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TRANSVERSAL BLEUSTEIN-GULAYEV (B.G.) SURFACE WAVES ON A PIEZOELECTRIC CERAMIC

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In this paper the results of investigations of piezoelectric ceramic of the type lead zirconate-titanate (PZT) used as a basis for acoustic-electric waves (B.G.) are presented.

The inhomogeneous structure of the ceramic, which results from a particular technological process, was observed to influence the surface wave propagation. The ceramic structure, which causes velocity differences in the propagation velocity of an acoustic wave in the surface layers, can preclude the possibility of transversal surface wave propagation or can create more favourable conditions for its propagation depending on whether the volume wave velocity increases or decreases within the surface layers.

Investigations were carried out with plate and interdigital transducers for the generation of waves on the ceramic.

1. Introduction

Piezoelectric ceramic of the PZT type, is a material possessing good piezoelectric properties and is cheap and readily available. It has already found wide application in piezoelectric devices.

In view of the difficulties in obtaining suitable materials for acousto-electronic devices the idea emerged of using this piezoelectric ceramic as a basis for surface waves because of its characteristically large electromechanical coupling coefficient.

The currently produced ceramic has a basic fault, namely porosity. Porosity and graininess of the ceramic result from the technological process of its production. The obtained grain size (of the order of several or a dozen microns) constitutes an obstacle to the generation of elastic waves of high frequency. The discontinuity of the surface accounts for difficulties in polishing it suitably which is a basic condition for small surface waves attenuation at the higher frequencies.

Surface waves which are less sensitive to the surface condition are Bleustein-Gulayev (B.G.) waves which can penetrate quite deeply into the material.

Works on the utilization of the currently-produced ceramic (PZT) as a medium for surface waves [4] points to the possibility of using the ceramic at intermediate frequencies for colour television, and in delay lines at frequencies up to 30 MHz [5].

The technology of piezoelectric ceramics is constantly developing. Its properties are constantly being improved and this encourages the investigation into the generation and propagation of surface waves in ceramics. At present, only the conclusions drawn at lower frequencies are of a more general character, as results from the following pages of this paper.

2. Properties of Bleustein-Gulayev waves

A B.G. wave constitutes a special case of a Love wave which is propagating at the boundary of two media, in which molecules on the surface of the body and in its proximity are set into motion transversal to the direction of wave propagation. The motion of the molecules is related to the shear deformations in the plane of wave propagation. However, the conditions for the generation of B.G. waves are different from those for the generation of Love waves and are defined by the properties of the piezoelectric material.

B.G. waves can be considered to be a limiting state towards which a transversal volume wave moves under certain boundary conditions [1]. The properties of B.G. waves can be easily assessed with the aid of the relevant equations.

The propagation velocity of a B.G. wave at a free surface is described by the formula

$$v_s^2 = \frac{c}{\varrho}(1+k^2)\left[1-\left(\frac{1}{1+\varepsilon/\varepsilon_0}\frac{k^2}{1+k^2}\right)^2\right], \tag{1}$$

where c is the shear modulus, ϱ — the density of the material, ε_0 — the electric inductive capacity (permittivity) of the medium adjoining the air surface, ε — the electric inductive capacity of the material, and k — electromechanical coupling coefficient of the material.

In the case of a piezoelectric for which $\varepsilon/\varepsilon_0 = 730$, this velocity is very near to the velocity of the transversal wave expressed by the formula

$$v_T^2 = \frac{c}{\varrho}(1+k^2). \tag{2}$$

The velocity of the B.G. wave at a surface with a thin metallization layer and for which $\varepsilon_0 \to \infty$ and $1/(1+\varepsilon/\varepsilon_0) \to 1$ can be assumed, is given by

$$v_{sm}^2 = \frac{c}{\varrho}(1+k^2)\left[1-\frac{k^4}{(1+k^2)^2}\right] = \frac{c}{\varrho}\frac{1+2k^2}{1+k^2}. \tag{3}$$

It can be seen that the velocity of the B.G. wave at a metallized surface is smaller than the velocity of the transversal wave. For instance, for a piezoelectric ceramic with a coefficient $k = 0.5$ this velocity is $v_{sm} = 0.98v$, i.e. the difference in velocity is barely $2\,^0/_0$. The penetration depth of the B.G. wave in the case of non-metallized surface is expressed by the formula

$$h = \frac{\lambda}{2\pi k^2}\left(1 + \frac{\varepsilon}{\varepsilon_0}\right). \tag{4}$$

In the case of a piezoelectric ceramic $\varepsilon/\varepsilon_0 = 730$, hence $k = 0.7$ and $h = 237\lambda$. Thus the B.G. surface wave is in this case very weak, all the elastic energy being bound with the transversal volume wave.

