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Shear Horizontal Surface Waves on Piezoelectric Ceramic with Layered Structure

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Abstract. This paper presents theoretical and experimental results describing the propagation of SH (shear, horizontal) surface waves on a piezoelectric ceramic with a surface layer of different polarization than that in the substrate. An analytical formula for the group velocity of the SH surface waves is developed. The velocity of impulses of the SH surface waves is determined experimentally. Further, the theoretical results are compared to the experimental values.

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In [1] Kiełczyński and Pajewski presented theoretical results describing the phase velocity and amplitude distribution of SH (shear, horizontal) surface waves propagating in a piezoelectric ceramic with a surface layer of different polarization than that in the substrate. The surface structures considered are waveguides for SH surface waves and can be employed in the construction of some acousto-electric devices, such as directional couplers or resonators [2, 3].

In this paper we present experimental and theoretical results for SH surface waves propagating in two surface structures of a piezoelectric ceramic shown schematically in Figs. 1. Further, the experimental results are compared to the calculated values for the phase and group velocities of the SH surface waves.

The structures considered consist of the piezoelectric substrate $x_3<0$ of a piezoelectric ceramic polarized along the axis x_2 and of the surface layer $0<x_3<h$ made also of a piezoelectric ceramic polarized along the axis x_1 (Fig. 1a) or entirely depolarized (Fig. 1b). The interface at $x_3=0$ is always metallized. Therefore ferroelectric domains in the crystallites in the surface layer and in the substrate are electrically isolated. Moreover, SH surface waves and Rayleigh waves which can, of course, propagate in the considered structures, are totally decoupled.

In the sequel SH surface waves of mechanical vibrations polarized along x_2 and propagating in the considered structures in the direction x_1 will be analysed. Piezoelectric ceramic in the surface layer $0<x_3<h$ is piezoelectrically nonactive for transverse vibrations polarized along x_2. Thus the mechanical displacement u_2 of the SH surface waves is accompanied by an electric potential only in the substrate region $x_3<0$.

SH surface waves propagating in the considered structures are highly dispersive [1], i.e., their phase and group velocities are significantly different.

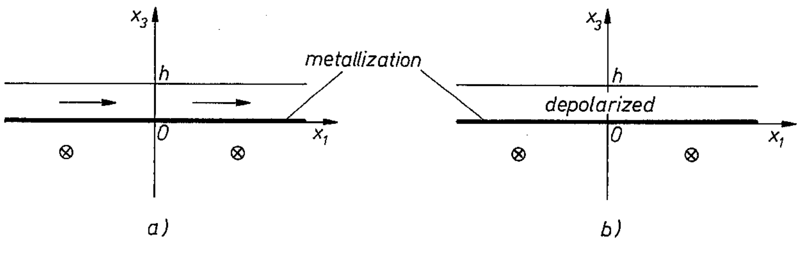

Fig. 1. Considered surface structures of piezoelectric ceramics. (h: thickness of the surface layer. →, ⊗: directions of polarization)

In Sect. 1 the group velocity of the SH surface waves is determined theoretically. Section 2 contains the results of the experiment and the discussion.

In the appendix we analyse the possible existence of Maerfeld-Tournois waves [4] which can propagate in the studied structures.

1. Group Velocity of the SH Surface Waves

Material parameters of the piezoelectric ceramic in the substrate $x_3 < 0$, such as elastic, piezoelectric or dielectric constants and density, are described, respectively, by c_{44}, e_{15}, ε_{11}, and ϱ. On the other hand, the appropriate quantities corresponding to the surface layer $0 < x_3 < h$ will be denoted by the upper index "^", e.g., $\hat{c}_{66}$, $\hat{c}_{44}$, and $\hat{\varrho}$ denote, respectively, the elastic constants and density of the piezoelectric material in the surface layer.

The dispersion relation for SH surface waves propagating in the examined structures (Fig. 1) is given by the following relation [1]

$$\Omega(\omega, k) = b^1 \tan(kb^1h) - rhs = 0\,, \tag{1}$$

where ω and k are, respectively, the angular frequency and wavenumber of the SH surface wave. The factors b^1 and rhs are functions of ω and $k = \omega/v_{ph}$, where v_{ph} denotes the phase velocity of the SH surface wave.

The group velocity $v_g = \partial\omega/\partial k$ of a wave can be obtained from the known relation [5], i.e.,

$$v_g = -\frac{\partial\Omega/\partial k}{\partial\Omega/\partial\omega}\,. \tag{2}$$

Employing (1 and 2) the group velocity v_g of the SH surface waves is given by

$$v_g = \frac{\hat{v}_{44}^2}{v_{ph}} \frac{A + \dfrac{\bar{c}_{44}}{\hat{c}_{66}} b^1 \left(\dfrac{1}{b^a} - k_{15}^2\right)}{A + b^1/b^a}\,, \tag{3}$$

where

$$A = \tan(kb^1h) + kb^1h[1 + \tan^2(kb^1h)]\,, \tag{4}$$

$$b^a = \left[1 - \left(\frac{v_{ph}}{\bar{v}_{44}}\right)^2\right]^{1/2} \tag{5}$$

and

$$\bar{c}_{44} = c_{44} + \frac{e_{15}^2}{\varepsilon_{11}}\,, \qquad k_{15}^2 = e_{15}^2/(\bar{c}_{44}\varepsilon_{11})\,,$$
$$\bar{v}_{44} = (\bar{c}_{44}/\varrho)^{1/2}\,, \qquad \hat{v}_{44} = (\hat{c}_{44}/\hat{\varrho})^{1/2}\,. \tag{6}$$

