THEORETICAL AND EXPERIMENTAL DEVELOPMENTS IN ULTRASONIC EVALUATION OF PERIODIC SURFACES

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ABSTRACT

Most ultrasonic NDE experiments and their theoretical models deal with perfectly smooth interfaces, but true materials generally exhibit rough interfaces. As an approach to include the ultrasonic scattering which occurs on the different interfaces along the beam path, the reflection factors of acoustic waves diffracted by periodic surfaces is investigated theoretically and experimentally by looking at the frequency dependence of the reflected signal. Mode conversion bulk and surface waves are shown to be the result of strong coupling between the incident wave and the geometry of the grating. As a consequence, the geometrical parameters of the interface can be obtained to within 5%.

INTRODUCTION

Experiments of elastic wave diffraction from periodic interfaces have recently been discussed.[1] The existence of sharp minima observed in the spectrum of the scattered waves has been identified as the mode-converted signals along the interface with bulk or surface wave velocities.

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In this paper we show that the frequency position of the observed discontinuity can be related to the geometry of the surface, and to the physical properties of the materials. The theoretical problem is formulated in terms of an integral equation for the particle displacement. Numerical results, in the case of a uniform infinite plane wave, are compared to the experimental data.

THEORETICAL FORMULATION

The diffraction of elastic waves by a stress-free periodic surface is solved rigorously. The problem is formulated analytically by the use of an integral representation of the scattered field in terms of the surface displacement of a suitable canonical problem. The solution of this problem follows the method described by Fokkema and Van der Berg,[2] and numerical results have been presented for scattering by a crack having a sinusoidal profile.[3]

The solid is assumed to be homogeneous, isotropic, perfectly elastic and spatially periodic. The wave is uniform and plane. The case of a two dimensional problem is considered (Fig. 1).

The reflected field is expressed as a sum of plane waves of the form:

$$u^r = \sum_{m=-\infty}^{+\infty} R_m^L \exp[iK_m^L \cdot x] + \sum_{m=-\infty}^{+\infty} R_M^T \exp[iK_m^T \cdot x] \qquad (1)$$

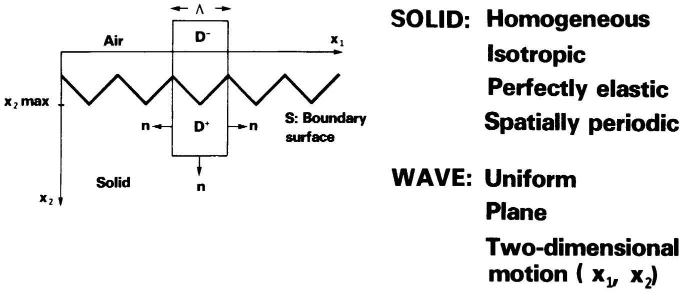


Fig. 1. Configuration of the problem to which the elastodynamic diffraction theory is applied.

where $R_m^{L,T}$ = reflection factors (L = longitudinal wave, T = transverse wave). The reflected displacement field at the point $\underline{x}$ within the solid is then obtained by using the total surface displacement in an integral representation:

$$u_k^{r}(x) = \int_L U_{ki}^{G}(x, x')\tau_{ij}^{r}(x') - U_i^{r}(x')\tau_{kij}^{G}(x, x')n_j(x')ds(x') \tag{2}$$

where u_{ki}^{G} and τ_{kij}^{G} are functions of the Green's tensor.

The reflection factors for the longitudinal (L) and the transverse (T) waves are then given by:

$$R_m^{L,T} = \frac{i(k^{L,T})^2}{2C\omega^2 k_{2,m}^{L,T\Lambda}} \; u_i(\underline{x})T_{ij,m}^{L,T}n_j(\underline{x})\exp[=ik_m^{L,T} \cdot x']ds(x') \tag{3}$$

m = propagating spectral order.

The total surface displacement has been obtained numerically from the integral equations by approximation u^r as a weighted sum of polynomials of the third order (cubic spline).