In the case of a metallized surface when $\varepsilon_0 \gg \varepsilon$, we have

$$h = \frac{\lambda}{2\pi k^2}, \quad h = 0.64\lambda, \tag{5}$$

thus the larger part of the energy is concentrated in a surface layer 0.6λ thick.

The properties of acousto-electric waves can be utilized for investigating the structure of a piezoelectric ceramic. A necessary condition for the propagation of a transversal wave on the surface of a medium is that the velocity of the surface wave be smaller than the velocity of the transversal volume velocity. This condition is satisfied in the case of a piezoelectric ceramic when the ceramic is covered with a metallic layer which brings about a reduced rigidity of the surface layer by eliminating the internal electric field.

3. Methods of the generating acousto-electric waves in a ceramic

The generation of acousto-electric waves is quite a complicated problem, since along with the surface wave transversal and longitudinal bulk waves are generated. The isolation of the surface wave is thus complicated, especially in the case where the velocities of the transversal bulk wave and the surface wave are nearly the same.

The process of exciting a surface wave by means of a digital transducer, as is widely used, requires an especially selective transducer. Digital transducers with a large number of teeth meet such a requirement, but in practice this causes some difficulties. In the investigation of ceramics transducers with a smaller number of teeth or plate transducers can be used.

The latter are especially well-suited for the investigation of the properties of materials by means of surface waves. In order to excite surface waves using a plate transducer, it is sufficient to place at the side of the plate a transducer with transversal vibration and polarization parallel to the surface. It is a good practice for the transducer width to cover the thickness of the surface layer in which the generation of waves occurs. This procedure for the generation of surface waves is of considerable practical importance, since owing to it we may avoid the laborious process of making digital transducers on the ceramic.

4. Experimental results

A digital transducer with four pairs of electrodes and an active tooth length of 4 mm, and also plate transducers, were used for the generation of B.G. surface waves. With the aid of two identical transducers a line, polarized vertically to the direction of the wave propagation and parallel to the plate surface, was constructed on the plate piezoelectric ceramic. The shape of the plate is shown in Fig. 1.

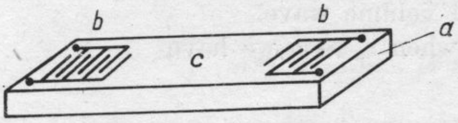

Fig. 1. Digital transducer on ceramic plate to be examined

a) plate of piezoelectric ceramic, *b*) transmitting and receiving transducer, *c*) metallized surface

In the case under consideration the wave generation is related to the piezoelectric constant d_{15} which produces shear deformations under the action of an electric field.

The properties of transducers and lines were investigated using pulses of the order of microsecond with different carrier frequencies. At first, measurements were made on ceramic with a free surface and, secondly, with a metallized surface.

It results from the work of REDWOOD et al. [4] that in the case of a non-metallized surface the coupling of the surface wave is very weak and its penetration depth very large, so that practically only a transversal wave is generated in the thin plate.

Investigations performed with home-made ceramic, in which the direction of the pressure during pressing was vertical to the surface along which the wave was propagating, gave no positive results (Fig. 2).

Measurements of the transversal wave, generated by an interdigital transducer on plates with metallized and free surfaces, have not shown any essential differences. Indeed, in some cases the velocity of waves on the metallized specimens was higher than the velocity on the non-metallized ones (Fig. 2). Thus the necessary condition for the existence of transversal surface waves was not met.

For further investigations the specimen used were cut from round plates, made in such a manner that the direction of the pressure during pressing was parallel to the surface at which the surface wave was propagating.

