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SURFACE WAVE MODE CONVERSION BY ELECTROMAGNETIC GENERATION OF ULTRASOUND*

STANISLAV KOLNÍK,** JOZEF KLIMKO,** Žilina

Mode purity and mode conversion of surface acoustic waves are determined by the boundary conditions on the surface of a solid. It is shown in this article that the electromagnetic contactless generation in metals enables a pure Rayleigh mode excitation. An approximative approach using the Huygens—Fresnel principle is applied to judge the influence of some typical perturbations of free boundary conditions on the nature of propagating waves.

КОНВЕРСИЯ АКУСТИЧЕСКОЙ МОДЫ ПОВЕРХНОСТНЫХ ВОЛН С ПОМОЩЬЮ ЭЛЕКТРОМАГНИТНОГО ГЕНЕРИРОВАНИЯ УЛЬТРАЗВУКА

Монохроматичность и конверсия акустической моды поверхностных волн определяется граничными условиями на поверхности твердого тела. В статье показано, что бесконтактное электромагнитное генерирование в металлах позволяет возбуждать чистую моду Рэлея. Для оценки влияния некоторых типичных нарушений свободных граничных условий на природу распространяющихся волн применено приближение, использующее принцип Гюгенса–Френеля.

I. INTRODUCTION

Acoustic mode purity has a fundamental importance in the work of modern acoustoelectric and acoustooptic elements. An acoustic element is requested to influence the acoustic signal in a needed manner only; an acoustic device must be planned and constructed as a one-mode device to obtain adequate efficiency. The conversion from the primary mode means to insert disturbing influences. Acousto-optic elements are realised by using system of bounded layers with different mechanical and optical properties — for example — the connection of a thin film guiding optical waves to a surface travelling surface acoustic waves (SAW).

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** Technical University of Transport Engineering, Department of Physics, CS — 010 88 ŽILINA.

A perturbation of standard acoustic boundary conditions (for excitation and propagation of a pure SAW) is presented by any connection of two media. An unavoidable consequence of perturbed boundary conditions is mode conversion. In the present article special attention is paid to noncontact electromagnetic SAW generation via a meander coil. However, there is to be taken into account the somewhat lower efficiency of electromagnetic SAW generation when compared with other techniques based on piezoelectric principles; this disadvantage is in many cases compensated by the advantage of contactless ultrasonic operation in a metal as a medium with significant elastic isotropy.

In the SAW electromagnetic generation itself one can satisfy the stress free boundary conditions but in practical applications we cannot exclude some cases of boundary conditions perturbation. The correct analytical solution of such boundary problems is in principle: the solution on a free surface must be transformed at the point of perturbation in the solution in the range with the perturbed surface. It may be gained in general by the assumption that there exists in addition to the incident pure SAW a reflected SAW travelling in the opposite direction, a perturbed transmitted SAW and a set of bulk acoustic waves. With respect to the complicated analytical nature of the Rayleigh waves one gains in this way a system of transcendental equations and only an approximating approach allows to determine the amplitude of the separate modes and the propagation directions of these modes. An applicable approximation is simple in the case of an isotropic metal medium; the Huygens—Fresnel principle [1] will be used in our considerations.

II. ELECTROMAGNETIC SAW GENERATION

The electromagnetic acoustic wave generation and therefore the SAW generation in metals may be considered as the response of the solid body forces equal to the Lorentz forces produced by a system of eddy currents induced in a surface metal layer by an alterning current in a meander coil. This coil is usually placed at the distance d to the metal surface in the presence of a static magnetic field $\boldsymbol{B}$.

The arrows show the actual Lorentz force direction and Λ_R is the acoustic wavelength (Fig. 1a).

A correct solution of the electromagnetic generation of acoustic waves requires Ampere's law to be applied in the form

$$\boldsymbol{f} = q\boldsymbol{w} \times \boldsymbol{B},$$

where q is the electric charge, $\boldsymbol{w}$ its relative velocity in the system with the static magnetic field $\boldsymbol{B}$; further it is necessary to respect all mechanisms of the electron momentum transport to the metal ions, the properties of the electron ensamble and the phase conditions for the ion vibrations. This approach is very cumbersome and

it is useful to take a series of approximations [2] accompanying the conception of the Lorentz forces due to eddy currents. An approximating determination of the resulting nature of the acoustic field in an arbitrary experimental arrangement is possible and we can find the solution of all cases corresponding to SAW and to bulk waves generation.

