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AN ULTRASONIC TECHNIQUE FOR SIZING SURFACE CRACKS

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ABSTRACT

Rayleigh surface waves are proposed as a non-destructive method to find the depth of surface cracks. The paper describes how dynamic photoelasticity was used to develop an understanding of the subsurface interactions between R-waves and a narrow slot. A frequency analysis of the transmitted wave confirmed that the slot acts as a low pass filter for the high frequency Fourier components of the input wave. It is then shown that the high frequency cut-off in the spectrum of the transmitted wave from broadband ultrasonic surface pulse can be used to determine the depth of surface slots.

INTRODUCTION

During recent years investigators started to recognize the potential value of Rayleigh waves for characterizing surface and near surface defects (1). This wave has its energy confined to a depth of approximately two times its wavelength (2) which makes it eminently suitable for interrogating near surface defects. Reinhardt and Dally (3) used photoelastic visualization to study the interaction of Rayleigh waves with surface flaws. They found the variation of transmission and reflection coefficients for slots with depths up to half of the Rayleigh wavelength. Bond (4) used finite difference modeling to obtain quantitative information on the interaction of Rayleigh waves with boundary and flaw configurations that were analytically intractable. Silk (5) and Hall (6) used timing methods on the Rayleigh wave to find the depths of slots and cracks with well defined tips.

Ultrasonic frequency analysis has been used mainly to characterize internal flaws. Adler (7) used this method to determine the shape of buried flaws. Morgan (8) analyzed the reflected signal from a slot milled in aluminum and found certain modulations in the frequency spectrum. These are caused by resonances of the crack faces and as such should contain the necessary information to characterize cracks. Ayter and Auld (9) used analytical methods to relate these resonant frequencies to crack size.

This paper describes an experimental study using the spectral analysis of signals to determine the depth of surface cracks. The technique has much potential for research because there are several different modes of converted and scattered signals that should be investigated to find how they correlate to crack depth. Some theoretical analyses of Rayleigh wave scattering by surface defects has been done by Tittmann (10) and Auld (11), but experimental and numerical studies are needed to fully develop this method to the point where it can provide quantitative information about surface and subsurface defects.

DYNAMIC PHOTOELASTICITY

Dynamic photoelastic visualization (12) of the interaction between Rayleigh waves and slots (13) were obtained on models made from 6.3 mm (1/4 inch) thick sheet of a polyester type material "Homalite-100." R-waves were generated by exploding small lead azide charges on the top edges of the plates. For each slot (width 1 mm) a sequence of 16 dynamic photographs were obtained. These showed the incident Rayleigh wave, its interactions with the slot, and the transmitted and reflected waves after the interaction. Figure 1 shows the photoelastic fringe pattern after the interaction. The following notation was devised to indicate the various waves. A capital letter indicates the wave type, P for longitudinal wave, S for shear wave, PS for Von-Schmidt wave, and R for Rayleigh wave. A subscript indicates the wave type from which a particular mode converted wave (capital letter) was generated. A superscript identifies the point of origin on the model of reflected or mode converted waves. A subscript differentiates between a reflected (r) or transmitted (t) component.

![Fig. 1 Photoelastic visualization of R-wave after interaction with a slot.](image)

In this manner the notation $S_R^2$ indicates a shear wave formed by mode conversion of the original R-wave at the first upper corner of the slot, point I on Fig. 1. $R^2_r$ will be the Rayleigh wave reflected from the original R-wave at the slot tip (point 2). $S$ is an input shear wave which is strong in the interior and reduces to zero at the surface.
The photoelastic results show clearly that the pattern of mode conversions and the intensity of the various waves depend strongly on the depth of the slot.

There are two mode converted longitudinal waves \( p_2 \) and \( p_1-2 \). It is not clear from which wave the two fronts \( p_2 \) and \( p_1-2 \) are generated. The source for the former is point 2, and for the latter point 2 and/or the face 1-2. The interaction between the slot and the Rayleigh wave is the most interesting. It is known that the depth of the Rayleigh wave is a function of the wavelength. As the R-wave approaches the slot, it strikes it from the slot opening to the slot tip. The particle motion at the slot opening will contain all the Fourier components, i.e., all the wavelengths of the input wave. The particle motion at the tip will be mainly due to the long wavelength parts of the R-wave.

The interaction of the upper portion of the wave with the slot opening (point 1) generates a reflected R-Fo-wave. A shear wave, \( S_x \), is produced by mode conversion from the R-wave and a transmitted Rayleigh wave turns around the corner and continues down the front face of the slot to the tip. Here a portion of the R-wave mode converts to a shear wave \( S_x \), another portion is reflected back up the front face as \( R_F \) and the remainder proceeds around the tip and up the face of the slot.

The deeper particle motion of the R-wave will interact with the slot differently. The energy distribution in the Rayleigh wave as it interacts with the slot is sketched approximately in Fig. 2. The figure shows that the deeper particle motion (corresponding to the long wavelengths) goes under the slot and forms another Rayleigh wave, called here a "undercut" R-wave. The deeper particle motion will also form a shear wave at the slot tip which will scatter from the tip. The transmitted signal called \( R_r \) is a composite of all the R- and S-waves diffracted from the crack tip. The shear wave is present in the transmitted response at the surface because unlike the input S-wave it does not graze the surface but strikes at an angle.