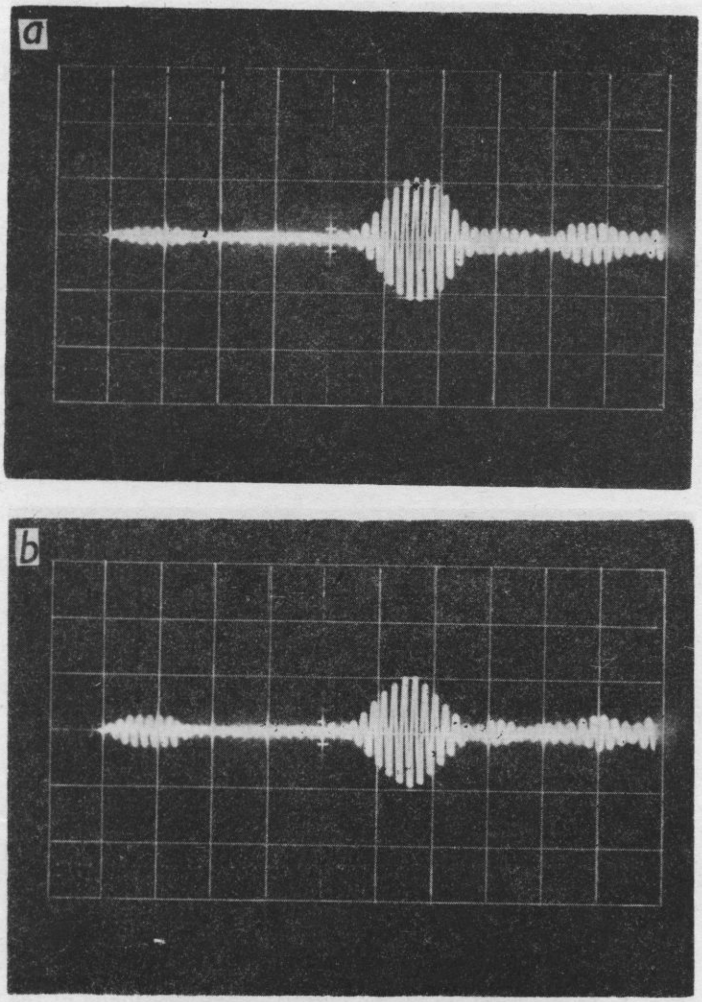

Fig. 2. Pulses received at the output of the line in Fig. 1
(f = 2870 MHz; 2 μs/div)
a) free surface v_s = 2380 m/s, *b*) metallized surface v_{sm} = 2380 m/s

Figures 3a, b show acoustic pulses generated and received on the surface of such a specimen by digital transducers at a frequency of approximately 2.5 MHz. Figure 3a shows pulses propagating along the free surface: the first impulse corresponds probably to the surface wave, the following ones to pulses reflected from the specimen ends. Figure 3b shows a surface wave on a metallized surface, in which case the reflections are weaker due to the bevelled edges of the specimen, while the increasing surface wave pulse can be seen early. From the difference of the wave velocities (Figs. 3a and 3b, Figs. 5a and 5b) it is possible to calculate the electromechanical coupling coefficient k_s according to the formula $k_s = v_s - v_{sm}/v_s$. In this case $k_s = 0.23$.

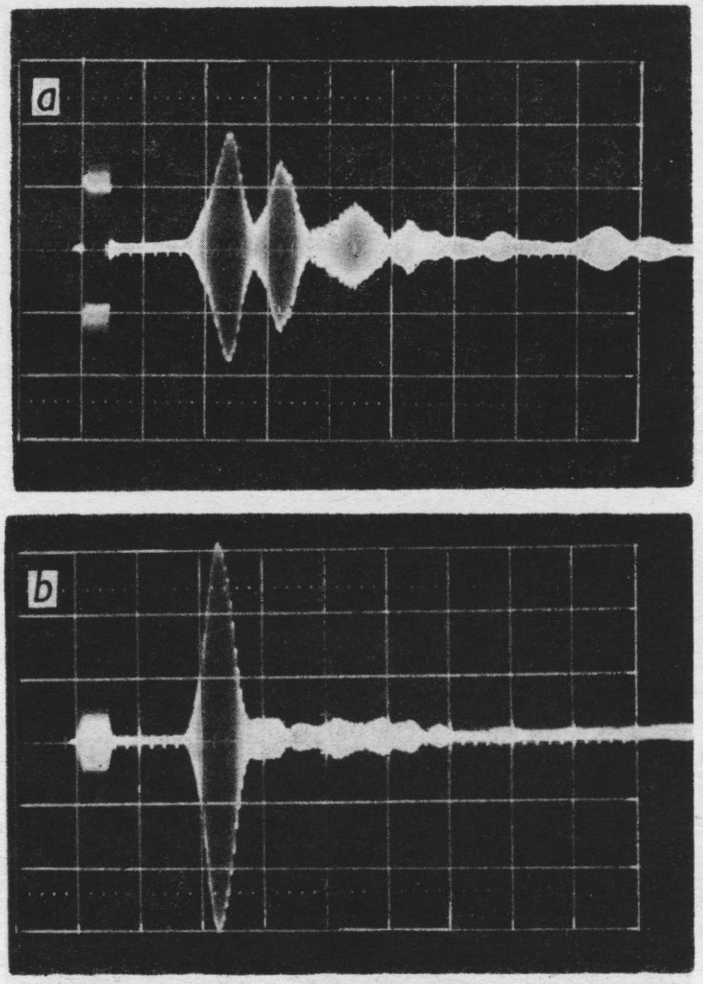

Fig. 3. Pulses received at the output of the line made of the ceramic plate ($f = 2.5$ MHz, 5 μs/div)