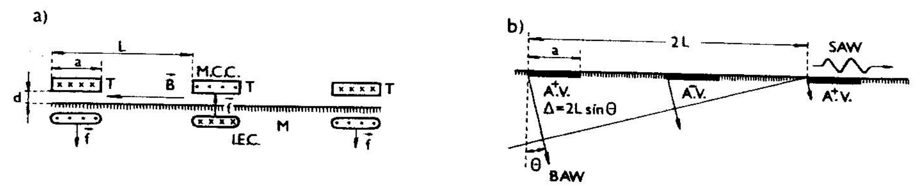

Fig. 1. Contactless electromagnetic generation of SAW on a metal surface. a) Cross-section of three turns of a meander coil: a — the width of a conducting meander ribbon, L — the separation of two parallel ribbons, d — the distance between the metal surface and the meander coil, $M.C.C.$ — meander coil current, $I.E.C.$ — induced eddy current. By crosses xxx and points... there is shown the opposite direction of an instantaneous current; $\boldsymbol{f}$ is the Lorentz force acting on the induced eddy current in the metal M in the presence of a static magnetic field $\boldsymbol{B}$. b) Approximation of the situation in figure: a) The effective width of the region with non zero acoustic vibrations $A.V.$ is shown as a; Θ is the angle of an selected propagating mode, Δ is the path difference for two acoustic waves spreading from sources of spatial separation $2L$; BAW — bulk acoustic wave

The signs ± in Fig. 1b correspond to the opposite phase of acoustic vibrations; a means the effective width of the region with non zero acoustic vibrations and $L - a$ is the width of the region where no primary acoustic vibration exist. Assuming an identical amplitude of acoustic vibrations in the whole region of the width a one determines the acoustic field in a similar way as the optical field of a diffracting grating. Therefore one can await the interference maxima in the directions with

$$\sin \Theta = n\Lambda / 2L, \quad (1)$$

where n is the interference order.

In the case $\Theta = \pi/2$ condition (1) gives for the SAW generation the phase condition

$$2L = n\Lambda_R \quad \text{and} \quad n = 1, 3, 5, \ldots$$

If $\Theta < \pi/2$, there exist bulk modes propagating in directions satisfying condition (1).

The determination of acoustic fields with the help of a harmonic signal (electric current in meander coil turns) is simple. Some difficulties occur in the case of complicated signals (amplitude, phase an frequency structure) and there is the question of the acoustic mode conversion. A more complicated situation arises in the case of a solid layer of the thickness $h \sim \Lambda_R$. One can generate via a meander coil in such a metal layer- plate- dispersive acoustic modes having the nature of Lamb waves and especially asymmetric modes [3].

III. SAW BOUNDARY CONDITIONS AND THE CONSEQUENCES OF THEIR PERTURBATION

Let us consider a boundary in the xy plane between two media of different acoustic properties (Fig. 2). The boundary conditions at the interface of two solids request a particle velocity $\boldsymbol{v}$ and traction forces to be continuous at all points of the interface [4], also

$$\boldsymbol{v}|_{z=0} = \boldsymbol{v}'|_{z=0}$$
$$\mathbf{T}\cdot\boldsymbol{n}|_{z=0} = \mathbf{T}'\cdot\boldsymbol{n}|_{z=0} \qquad (2)$$

where $\boldsymbol{v}$ is the particle velocity vector, $\mathbf{T}$ is the stress tensor and $\boldsymbol{n}$ is the unity vector in the considered direction. At the interface $z=0$ six scalar equations express boundary conditions. At a free boundary three stress tensor components can be used only.

Free boundary conditions on the surface of the solid can be perturbed in principle by two different ways: 1) by a shear change of the topographic nature of the surface (a strip or strip array, a slot or slot array — Figs 2c and 2d).
2) by a partial coating of the surface by a layer of another material acoustically bound to the substrate solid (thin or thick film, electrodes, etc.).

The analytical solution of boundary problems in the case of a "perturbed" surface must depend on the parameters a, h (Figs 2c, d) and on the acoustic properties of the solid. The correct solution can be found with respect to the modified conditions (2) in the point of perturbation x_p. Usually one takes the displacement on the free surface in the form of the Rayleigh waves in the known form [6] $\boldsymbol{u} = (u_x, 0, u_z)$

$$u_x = AF\,[\exp(-qz) - 2q\eta(\eta^2+F^2)^{-1}\exp(-\eta z)]\sin(\omega t - Fx)$$
$$u_z = Aq\,[\exp(-qz) - 2F^2(\eta^2+F^2)^{-1}\exp(-\eta z)]\cos(\omega t - Fx),$$

where $F=\omega/V_R$; $q=(F^2-H^2)^{1/2}$; $\eta=(F^2-\varkappa^2)^{1/2}$; $H=\omega/V_l$; $\varkappa=\omega/V_t$. V_R is the Rayleigh wave velocity, V_l is the longitudinal wave velocity, V_t is the transversal wave velocity.

