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Scattering of Rayleigh waves by a groove of arbitrary depth

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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/λ ≪ 1 and h/a ≫ 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.5–7 Experimental studies of SAW scattering by shallow grooves have also been reported for scattering into surface waves1–5 and into the volume of the medium.1,10

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/λ ≪ 1) characterized by ratios h/λ ≪ 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/λ ≫ 1 as a result of the solution of boundary integral equations12 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/a = 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. 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(t) and Dτ(t) of longitudinal and shear bulk waves were measured for a fixed groove depth h. The measurements of D(t) and Dτ(t) were then repeated for different values of the groove depth, which was

![FIG. 1. Experimental arrangement.](image-url)
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

![Diagram](image-url)
Fig. 2a that the angular scattering diagrams for longitudinal waves vary considerably with the ratio of the groove depth to the Rayleigh wavelength \( \lambda \). The scattered field is displayed fairly uniformly with respect to the angles \( \theta \) for small values of \( h/\lambda \), consistent with previous theoretical and experimental results,\(^4\),\(^5\),\(^6\) for shallow grooves (\( h/\lambda < 1 \)). For large values of \( h/\lambda \) (corresponding to \( h = 34 \) mm under the experimental conditions), a trend of the scattered-field energy and the concentration of the scattered-field energy in the direction of angles \( \theta \approx 135^\circ \) (in the backscattering zone) is observed. This fact agrees with the results of numerical calculations\(^1\) and experiments\(^2\) on the scattering of a Rayleigh wave by the edge of a 50° elastic wedge (quarter-space).

The scattered field exhibits a complex behavior in the intermediate range of values of \( h/\lambda \); the curves of the scattered-wave amplitudes vs \( h/\lambda \) tend to oscillate at fixed values of the angle \( \theta \) smaller than \( \approx 110^\circ \).

The angular scattering diagrams for shear waves (Fig. 2b) evolve somewhat differently with variation of the parameter \( h/\lambda \). They are consistent with the groove depth \( h \) to the Rayleigh wavelength \( \lambda \). The scattered field is displayed fairly uniformly with respect to the angles \( \theta \) for small values of \( h/\lambda \) and then behave very irregularly in the intermediate range (\( h = 0.75-1.25 \) mm), experiencing oscillations as a function of \( h/\lambda \) at fixed values of the angle \( \theta \). The latter is more or less stabilized as \( h/\lambda \) is increased, and it differs from the longitudinal-wave case in that the scattering maximum is now formed in the vicinity of \( \theta \approx 90^\circ \), 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 (\( h/\lambda = 12.3 \)).

The surface-wave reflection (R) and transmission (T) coefficients obtained by the rf pulse method (curves 1 in Figs. 3a and b) 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.\(^4\),\(^5\),\(^6\) (see also curves 2 in Figs. 3a and b). The existing quantitative differences, as mentioned, are 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 \( h/\lambda \geq 1 \). 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.\(^1\)


\(^16\) A. K. Gauthesen, Wave Motion 8, 27 (1986).

\(^17\) W. Papiewski and M. Stasiowski, Arch. Acoust. 8, 3 (1983).