m/s (a), 750 m/s (b) and 1500 m/s (c). Materials Al (1), Ag (2) and Au (3) used as massloading layers.

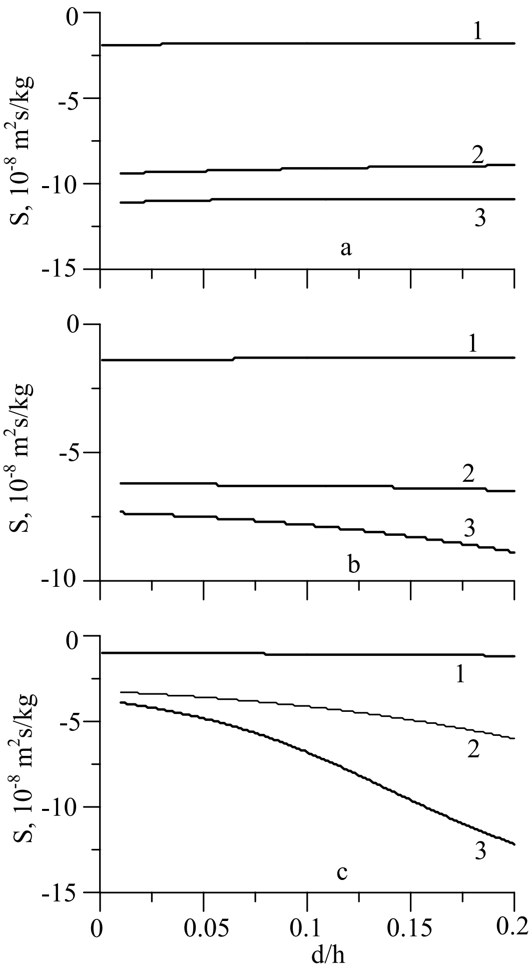

Figure 3: The normalized gravimetric sensitivity S versus normalized massloading thickness d/h for S_0 wave in X–Y+25^0 $LiTaO_3$ plate at hf = 500 m/s (a), 750 m/s (b) and 1500 m/s (c). Materials Al (1), Ag (2) and Au (3) used as massloading layers.

the sensitivity can behave either linearly or in a more complicated way. It should also be noted that the sensitivity of the A_0 wave is maximal at $\rho_{ld}/\rho < 1$ (ρ is the density of the substrate), and the sensitivities of the SH_0 and S_0 waves are maximal at $\rho_{ld}/\rho > 1$. Also it has been found that sensitivity S increases with the load layer density.

2.3 Results of the theoretical analysis of gravimetric sensitivity to dielectric nonpiezoelectric load

The influence of dielectric nonpiezoelectric massloading layers on characteristics of A_0, S_0 and SH_0 acoustic waves in $LiTaO_3$ plates is also interested from practical point of view. This problem have been solved by using the method described in item 2.1 of this paper.

In the course of the theoretical analysis, we calculated velocities of A_0, S_0 and SH_0 waves in a thin (as compared to the wavelength) lithium tantalate plate in the presence of a mass load made of various materials. Figure 5 shows dependencies of normalized sensitivity *S* on normalized thickness *d/h* of layers of SiO_2 and KI for the above wave modes with parameter *hf* = 500 m/s. In this case the choice of materials for the mass load was determined by their density and dielectric permittivity. The orientation of the substrate was chosen such that the piezoelectric activity of the considered wave was maximal (item 2.2 of this paper). As the value of an undisturbed velocity, the value of this velocity corresponding to a plate with electrically open surfaces was used. It has been found that dielectric nonpiezoelectric mass load decreases velocities of acoustic waves as perfectly conducting massloading. Although the velocity of the A_0 wave