We can approximatively suppose that at the place of perturbation the following waves arise: a reflected SAW, a perturbed "refracted" SAW and a system of longitudinal and transversal reflected and refracted bulk waves. The amplitudes of these waves depend on the perturbation parameters and on the acoustic properties of the solid.

In the case $a \ll \Lambda_R$ or $h \ll \Lambda_R$ the influence of perturbation can be neglected. A simple case occurs by a slot if $a \gg \Lambda_R$, $h \gg \Lambda_R$; it follows from Eqs. (2) that the only reflected SAW arises.

In the case of a strip with $a \gg \Lambda_R$, $h \gg \Lambda_R$ reflected SAW and refracted bulk modes occur. We can survey this situation using the results of light diffraction on an

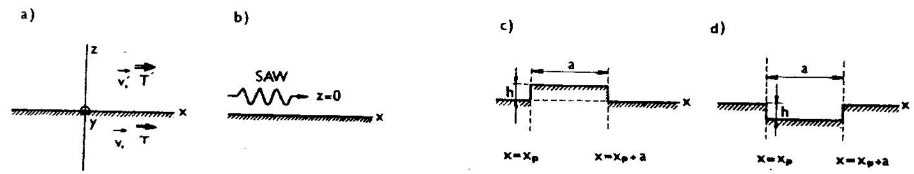

Fig. 2. Interface of two media and some typical cases on the stress free surface of a solid. a) Interface of two different solids with a rectangular coordinate system x, y, z; $\boldsymbol{v}$, $\boldsymbol{v}'$, $\mathbf{T}$, $\mathbf{T}'$ particle velocity vectors and stress tensors in two neighbouring media, respectively. b) A stress free surface of a solid medium occupying the half space with $z \leq 0$. c) A "single strip" type of free surface perturbation. d) A "single slot" type of free surface perturbation

edge [1]. However, in our case there exists a significant dissimilarity with the optical case: the amplitude of SAW is an exponential function of the coordinate z and therefore the distribution of the total acoustical intensity behind the edge must be of a different nature when compared with the optical one and this intensity is believed to be qualitatively given by the curve b shown in Fig. 3. The curve a shows the optical intensity distribution on an edge; the curve b shows the believed acoustic intensity distribution due a diffraction of a SAW. The resulting acoustic field for $x > x_p$ is a superposition of an infinite number of bulk waves.

The correct solution of this case is unknown and practically unattainable.

The case of $h \sim \Lambda_R$ leads to a perturbed SAW with a changed velocity [5]. The surface coating by another material in the form of a strip (or strip system) creates a situation similar in principle to that with a geometrical surface perturbation; the consequences following from various acoustic properties of both media are to be expected.

A periodic strip (or slot) array showing the separation of its elements $D-a$ (Fig. 4) arouses waves as a result of a multiple beam interference of elementary acoustic waves spreading by separate strips (slots). The angle of amplitude maximum in this wave system depends on the "lattice" parameter a and on the "lattice" constant D.

The amplitude maximum satisfies the condition

$$D\sin\Theta_m = n'\Lambda_R, \qquad (3)$$

where $n' = \pm 1, \pm 2, \ldots$. The periodic strip (slot) system produces the conversion of incident SAW into bulk waves by $\Theta_m < \pi/2$ and therefore according to Eq. (3)

$$nD > 2n'L$$

and in a simple case $D > 2L$. It seems to be clear that the inverse procedure is possible and bulk into surface waves conversion occurs by the diffraction of incident transversal bulk waves on the surface provided with a periodic strip (slot) system with $D = \Lambda_R$.

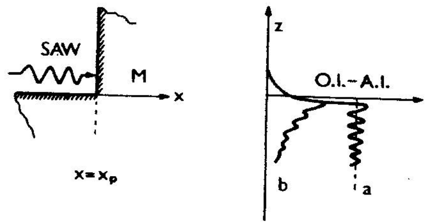

Fig. 3. Illustration of the SAW diffraction on an edge. a — the optical intensity *O.I.* distribution, b — acoustical intensity *A.I.* distribution with respect to the exponential decrease of the SAW amplitude

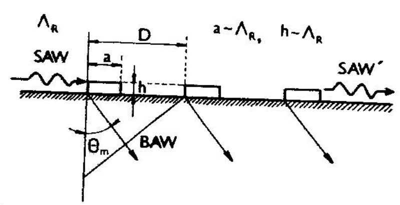

Fig. 4. Part of a periodic stripp array realised by a system of parallel ribbons on a solid surface. *D* — the separation of ribbons, *a* and *h* — ribbon width and heigh, respectively; *SAW* — incident surface acoustic wave, *SAW'* — transmitted surface acoustic wave, *BAW* — bulk acoustic wave

The nature of waves excited in this way depends on the polarization of an incident wave and can be determined by a detailed analysis similar to that of the surface wave into bulk wave conversion.