a) free surface $v_s = 2380$ m/s, b) metallized surface $v_{sm} = 2320$ m/s

The investigations of wave propagation on the non-metallized surface supported the suggestion that the first pulse in Fig. 3a is the one arising from the transversal surface wave. The thin metal coating on the surface causes a considerable increase in this pulse and reduces the wave velocity (Fig. 3b).

In order to identify more exactly the surface and transversal bulk waves, experiments were performed on large perpendicular parallelepiped of piezoelectric ceramic of foreign manufacture (Philips). Plate transducers, placed on side walls of the perpendicular parallelepiped (Fig. 4), were used for the generation of transversal surface wave.

Surface and bulk waves in the case of both metallized and free surfaces were investigated. For this purpose the transmitting transducer within the

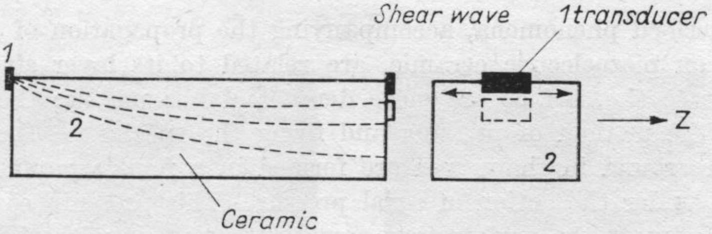

Fig. 4. Position of plate transducers for excitation of transversal surface wave
1 – transducer, *2* – ceramic to be examined

surface wave zone was immobilized, while the receiving transducer was moved away from the surface by 0.3, 1 and 2 mm. With such experiments evident differences were found in the image of the pulse at metallized and free surfaces.

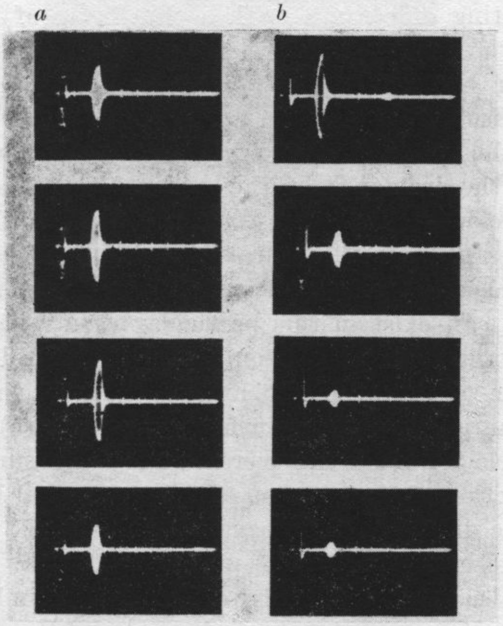

Fig. 5. Acoustic pulses excited by the plate transducers ($f = 5$ MHz, 5 μs/div)
a) free surface, receiving transducer placed at distances 0, 0.3 mm, 1 mm and 2 mm from the ceramic surface $v = 2440$ m/s, *b*) metallized surface, receiving transducer placed at distances 0, 0.3, 1 and 2 mm from the ceramic surface $v = 2380$ m/s

Figure 5a shows the image of the pulse at a free surface and Fig. 5b – at a metallized surface. In Fig. 5b it can be clearly seen that the decay of the received pulse as the transducer is shifted, while in Fig. 5a the pulse first increase and is observed to be followed by a decrease. The peak corresponds to an angle of about 20°.

The described phenomena, accompanying the propagation of surface and bulk waves on piezoelectric ceramic, are related to its layer structure. The layers nearer to the surface are more dense and less porous; their structure depends on the method of pressing and firing the specimens. Generally, the specimens are round in shape and are formed in a female mould of circular cross-section under the action of axial pressure. This pressure causes uneven compaction between the surface that comes into contact with the punch and the interior of the plate, caused by the inner friction of the ceramic composition. During firing the plate surface may have a higher temperature than the interior. This brings about a greater loss of lead from the surface layer and thus more intensive sintering. This process leads to an increased acoustic wave velocity in layers near to the surface and decreased velocity nearer the centre of the plate, the change being continuous. This property of the ceramic makes the generation and propagation of transversal surface waves difficult or even impossible. The coating of ceramic with a thin layer of metal and the subsequent decrease in the rigidity of the surface layer compensates only the higher rigidity of the layer because of inhomogeneous structure of ceramic. Consequently, the result is such as shown in Fig. 2.

