Scattering of Rayleigh waves by a groove of arbitrary depth

S. Zh. Zharylkapov and V. V. Krylov

Physics Faculty, M. V. Lomonosov State University, Moscow

(Submitted January 29, 1987)

Akust. Zh. **33**, 878–883 (September–October 1987)

The scattering of Rayleigh waves by a two-dimensional groove formed on the surface of an aluminum sample is investigated experimentally. A complete set of measurements of the scattered-field parameters, including the elastic characteristics of the scattered longitudinal and shear bulk waves and the reflection and transmission coefficients of the Rayleigh surface waves, is carried out for a broad range of groove depths.

The investigation of the specific characteristics of the scattering of surface acoustic waves (SAW's) by surface inhomogeneities in the form of grooves or cracks is extremely important for acoustoelectronics and ultrasonic flaw detection (see, e.g., the surveys in Refs. 1-5). Scattering by shallow grooves satisfying the conditions $h/\lambda \ll 1$ and $h/a \gg 1$, where h is the groove depth, a is its width, and λ is the surface wavelength, has been studied in the greatest detail to date. A large part of the theoretical results has been obtained by various modifications of perturbation theory in this case.[4-8] Experimental studies of SAW scattering by shallow grooves have also been reported for scattering into surface waves[1-3,9] and into the volume of the medium.[8,10]

Scattering by flaws with other relations between the characteristic dimensions has been investigated to a lesser degree. In particular, the case of cracks or slots ($a/\lambda \ll 1$) characterized by ratios $h/\lambda \ll 1$ has been analyzed, where the main results have been obtained by perturbation methods based on integral reciprocity relations.[11] A number of situations in the fundamental problem of SAW reflection and transmission at cracks have been analyzed in the case $h/\lambda \gtrsim 1$ as a result of the solution of boundary integral equations[12] or by direct numerical procedures.[13] Surface-wave scattering by grooves and cracks has also received scarce attention at the experimental level. Only investigations of the reflection and transmission of Rayleigh waves at cracks of arbitrary depths have been reported (Refs. 2, 13, and 14), and, to the best of our knowledge, only once have the angular characteristics of SAW scattering into the volume of a medium been measured for a deep crack at a fixed value of $h/\lambda = 12.3$ (Ref. 15). Systematic measurements of SAW scattering by grooves or cracks of arbitrary depth have evidently never been performed.

The objective of the present study is to give the results of experiments on the characteristics of Rayleigh wave scattering both into surface waves and into bulk waves at a vertical two-dimensional groove over a wide range of values of the parameter h/λ.

The experimental arrangement is shown schematically in Fig. 1. Rayleigh waves were generated on the surface of an aluminum half-disk of radius 10 cm and thickness 3 cm by means of a Plexiglas wedge (angle-beam transducer), which was bonded to the surface by an epoxy resin layer. A vertical scattering groove with a constant width a = 1 mm and a semicircular bottom was machine-cut into the flat end of the half-disk.

The scattered SAW's were received by means of an identical Plexiglas wedge, which was mounted either to the right or to the left of the groove (depending on whether the Rayleigh-wave transmission or reflection coefficient was to be measured). Longitudinal-mode piezoelectric ceramic wafers of diameter 1.5 cm with a resonance frequency of 2.04 MHz were mounted on both wedges. The losses in reciprocal transduction in this case were ~50 dB.

The scattered bulk-wave field was recorded by means of a specially designed transducer in the form of a Plexiglas slab with a rounded base to ensure reliable contact with the cylindrical surface of the sample. Piezoelectric ceramic wafers were mounted alternately on the slab by means of salol, viz.: a longitudinal-mode wafer of diameter 1.5 cm with a resonance frequency of 2.04 MHz for the reception of scattered longitudinal waves, and a transverse-mode wafer of diameter 1.5 cm and thickness 1.0 cm with a resonance frequency of 5 MHz for the reception of scattered shear waves. As in the case of the angle-beam transducers, mechanical contact was established between the bulk-wave transducer and the surface of the sample through epoxy resin, which ensured the possibility of its free movement along the perimeter.