DATA PROCESSING

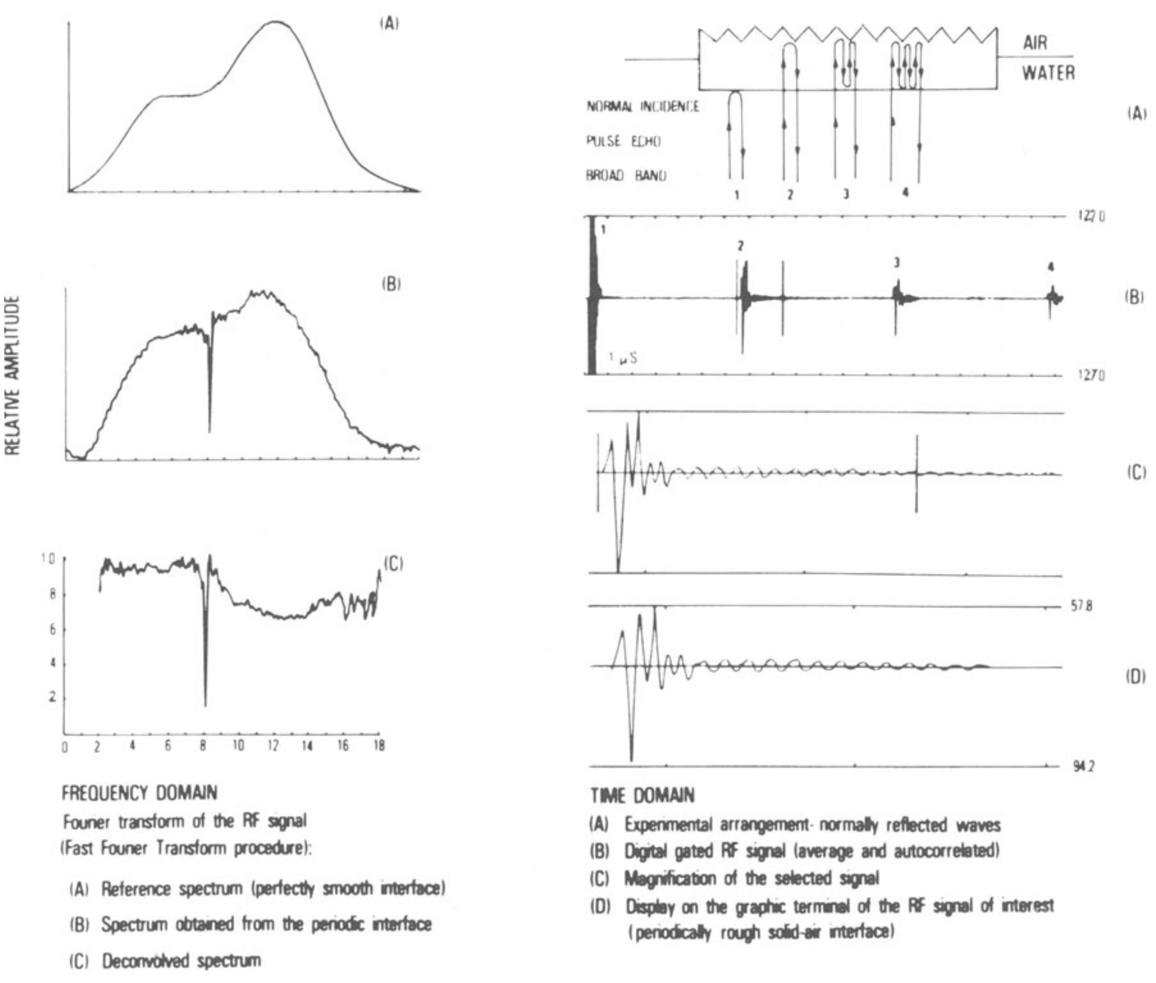
The results are obtained by looking at the frequency dependence of the reflected signal (ultrasonic spectroscopy). The different steps of the signal processing in the time domain and in the frequency domain are outlined in Fig. 2.

Time Domain (Fig. 2a)

The normally incident broad band signal, scattered from the different interfaces (paths 1, 2, 3, 4 ...) is received by the same transducer (Fig. 2a).

Then, the received RF signal is digitized through a transient recorder. The digital data stored on a minicomputer are averaged and autocorrelated. A digital gate (shown in Fig. 2a (B)) is used to select the portion of the signal to be processed (path 2: solid air interface).

The magnification of the gated signal (Fig. 2a (C)) shows the characteristic pattern of the RF signal scattered by a stress-free periodic surface. Only the signal of interest, displayed in Fig. 2a (D) is fed to a minicomputer, to obtain the spectrum.



FREQUENCY DOMAIN
Fourier transform of the RF signal
(Fast Fourier Transform procedure):

(A) Reference spectrum (perfectly smooth interface)
(B) Spectrum obtained from the periodic interface
(C) Deconvolved spectrum

TIME DOMAIN
(A) Experimental arrangement- normally reflected waves
(B) Digital gated RF signal (average and autocorrelated)
(C) Magnification of the selected signal
(D) Display on the graphic terminal of the RF signal of interest (periodically rough solid-air interface)

Fig. 2. Terminal graphic displays of the data processing in the time domain (a) and the frequency domain (b).

