Excitation and detection of elastic vibrations in piezoelectric crystals by a vortex electric field of an induction coil

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The conditions under which elastic waves can be excited and measured at the surface of a piezoelectric crystal and inside it by a vortex electric field are considered. Experiments on the excitation and detection of vibrations in piezoelectric crystals by induction coils are described for the first time and possible applications of this method are suggested.

Excitation of elastic vibrations in piezoelectric crystals is usually achieved by placing them in a quasistationary electric field of a capacitor and at hypersonic frequencies it can be accomplished by placing them in the capacitive gap of a coaxial resonator.[1,2] Piezoelectric crystals situated in an electric field generate internal piezoelectric forces with a surface density and bulk density[3]:

$$f_i^s = -e_{mij} E_m n_j ; \qquad f_i^v = -e_{mij} \partial E_m / \partial x_j , \tag{1}$$

where e_{mij}, E_m, and n_i are the components of the piezoelectric tensor, of the electric field vector, and of the unit vector of the interior normal to the surface. To excite

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elastic vibrations and waves with a polarization $\bar{\mathbf{p}}$, the field of the external sources must have such a configuration and direction that the projections of the piezoelectric forces on the direction of polarization would be nonvanishing:

$$f_i^s p_i = e_{mij} p_i n_j E_m = b_m E_m \neq 0; \qquad f_i^v p_i \neq 0. \tag{2}$$

Only surface forces are active in a uniform field. Maximum surface excitation of a piezoelectrically active wave, with a piezoelectric vector $\mathbf{b} \neq 0$, which propagates into the crystal normal to the surface, can be achieved by directing the crystal field at this surface-parallel to its piezoelectric vector.[4] The propagation of a piezoelectrically active acoustic wave is accompanied by an electric field wave which is associated with it.[5] The properties of this wave, which depend on the orientation of its piezoelectric vector relative to the wave normal, determine the conditions under which the acoustic wave is detected. The waves whose piezoelectric vector is directed along the wave normal or forms an acute angle with it, are accompanied by a potential electric field wave whose amplitude is proportional to the projection of the piezoelectric vector onto the wave normal $(b_m n_m \neq 0)$. To excite these waves and the natural vibrations of the piezoelectric plates which are associated with them, the field must be directed normal or at an acute angle to the crystal surface. These waves are excited and detected in a capacitor and are used in ultrasonics. The waves whose piezoelectric vector is perpendicular to the wave normal $(b_m n_m = 0)$ are accompanied by a vortex electric field wave. These waves can be excited superficially by directing the field tangentially to the surface. Since these waves are slightly excited in the capacitor only due to the edge effects, they are of no practical use. The elastic waves which are not active piezoelectrically $(b_m = 0)$ cannot be excited at the surface, but they can be excited by bulk forces, according to Eq. (1), in a nonuniform field.

A nonuniform vortex electric field produced by a time-variable magnetic flux such as an induction coil can be used in several piezoelectric crystals to excite elastic waves which are not active piezoelectrically and piezoelectrically active waves which are not excited in the capacitor. In the case of piezoelectric crystals of class 32 (α quarz), class 422 (paratellurite) and class 622 (β quarz), for example, a degenerate transverse wave can be excited at the Z-cut surface, which is perpendicular to the X_3 acoustic axis, by a field directed tangentially to the surface. The longitudinal waves, however, are piezoelectrically active and are therefore not excited at the surface. If, on the other hand, a cylindrical rod of a Z-cut quarz is placed coaxially in the induction coil in such a way that its magnetic induction would be parallel to the X_3 axis of the quarz rod, then the circular-shaped field lines of the vortex electric field would be directed tangentially to the end faces of the cylinder and to its lateral surface. In the uniform-induction approximation $B_3 = B_0 \sin \omega t$, the vortex field would have the following components:

$$E_1 = a x_2, E_2 = -a x_1, E_3 = 0, \tag{3}$$

where $a = (\omega B_0/2) \cos \omega t$, $x_1 = r \cos \varphi$, $x_2 = r \sin \varphi$, r is the distance from the cylinder axis, and φ is an angle reckoned from the X_1 axis of the quarz. In this field the piezoelectric forces are active at the end faces. These radially directed forces increase with increasing distance from the midpoint of the end faces:

$$f_1^s = e_{14} a r \cos\varphi, \quad f_2^s = e_{14} a r \sin\varphi, \quad f_3^s = 0. \tag{4}$$

These forces should produce nonuniform transverse vibrations. The lateral surface of the quarz cylinder of radius r_0 is affected by the piezoelectric forces

$$f_1^s = e_{11} a r_0 \sin 2\varphi, \quad f_2^s = e_{11} a r_0 \cos 2\varphi, \quad f_3^s = e_{14} a r_0, \tag{5}$$

which account for the complex deformation of the cross section of the quarz cylinder.