The scattered bulk waves were measured after the input of rf voltage pulses with a center frequency of 2.04 MHz and a duration of 5 μs to the radiating angle-beam transducer (the shear-wave transducer operated in the nonresonant regime in this case). The angular scattering functions $D_\ell(\theta)$ and $D_t(\theta)$ of longitudinal and shear bulk waves were measured for a fixed groove depth h. The measurements of $D_\ell(\theta)$ and $D_t(\theta)$ were then repeated for different values of the groove depth, which was

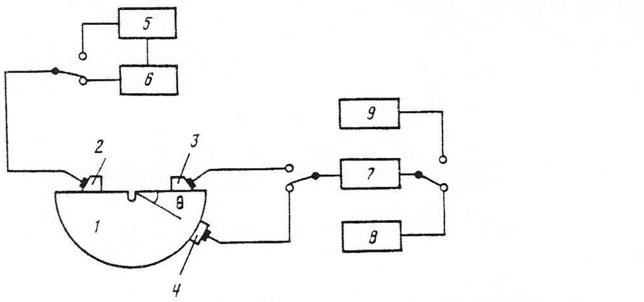

FIG. 1. Experimental arrangement. 1) Aluminum sample; 2) radiating angle-beam (wedge) transducer; 3) receiving angle-beam transducer; 4) scattered-bulk-wave transducer; 5) video pulse generator; 6) modulated harmonic signal generator; 7) wideband amplifier; 8) oscilloscope; 9) spectrum analyzer.

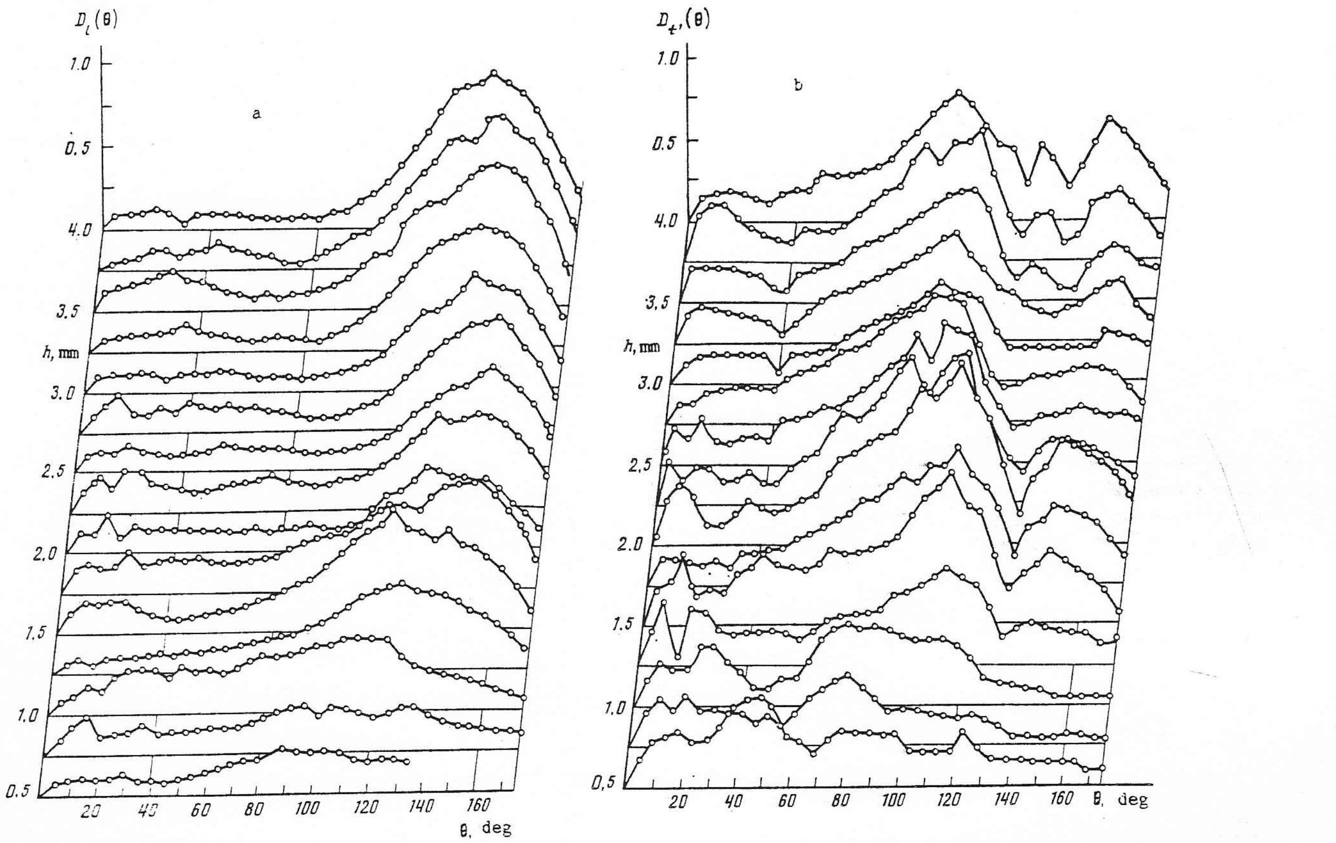

FIG. 2. Angular scattering patterns of longitudinal (a) and shear (b) bulk waves for various depths h of grooves having a constant width a =1 mm; frequency 2.04 MHz.