In particular, for the surface structure illustrated by Fig. 1a, one has

$$b^1 = \left[\left(\frac{v_{ph}}{\hat{v}_{66}}\right)^2 - \left(\frac{\hat{v}_{44}}{\hat{v}_{66}}\right)^2\right]^{1/2}, \tag{7}$$

and for the surface structure shown in Fig. 1b

$$b^1 = \left[\left(\frac{v_{ph}}{\hat{v}_{44}}\right)^2 - 1\right]^{1/2}. \tag{8}$$

From (3) it is clear that the group velocity v_g of the SH surface waves can be determined for a known value of the phase velocity v_{ph}. For a very thin surface layer, i.e., for $kh \to 0$, the factor $b^a \to k_{15}^2$ and $v_g \approx v_{ph} \approx \bar{v}_{44} \cdot (1 - k_{15}^4)^{1/2}$. This means that the velocity of the SH surface waves equals, in this case, the velocity of the Bleustein-Gulyaev (B–G) surface waves [6] propagating on a metallized surface of the substrate. By constrast to the analysed SH surface waves, B–G waves are dispersionless.

2. Experimental Results and Discussion

The velocity of the SH surface waves was measured on rectangular $25 \times 12 \times 10\ \mathrm{mm}^3$ samples made of a piezoelectric ceramic of the PZT type. The whole volume of the sample was polarized along the axis x_2. One polished surface of the sample was metallized (Al) in vacuum. Subsequently a thin layer of the same piezoelectric ceramic material, polarized along the axis x_1 or totally depolarized, was bonded with glue. Afterwards, the upper surface of the surface layer was polished in order to obtain a thickness equal to ~ 0.3 mm. The surface structures prepared in this way are quasi-monolithic waveguides for SH surface waves.

It is worthy to mention here that we tried also to fabricate totally monolithic surface waveguides in monolithic samples of the piezoelectric ceramic PZT. The surface layer of longitudinal polarization (Fig. 1a) was prepared by employing very thin polarizing electrodes of the width ~ 1 mm. On the other hand, to obtain a nonpiezoelectric surface layer (Fig. 1b), incomplete polarizing electrodes (Ref. 1, Fig. 4) were applied. These and other attempts were not satisfactory, i.e., the velocity of the SH surface waves propagating in the prepared structures was not a function of frequency. This means that the ceramic samples were polarized uniformly in the whole volume or that the thickness of the surface layer was too large, namely that it exceeded ~ 2 mm. The obtained results can be understood on the basis of Auld's papers [2, 3] which show that the width of the transition zone from one polarization state to another varies from ~ 0.1 to 2.0 mm, depending on the type of the ceramic used. The lower limit is achieved for a "soft" piezoelectric ceramic, such as PZT-5H, and the upper limit in a "hard" ceramic, e.g., PZT-4.

SH surface waves were generated and detected by plate piezoelectric transducers bonded appropriately to the edges of the samples. The velocity of the SH

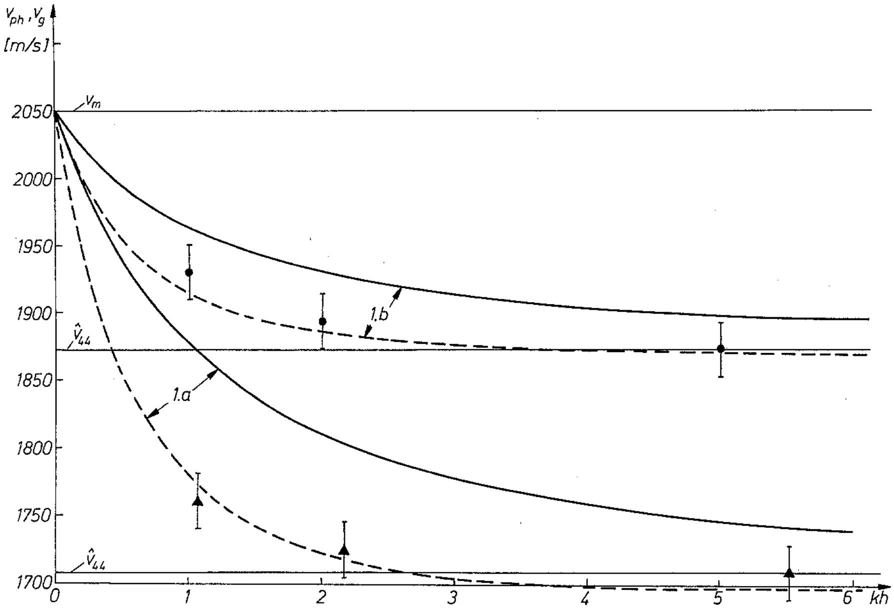

Fig. 2. Calculated phase v_{ph} (——) and group v_g (– – – –) velocities of the SH surface waves propagating in the surface structures shown in Fig. 1a and b, as a function of kh, where k is the wavenumber of the SH surface wave. ●, ▲ experimental values

surface wave was determined by measuring the transition time of surface wave impulses travelling along the sample on a known distance. Ultrasonic impulses had several μs of duration and possessed a carrier frequency varying from 1 to 10 MHz. The accuracy of the measurements was estimated to $\pm 1\%$.