In addition, the vortex field is nonuniform [Eq. (3)]. According to (1), this field should activate the bulk piezoelectric forces inside the quarz cylinder:

$$f_1^v = f_2^v = 0, \; f_3^v = e_{14} \,\mathrm{curl}_3 \,\overline{\mathrm{E}} = - e_{14} \dot{B}_3 = - e_{14} \,\omega B_0 \cos\omega t\,. \tag{6}$$

In a short induction coil, these nonuniform forces should produce in the bulk cylinder a bulk excitation of the longitudinal waves and of the accompanying natural vibrations. We should point out that all piezoelectric forces which are produced by the vortex field increase with increasing frequency.

We used a composite resonator (Fig. 1) to determine whether the induction coils could excite the ultrasonic waves and detect them in the Z-cut of the quarz. The Z-cut quarz cylinders (2) 10 mm long and 10 mm in diameter are coaxially attached with phenyl salicylate to the end faces of the glass cylinder (1) 62 mm long and 40 mm in diameter. Each of these Z-cut quarz cylinders is fitted with a 100-turn coil of 0.1-mm-thick wire. The exciting coil (3) is connected to a cw oscillator and the measuring coil (4) is connected to an oscilloscope. When the oscillator frequency varied smoothly, resonance peaks were seen on the oscilloscope screen at frequencies 383, 386, 389, and 394 kHz which corresponded to the natural vibrations of the composite resonator. When the oscillator was held at 40 V, the resonance peaks were on the order of several millivolts and were an order of magnitude higher than the signal from the direct inductive coupling between the coils, which was attenuated by the screen (5) and which did not depend on the frequency: By using thin (0.3 mm) Z-cut quarz plates we were able to excite the resonator at a frequency of 14.435 MHz. The electromagnetic field of the exciting coil has, in addition to the vortex electric field, a potential field between the coil and the screen and between each turn on the coil. We ran several control experiments to determine the relative contribution of these fields to the excitation of the waves. No resonances were observed when the coils were replaced by electrodes. An increase in the number of turns on the measuring coil increased the peak vibration amplitude, consistent with its behavior upon application of a vortex field associated with the piezoelectrically active elastic vibrations of the quarz cylinder

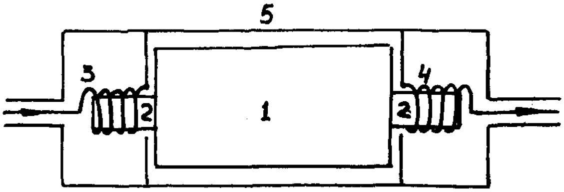

FIG. 1.

inside this coil. We have also observed no vibrations when quarz was replaced by glass cylinders, ruling out in this case the importance of the ponderomotive forces in a nonuniform vortex field. We can therefore assume that the natural oscillations of the composite resonator, which were observed in the principal experiment, were excited by the vortex electric field of the induction coil and then measured by it.

A symmetric bridge consisting of two coils and two resistors also was used to excite and record the ultrasonic waves by a vortex field. Upon the insertion into one of the coils of a piezoelectric crystal set to its natural vibration frequencies we measured the signal for the loss of bridge balance. This method was used to set up vibrations in other cuts of the quarz—in bismuth germanate and lithium niobate—and to excite torsional vibrations of a lithium iodate rod. The spectra of the vibration frequencies of the test crystals in this case were markedly different from the vibration spectra of these samples when they were inserted into the capacitor which was connected to a symmetric capacitance bridge.

The use of a vortex electric field to set up ultrasonic vibrations in piezoelectric crystals extends the range of the vibrational modes which can be used in ultrasonics. This excitation method, which will become more efficient at higher frequencies, can be applied in acoustooptic modulators and filters which utilize a collinear diffraction of light by ultrasound.

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