varied from 0.5 to 4 mm in 0.25 mm steps in the experiments. The measurements were repeated several times (the scatter of the experimental data was ∿10%) for each value of the depth h and the angle of observation θ, and the results were averaged statistically. The radiated SAW amplitude was held constant during this process. The measurement results for the largest maxima of each series of $D_\ell(\theta)$ and $D_t(\theta)$ curves are shown in Fig. 2. The level D_ℓ = 1 corresponds to ∿63 dB insertion losses in conversion of the electrical input signal into SAW's and in scattering and conversion of the scattered longitudinal wave into an electrical signal, and the level D_t = 1 corresponds to analogous ∿67 dB losses for the scattered shear waves. The relatively low level of the scattered shear-wave signal is attributable to the nonresonant operation of the given transducer.

The field of scattered surface waves (reflected and transmitted) was measured by a conventional procedure (see, e.g., Refs. 2 and 9) for each of the above-indicated depths h. Measurements were also performed for h = 4 mm by an ultrasonic spectroscopic procedure.[14] The latter entailed the input of a short voltage video pulse to the radiating angle-beam transducer with the resulting generation of SAW's over a wide range of frequencies. The propagating SAW was then recorded by the receiving angle-beam transducer, whose electrical output signal was sent to a spectrum analyzer. The frequency response of the scattering groove in this case could be determined by dividing the spectrum of the electrical signal from the scattered wave by the signal spectrum corresponding to Rayleigh-wave transmission from the radiating to the receiving transducer in the absence of the scattering flaw.

The duration of the input video pulse was chosen so that the direct (unscattered) signal spectrum corresponding to the product of the spectrum of the original rectangular video pulse and the transfer function of the two transducers would be sufficiently smooth over as wide a frequency range as possible. The optimum duration of the video pulse for our transducers with resonance frequencies of 2.04 MHz was found to be equal to 0.5 μs. The spectrum of the direct (reference) signal was localized in the interval 0.4-2.2 MHz.

The moduli of the surface-wave reflection coefficient R and the transmission coefficient T are plotted as a function of the parameter h/λ in Fig. 3 (curves 1) according to results obtained by the rf pulse method. Also shown for comparison are the values of R(h/λ) and T(h/λ) obtained by the ultrasonic spectroscopic technique for h = 4 mm (curves 2). The quantitative discrepancy between the curves obtained by the two procedures in the given situation characterizes the influence of the finite groove width (a = 1 mm), which was comparable with the Rayleigh wavelength at 2.04 MHz (λ = 1.4 mm) in the rf pulse measurements. In the spectroscopic measurements, on the other hand, the groove width a was commensurate with λ only at the upper end of the SAW spectrum and was considerably smaller than λ at the lowest frequencies of the spectrum. This situation is typical of SAW scattering by narrow slots or cracks, for which measurements by both of the indicated procedures give identical dependences on h/λ (see, e.g., Refs. 2, 13, and 14).

We now discuss the results. It is evident from

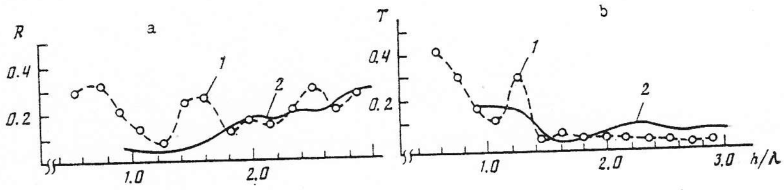

FIG. 3. Reflection (a) and transmission (b) coefficients for Rayleigh waves at a groove vs parameter h/λ, measured by: 1) the rf pulse method at a frequency of 2.04 MHz; 2) by the ultrasonic spectroscopic technique for a groove of depth h = 4 mm.

Fig. 2a that the angular scattering diagrams for longitudinal waves vary considerably with the ratio of the groove depth h to the Rayleigh wavelength λ. The scattered field is distributed fairly uniformly with respect to the angles θ for small values of h/λ, consistent with previous theoretical and experimental results[6,8,10] for shallow grooves ($h/\lambda \ll 1$). For large values of h/λ (corresponding to h = 34 mm under the experimental conditions), a tendency toward stabilization of the scattering diagram and a concentration of the scattered-field energy in the direction of angles $\theta \sim 135°$ (in the backscattering zone) is observed. This fact agrees with the results of existing numerical calculations[16] and experiments[17] on the scattering of a Rayleigh wave by the edge of a 90° elastic wedge (quarter-space). The scattered field exhibits a complex behavior in the intermediate range of values of h/λ; the curves of the scattered-wave amplitudes vs h/λ tend to oscillate at fixed values of the angle θ smaller than $\sim 110°$.