The experimental results are plotted in Fig. 2. For comparison, in the same figure the calculated values of the phase v_{ph} and group v_g velocity are drawn as well.

The measured velocity of the SH volume wave propagating in the substrate $x_3 < 0$ in the samples shown in Fig. 1 was $\bar{v}_{44} = 2294$ m/s. It can be assumed that this velocity equals the velocity of the B–G surface waves propagating on the free surface of the substrate v_f. Moreover, the measured velocity of the B–G surface waves propagating on a metallized surface of the substrate was $v_m = 2049$ m/s. Employing the measured velocities v_f and v_m, one can calculate the electromechanical coupling coefficient of the substrate from the standard formula: $k_{15}^2 = [1 - (v_m/v_f)^2]^{1/2} = 0.45$.

For high frequencies of the SH surface waves, i.e., for $kh \to \infty$ their phase and group velocities tend to the velocity of volume SH waves in the surface layer $\hat{v}_{44} = (\hat{c}_{44}/\hat{\varrho})^{1/2}$.

It can be assumed that the density of the surface layers in the structures from Figs. 1 is identical. On the other hand, their elastic constant $\hat{c}_{44}$ is not the same, i.e., the surface layer from Fig. 1a $\hat{c}_{44}$ is greater than that shown in Fig. 1b. Namely, for the considered structures the velocity v_{44} was measured to be, respectively, 1706 m/s (Fig. 1a) and 1852 m/s (Fig. 1b).

From Fig. 2 it is clear that impulses of the SH surface waves propagate in the considered structures with a velocity closer to the group velocity than to the phase velocity, as one might expect.

3. Conclusion

The considered surface structures of piezoelectric ceramics are efficient waveguides for SH surface waves. This fact was verified experimentally and explained theoretically.

Monolithic surface waveguides for SH surface waves can be made in a soft piezoelectric ceramic, such as PZT-5H, where the width of the transition zone is of order ~0.1 mm.

Appendix

Maerfeld-Tournois Waves in the Considered Structures

In experimental practice one frequently obtains a series of impulses which are difficult to identify. Therefore we analyse here the possibility of the existence of Maerfeld-Tournois (M-T) waves [4] at the interface between two ceramic half spaces of different polarization. Maerfeld-Tournois waves will be examined in two infinite structures obtained from those presented in Fig. 1 when the thickness of the surface layer tends to infinity, i.e. when $h \to \infty$. The M-T waves propagating in the direction x_1 have only one transverse (SH) component of mechanical displacement u_2 decaying to zero for $|x_3| \to \infty$.

Using the appropriate equations of motion and boundary conditions at the interface $x_3 = 0$ [7], one obtains the dispersion relation for M-T waves propagating in the considered structures in the following form:

$$b^a + \frac{\hat{c}_{44}}{\bar{c}_{44}} |b^1| = k_{15}^2 , \qquad \text{(A.1)}$$

where b^a, $b^1 = j \cdot |b^1|$ are described, respectively, by (5, 6, and 8). Equation (A.1) was developed under the assumption that the phase velocity v_{ph} of the M-T wave satisfies the following conditions:

$$v_{ph} < \bar{v}_{44} \quad \text{and} \quad v_{ph} < \hat{v}_{44}. \tag{A.2}$$

After examination of (A.1), it follows that the necessary condition for the existence of the M-T waves is as below

$$(\hat{v}_{44}/\bar{v}_{44})^2 \geqq 1 - k_{15}^4 \quad \text{or} \quad \hat{v}_{44} \geqq v_m. \tag{A.3}$$

The above condition is, in general, very difficult to satisfy for two bonded piezoelectric ceramics. For example, if piezoelectric ceramics in both regions outside the interface $x_3 = 0$ have the same mechanical and dielectric parameters, i.e., $\hat{c}_{44} = c_{44}$, $\hat{\varrho} = \varrho$, and $\hat{\varepsilon}_{11} = \varepsilon_{11}$, then the condition (A.3) leads to contradiction, i.e., to the relation $k_{15}^2 \geqq 1$. Thus M-T waves cannot propagate in the structures examined. Moreover, this fact is confirmed by experimental results which show that $v_m = 2049$ m/s is always greater than $\hat{v}_{44} = 1706$ m/s or 1852 m/s.

If the interface $x_3 = 0$ is nonmetallized, then the appropriate condition for the existence of the M-T waves is more restrictive than the condition (A.3). In conclusion, it can be stated that SH waves of the Maerfeld-Tournois type propagating at the interface between two piezoelectric ceramics, which are not reversely polarized, are rather difficult to generate and observe.

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