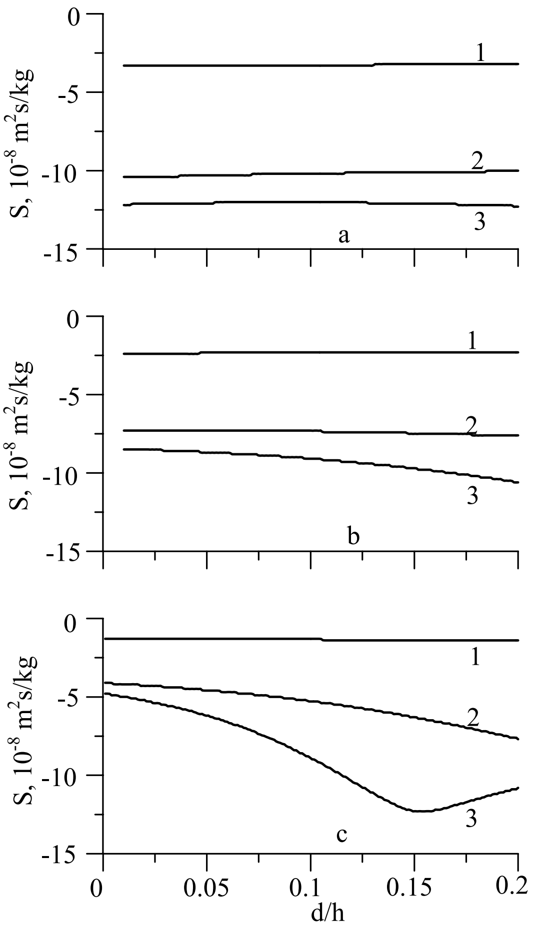

Figure 4: The normalized gravimetric sensitivity S versus normalized massloading thickness d/h for SH_0 wave in Y–X $LiTaO_3$ plate at hf = 500 m/s (a), 750 m/s (b) and 1500 m/s (c). Materials Al (1), Ag (2) and Au (3) used as massloading layers.

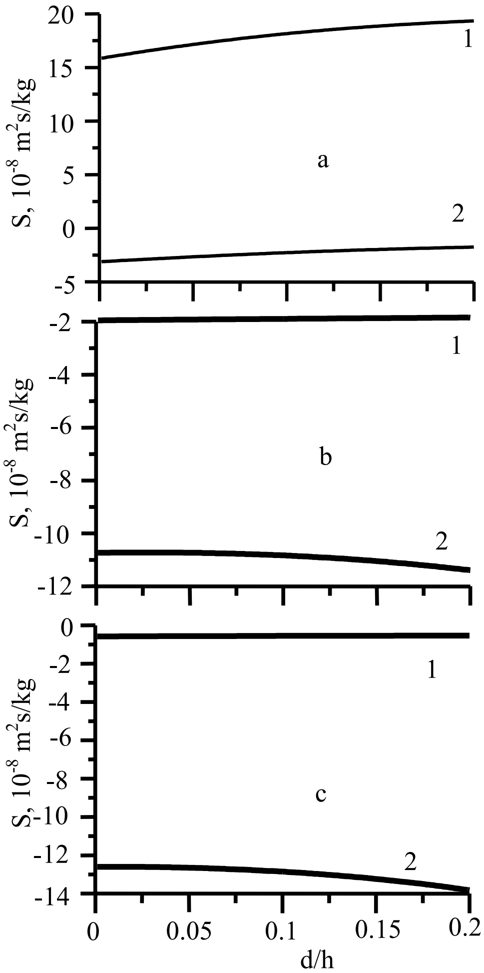

Figure 5: The normalized gravimetric sensitivity S versus normalized massloading thickness d/h for A_0 (a), S_0 (b) and SH_0 (c) waves in $LiTaO_3$ plate at hf = 500 m/s. Materials SiO_2 (1) and KI (2) used as massloading layers.

propagating in the structure of the SiO_2 layer/$LiTaO_3$ plate increases with an increase in the layer thickness (Fig. 5a). It can also be shown that gravimetric sensitivity *S* increases for all wave modes as dielectric permittivity of the dielectric load material decreases.

It has been found that the acoustic plate waves have a larger gravimetric sensitivity than the Rayleigh SAWs and SH SAWs in the same material.

3 Summary

The conducted numerical analysis of the influence of a perfectly conducting/dielectric nonpiezoelectric mass load on various modes of acoustic waves has shown that the gravimetric sensitivity generally has a complex frequency dependence and depends on both the plate thickness and the load material. In our opinion, normalized gravimetric sensitivity $S = S_m/f$ is a more informative characteristic. In most cases, at small values of the load thickness, this sensitivity only slightly depends on the wave frequency. Sensitivities to a mass load of all zeroth-order wave modes propagating in piezoelectric plates is higher than those of the Rayleigh and SH SAWs. It should also be noted that in most cases the mass load decreases the wave velocity, although opposite situations can exist. For example, the velocity of the A_0 wave propagating in the structure of the Al layer/$LiTaO_3$ plate or SiO_2 layer/$LiTaO_3$ plate increases with the layer thickness for all values of parameter hf. For each substrate a load material should exist that virtually no effect on the velocity of the A_0 wave. As the normalized plate thickness reduces, the sensitivity of the studied zeroth-order waves increases. The gravimetric sensitivity *S* increases for all wave modes as dielectric permittivity of the dielectric load material decreases.

Acknowledgments

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