Frequency Domain (Fig. 2b)

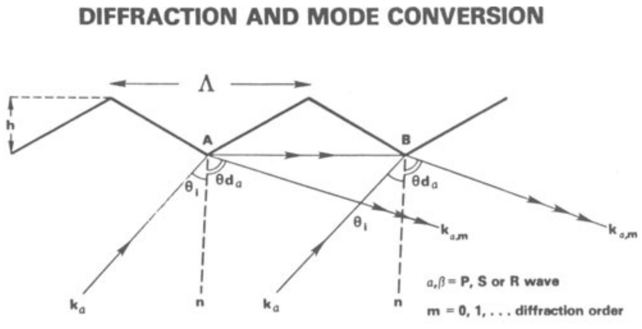
The spectrum of a normally reflected signal (Fig. 2b(A)) from a perfectly smooth surface of the same material is used as reference.

A typical result of the amplitude spectrum of a reflected signal from a periodic solid-air interface is shown in Fig. 2b (B). The sharp discontinuity, observed at a given frequency, can be related to the geometrical and the physical properties of the interface.

Then the spectrum of the scattered wave from the rough surface is deconvolved by the reference spectrum (Fig. 2b (C)).

RESULTS

The classical grating equation is applied to a broad band signal. Accordingly, at different angles of incidence the various frequencies will diffract to different angular positions, following the equation given on the left-hand side of Fig. 3.



MAXIMUM OF DIFFRACTION

a) Incidence θ_i

$$\sin\theta_i = \frac{\lambda_{i,\alpha}}{\lambda_{d,\beta}} \sin\theta_d - m\frac{\lambda_{i,\alpha}}{\Lambda}$$

$$f = -\frac{mv_{i,\alpha}}{\Lambda\left(\sin\theta_i - \frac{v_{i,\alpha}}{v_{d,\beta}}\sin\theta_d\right)}$$

b) Normal Incidence; ($\theta_i = 0$)

a) Bulk wave $f = m\frac{v_{d,\beta}}{\Lambda \sin\theta_d}$

b) Mode converted Rayleigh wave

$$f_R = m\frac{v_{d,R}}{\Lambda}$$

Fig. 3.

A special arrangement is investigated when the incident wave is normal to the grating and the transducer is used both as the transmitter and the receiver. In this case, the equation of diffraction is given by the expression shown on the right-hand side of Fig. 3. These last two equations give the frequency position of the diffracted wave for a bulk wave diffracted along the direction Θ_d and for a Rayleigh wave propagating along the surface ($\Theta_d = \pi/2$).

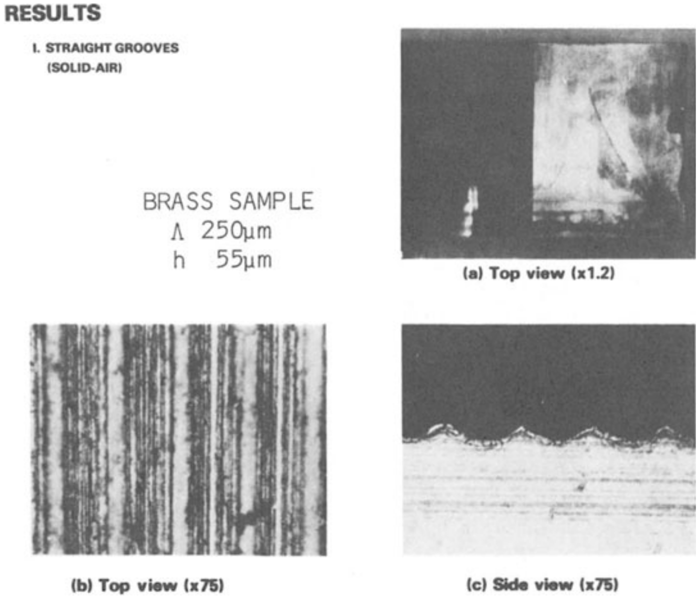
Figure 4a shows the microphotography of a brass sample with straight grooves (periodicity $\Lambda = 250$ μm, peak to valley height is $h = 55$ μm).

Figure 4b represents the relative amplitude spectrum of a normally incident reflected signal. The significant feature is the minimum which occurs at 8 MHz on the experimental spectrum (dashed lines on Fig. 4b). This phenomenon is interpreted as a strong coupling between the surface and the ultrasonic wave. Mode conversion occurs for a frequency given by the expression shown in Fig. 3 (bottom right). The mode converted surface wave propagates along the rough surface with a velocity close to the Rayleigh velocity. Along this path, the edges of the profile, distant of Λ one from the other, reradiate the energy toward the normal of the mean plane of the surface. Interference between these reradiated waves and the direct specular reflected wave give rise to this minimum.