IV. SOME EXPERIMENTAL RESULTS AND DISCUSSION

By the electromagnetic SAW generation one can take stress free boundary conditions and the electromagnetic ultrasound generation can be realised as a contactless one. It means that the surface acoustic wave velocity equals the Rayleigh velocity determined in the case of an isotropic medium surface by the formula [4]

$$V_R = V_t \frac{0.87 + 1.12\sigma}{1 + \sigma}, \qquad (4)$$

where

$$\sigma = \frac{1 - 2(V_t/V_l)^2}{2[1 - (V_t/V_l)^2]}$$

is the Poisson ratio ranging from 0 to 0.5 for actual materials.

In our experiments we use mechanically isotropic aluminium alloy samples (96 % Al + 4 % Cu) of rectangular form ($\approx 50 \times 25 \times 10$ in mm). A modified conventional electronic system for impulse echo velocity measurements was supplied at a 10.8 MHz frequency by a meander coil placed on the sample surface in a static magnetic field B. The magnetic field was adjustable in the range from zero to 1.1 Tesla in a 3 cm gap between poles of an electromagnet. The meander coil with 20 turns and of the geometry for 3.6 MHz was used at the third harmonic frequency.

Direct measurements of V_R by means of a SAW generation via the meander coil gave at room temperature $V_{RM} = (3.06 \pm 0.04) \times 10^3$ ms^{-1}. The value computed from the formula (4) is $V_{RC} = 2.992 \times 10^3$ ms^{-1}; the used bulk wave velocities V_l, V_t were measured with 11 MHz quartz transducers and were $V_l = 6.283 \times 10^3$ ms^{-1} $V_t = 2.214 \times 10^3$ ms^{-1}. The comparison of the measured and the calculated SAW velocities shows a reasonable agreement for the case of mechanically stress free boundary conditions. However, a detailed analysis with respect to formula (4) as regards the dependence of V_R/V_t on V_t/V_l shows same difficulties. The ratio $(V_{RM}/V_t) = 0.9520$ corresponds to $(V_t/V_l)_M = 0.280$, while $(V_{RC}/V_t) = 0.9300$ corresponds to $(V_t/V_l) = 0.54$; this latter value is more adequate. The value V_R/V_t is very sensible to the Rayleigh wave velocity. This fact induced us to study different influences on the Rayleigh wave velocity, especially the influence of the perturbed boundary conditions. As the measured velocity value deviation does not lie in the range of experimental errors we suppose that it is caused by the local elastic nature of the sample surface in the presence of a high static magnetic field. According to Viktorov [7] a static magnetic field on the conducting surface influences the nature of surface waves. A further study is now necessary to find an adequate solution of this problem; we suggest that the presence of a magnetic field may be equivalent to a special perturbation of boundary conditions.

We made further an extensive experimental study of aluminium alloy plates (96 % Al + 4 % Cu) of the thickness 0.2 cm at 10.8 MHz frequency. It has been shown that the measured velocity value of the present waves — generated via the meander coil — is the same as the velocity of the shear waves. This correspond to the basic properties of the dispersive Lamb waves (plate waves), namely to the asymmetric mode a_0. In the case of another aluminium alloy plate (93 % Al + 7 % Mg) of the thickness 0.06 cm we found the velocity value $V = 2.327 \times 10^3$ ms^{-1} corresponding similarly to Lamb wave.

V. CONCLUSIONS

In the case of acoustically contactless electromagnetic SAW generation there exists no conversion of surface into bulk waves. Mode conversion arises as a consequence of a stress free boundary condition perturbation. By the realization of a meander coil in a photolithographic way on a thin dielectric film evaporated on a conducting substrate perturbed surface waves occur; their velocity is different from the Rayleigh wave velocity. Here exist (in addition as a consequence of a finite frequency range) conditions for a surface into bulk wave conversion at separate turns of the meander coil. Similarly the connection of an acoustic on optical waveguide system leads to a mode conversion.

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