In the case of the specimen shown in Fig. 3, the reverse phenomenon can be observed. Here the influence of the surface layers has been eliminated. Furthermore, the velocity of the transversal waves in the surface layer is smaller and increases towards the centre of the plate. Such conditions favour the generation of acoustic transversal surface wave with acousto-electric properties. Such waves can exist in this particular case without the plate being metallized. The metallization process only increases the difference in velocity between the interior of the specimen and its surface, thus considerably increasing the pulse amplitude of the surface wave (Fig. 5).

The changing velocity of the transversal wave at the surface of the specimen also affects the direction of propagation of the transversal bulk wave, by causing deflection of the direction of propagation of the bulk wave. This explains the behaviour of the transversal wave pulses in Fig. 5a.

Redwood has also foreseen a similar deflection, but in his paper the change in the velocity of the transversal wave in layers near the surface has occurred for the metallized surface and was caused by a change in ridigity modulus [4], resulting from the decay of the electric field.

The described phenomena and their explanation provide some possibility for the rational utilization of the structure of a piezoelectric material to improve the efficiency of the generation of transversal surface waves. With the present state of technology it is possible to utilize layers whose properties have already been determined.

Transversal waves with polarization vertical to the ceramic surface (thus to the axis *z*) were also generated by using plate transducers according to the arrangement shown in Fig. 6. It can be seen from the photographs that

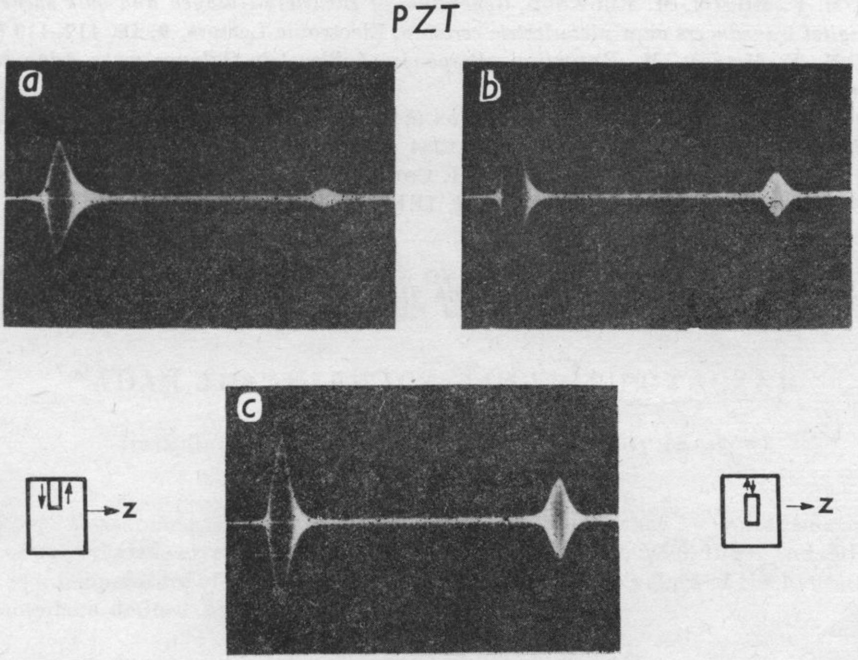

Fig. 6. Acoustic pulses on the piezoelectric ceramic when the transducer has a polarization vertical to the surface ($f = 2.358$ MHz, 2 μs/div)

a) transducers at a free surface $v_{T_2} = 2170$ m/s, b) at a metallized surface $v_T = 2170$ m/s, c) transducers situated at the distance from the surface $v_T = 2170$ m/s

in this case no surface wave effects have been achieved. The velocity of waves beneath the surface and at the centre of the specimen was the same: 2170 m/s. The lack of the occurrence of surface waves (e.g. Rayleigh waves) was probably due to the irregular surface.

Similar experiments to those on ceramic were performed with crystals of lithium iodate on the x and y surfaces. As a result of the measurements made with plate, mean values of the coefficient k_s for ceramic and lithium iodate were determined:

piezoelectric ceramic (PZT): $k_s = 0.24$, $k = k_{15} = 0.56$;
lithium iodate LIO_3: $k_s = 0.3$, $k = k_{15} = 0.65$.

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