The angular scattering diagrams for shear waves (Fig. 2b) evolve somewhat differently with variation of the parameter h/λ. They are consistent with the theory for small values of h/λ and then behave very irregularly in the intermediate range (h = 0.75-1.25 mm), experiencing oscillations as a function of h/λ at fixed values of the angle θ. The pattern more or less stabilizes as h/λ is increased, but it differs from the longitudinal-wave case in that the scattering maximum is now formed in the vicinity of $\theta \sim 90°$, i.e., in the direction of the normal to the surface. The above-mentioned concentration of scattered transverse-wave energy in the vicinity of the normal has also been observed in Ref. 15 for SAW scattering by a narrow slot of fixed depth (h/λ = 12.3).

The surface-wave reflection (R) and transmission (T) coefficients obtained by the rf pulse method (curves 1 in Figs. 3a and 3b, which are the only ones that can be compared with the above-discussed bulk-wave scattering diagrams) are also characterized by oscillations as a function of the depth parameter and are qualitatively similar to the analogous curves for narrow slots[2,13,14] (see also curves 2 in Figs. 3a and 3b). The existing quantitative difference, as mentioned, is attributable to the influence of the finite groove width. The oscillatory behavior of the observed curves in all the investigated cases is doubtless associated mainly with resonances of Rayleigh waves propagating along the surface of the groove.

In conclusion we note that the experimental data obtained here should be useful not only for direct practical applications, but also to check numerical scattering calculations in the interval $h/\lambda \gtrsim 1$. Moreover, they carry information about SAW scattering by a groove over a wide range of depths and angles of observation and should therefore be of interest from the standpoint of the formulation and solution of inverse sound-scattering problems in solids.[18]

1. R. C. Williamson, "Reflection grating filters," in: Surface Wave Filters: Design, Construction, and Use, H. Matthews (ed.), Wiley, New York (1977), p. 381.
2. I. A. Viktorov, Acoustic Surface Waves in Solids [in Russian], Nauka, Moscow (1981).
3. G. S. Kino, "NDT with Rayleigh and optical waves," in: Proc. Int. Symp. Rayleigh Wave Theory and Application, E. A. Ash and E. G. S. Paige (eds.), Springer-Verlag, Berlin (1985), p. 300.
4. Yu. V. Gulyaev and V. P. Plesskii, Radiotekh. Elektron. 25, 1569 (1980).
5. A. D. Lapin, Akust. Zh. 29, 212 (1983) [Sov. Phys. Acoust. 29, 123 (1983)].
6. J. P. Parekh and H.-S. Tuan, J. Appl. Phys. 48, 994 (1977).
7. S. V. Biryukov, Akust. Zh. 26, 494 (1980) [Sov. Phys. Acoust. 26, 272 (1980)].
8. A. Ronnekleiv and J. Souquet, "Surface to bulk wave scattering from grooves," in: IEEE 1975 Ultrasonics Symp. Proc., IEEE, New York (1975), p. 279.
9. S. V. Korolev, V. A. Krasil'nikov, and V. V. Krylov, Akust. Zh. 31, 138 (1985) [Sov. Phys. Acoust. 31, 81 (1985)].
10. E. Baron, M. De Billy, and G. Quentin, Rev. Phys. Appl. 20, 369 (1985).
11. B. A. Auld, S. Ayter, and M. Tan, "Theory of scattering of Rayleigh waves by surface breaking cracks," in: IEEE 1978 Ultrasonics Symp. Proc., IEEE, New York (1978), p. 384.
12. Y. C. Angel and J. D. Achenbach, J. Acoust. Soc. Am. 75, 313 (1984).
13. M. Hirao and H. Fukuoka, J. Acoust. Soc. Am. 72, 602 (1982).
14. V. Q. Vu and V. K. Kinra, "Application of ultrasonic spectroscopy to scattering of Rayleigh wave in a halfspace," in: Rev. Progr. Quantitative Nondestructive Evaluation, Proc. Ninth Ann. Rev., San Diego, CA, 1982, Vol. 2A, New York (1983), p. 539.
15. R. Tittmann, L. A. Ahlberg, and A. K. Mal, Traitement du Signal 2, 443 (1985).
16. A. K. Gautesen, Wave Motion 8, 27 (1986).
17. W. Pajewski and M. Szalewski, Arch. Acoust. 8, 3 (1983).
18. V. A. Burov, A. A. Goryunov, A. V. Saskovets, and T. A. Tikhonov, Akust. Zh. 32, 433 (1986) [Sov. Phys. Acoust. 32, 273 (1986)].

Translated by J. S. Wood