This sharp discontinuity does not appear in the theoretical spectrum (solid lines in Fig. 4b) as long as the model involves an infinite plane wave. Very recent calculations have shown that by using a finite beam, a similar minimum occurs with the same amplitude, at the same frequency position. In Fig. 5 it is shown that the same effect occurs with circular grooves. The circular grooves of a titanium disk which has been cut with a milling-cutter have been enlarged in Fig. 5a. Optical (top of the figure) and mechanical (bottom of the figure) measurements give the dimensions of the grooves ($\Lambda = 97$ μm, $h = 8$ μm).

The data obtained from ultrasonic backscattering measurements (water-solid interface) are in excellent agreement (Fig. 5b). These are obtained by measuring the frequency position of the minimum on the spectrum, and using the formula of Fig. 3.

The same approach was used to test diffusion bonded specimens with periodic contact (Fig. 6). The departure of the observed minima (2 MHz and 3.7 MHz) from the expected one (1.7 MHz and 3.4 MHz) may be due to the nonflatness of the contact, or induced stress, which appears because of the bonding process. The two experimental plots T 10(a) and T 10(b) correspond to the insonification from the two sides of the specimen, respectively.



(a) Top view (x1.2)

(b) Top view (x75)

(c) Side view (x75)

Fig. 4a. Microphotography of a grating with grooves on a plate (10 x 5 x 1.4 cm) of brass.

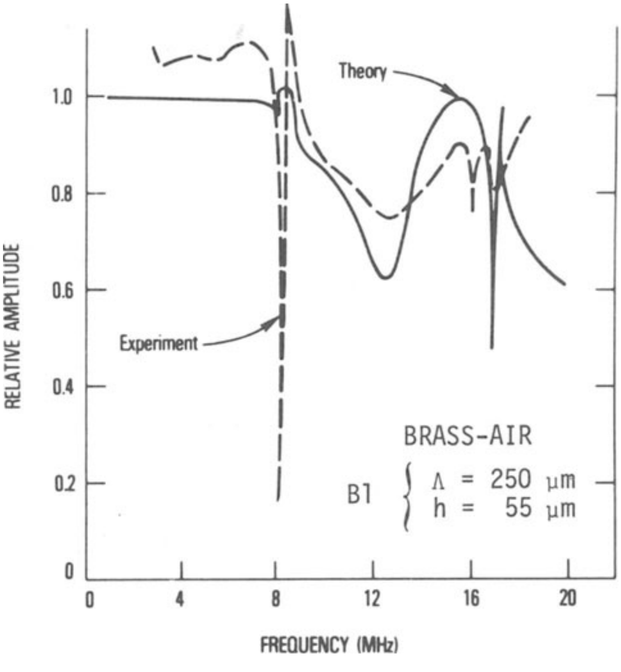
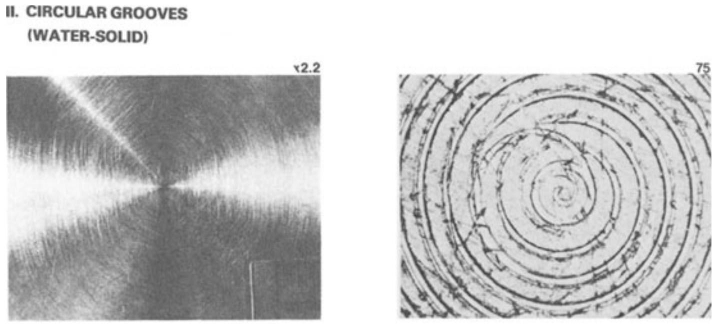
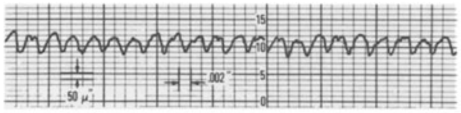


Fig. 4b. Backscattered amplitude spectrum of a normally incident broadband signal.

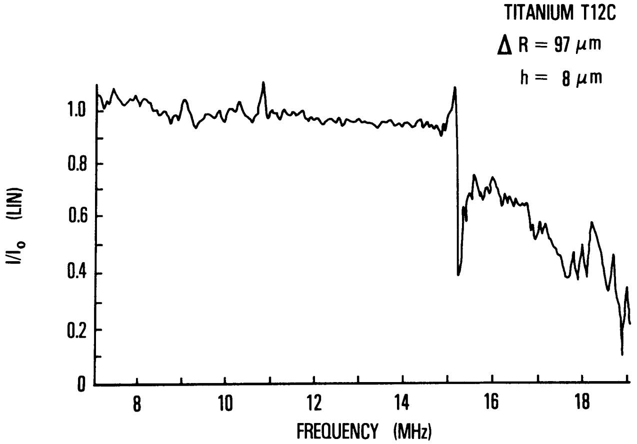


MICROPHOTOGRAPH



SURFACE PROFILE ALONG A RADIUS
(PROFILOMETER)

Fig. 5a. Optical and mechanical enlargement of the periodic profile made of circular grooves on a titanium disk.



NORMALIZED REFLECTED POWER SPECTRUM (NORMAL INCIDENCE θ = 0)

Fig. 5b.

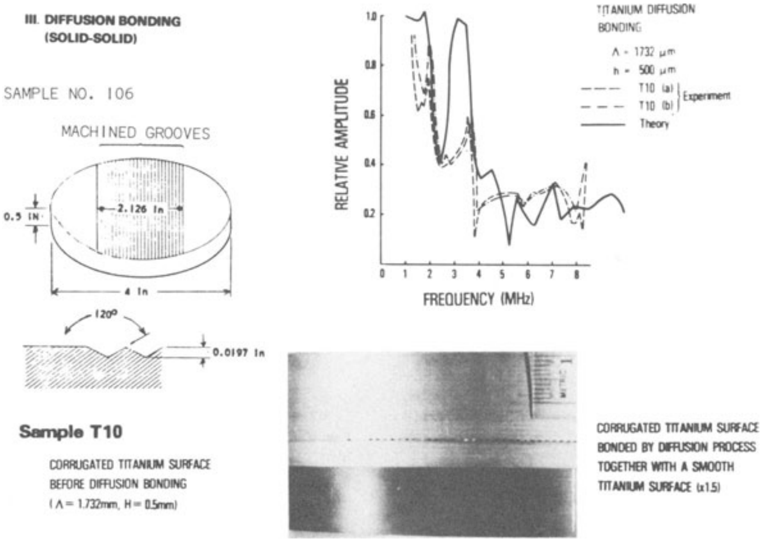


Fig. 6. Diffusion bonded periodic corrugated surface.

The same kind of anomalies in the spectrum appear if we consider the scattering effect from a finite penny-shaped region (a crack with periodic profile inside diffusion bonded titanium, Fig. 7). The minimum at 9.6 MHz (according to the equation of Fig. 3) corresponds exactly to a periodicity of 300 μm for a wave propagating in the Rayleigh velocity in titanium.

CONCLUSION

These results suggest the ability of spectroscopy analysis to relate the geometrical and/or the physical properties of a periodic specimen to the normally backscattered spectrum. The theory of diffraction, developed for a stress free surface, fits quite well the experimental data. However, the sharp minimum, due to the mode conversion process on the grating, is not included in the theory. Computations are now in progress to deal with such coupling phenomena by including the finite size of the beam.

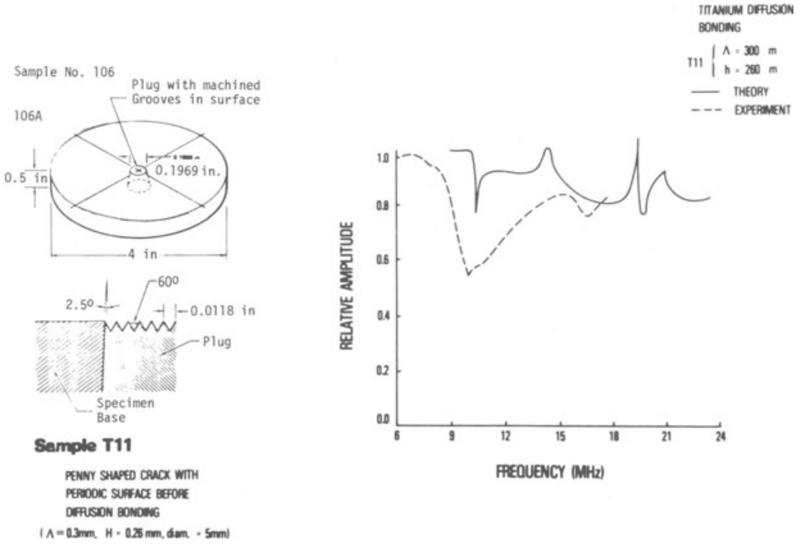


Fig. 7. Penny shaped crack with periodic profile inside diffusion bonded titanium.

ACKNOWLEDGEMENT

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