The fringe order of the transmitted wave at the surface gives the stresses at the surface. Plotting these gives the shape of the wave. When the frequency of the transmitted wave was analyzed, it was clear that the frequency spectrum depends on the depth of the slot. Figure 3 shows the magnitude of the spatial frequency distribution for the transmitted waves from each of the four slots. There are significant differences in the frequency spectrums. As the slot depth is increased from 2.8 to 12.9 mm, the high frequency content drops, while the low frequency content remains strong.

Fig. 3 Frequency magnitude curves for four different slots from transmitted waves in dynamic photoelasticity.

The photoelasticity results suggested that a slot will act as a low pass filter by cutting off the short wavelength (shallow) components while allowing the long wavelength (deep) components of a Rayleigh wave to pass underneath the tip. The frequency spectrum of the deeper portion of the R-wave contain the low frequency (long wavelength) components of the incident wave. It is, therefore, reasonable to suggest that the wavelength at which the frequency of the transmitted wave is "cut off" will be the frequency at which the wavelength relates to the depth of the slot. If this is true, the frequency spectrum of the transmitted wave will give quantitative information on the depth of surface slots.

An ultrasonic test was devised to test this hypothesis. The transducers used were 1-5.5 MHz, broadband, R-wave wedge transducers designed for use on steel. The important specification for them is that the incident wave should have wavelengths that will excite particle motions up to a distance from the surface which is deeper than the slot.

The models were steel blocks, with 0.43 mm wide, machined slots, which were 1, 2, 3, 4, 5, 8, 11, and 14 mm deep. These depths were selected from the consideration that the elliptical particle motion of a R-wave penetrates to a depth of 2. Thus, a wavelength in steel of 3 mm corresponds to a frequency of 1 MHz. It will excite particle motion as deep as 6 mm. It was anticipated that the maximum depth to which this analysis would work would be 5 mm. Beyond 6 mm depth there should not be any undercutting.

The test specimens were low carbon steel blocks, 50 x 50 x 180 mm. The slots were machined right across the top faces of the blocks, and the transducers were placed 50 mm on either side of the slots.
The signals received by the transducers for an uncut block and for slot depths of 2, 3, and 5 mm are shown in Fig. 4. The horizontal axes represent time. The sweep rate was 500 nanoseconds per division and the relative sensitivities for the vertical scales are all the same except for the first picture. On the same scale as the others this signal would have been five times larger than shown. Reading from left to right identifies the signals arriving at the "receiver" in sequence. The caption "R" indicates a Rayleigh wave. The first picture represents the "input" signal. This is a pure R-wave.

Fig. 4 Oscilloscope traces or amplitude vs time records for transmitted waves for different slot depths.

Two characteristics stand out:

1. A sharp signal, captioned R, is observed in all the pictures. The shape of this signal does not change significantly with slot depth. Only its amplitude changes slightly. This signal lags behind all other signals and the lag increases with slot depth. It is the Rayleigh wave which went all around the slot, and is called the "cut off" R-wave.

2. The form of the front signal which leads the cut off R-wave is the same for all the cracks. It has two peaks and a valley. As the slot depth increases from 1 to 5 mm, the signal decreases in amplitude and broadens out. This signal leads the cut off R-wave and could be composed of several interfering waves. These may include: (i) the shear wave that was diffracted by the tip of the slot from the incident shear wave and the deep portion of the R-wave; (ii) the undercut R-wave; (iii) other mode converted waves. Since this signal is a mixture of several waves, it is not perfectly smooth. The various waves present in this signal cannot be identified as they arrive at approximately the same time.

When the slot depth is more than 5 mm, the front signal becomes weak and disappears completely at 11 mm. This is because the depth of the slot becomes greater than the depth of input R-wave. Also the diffracted shear wave from the incident shear wave decreases due to increase in the angle of diffraction.

It is also seen that the cut off R-wave amplitude does not change significantly when the slots are deep. The signal is smaller for the 1 mm slot, and increases 2, 3, and 4 mm. This is because as the slot depth increases from 1 mm onward, a smaller portion of the energy is in the undercut wave. For slots deeper than 5 mm the amplitude of the R-wave changes little with depth. There is no undercutting. The amplitude falls slightly due to more efficient reflection or due to attenuation because the path length from transmitter to receiver is larger with deeper slots.
FREQUENCY ANALYSIS

The schematic of the computer hardware used for the analysis is shown in Fig. 5. The sample is taken from the ultrasonic pulser receiver through a Tektronix sampling oscilloscope. The sampling scope is interfaced to a LSI-11 minicomputer. The software in the system is capable of sampling the signal, finding the FFT, displaying it, and plotting it through a X-Y plotter.

The transmitted signals were sampled for all the machined slots. Care was taken to include all the transmitted signals in the sample, from the diffracted shear wave to the last signal, which is the cut off R-wave.

The frequency magnitude of all the transmitted signals is plotted in Fig. 6. These resemble very closely those in Fig. 3. The attenuation of frequencies starts from the high frequency end. Careful analysis of the figure reveals that all the curves approach the same plateau at higher frequencies. The plateau is, in fact, the curve corresponding to a slot of 5 mm. After the curves have dropped to the level of the plateau, they follow approximately the 5 mm curve. The curves for 8, 11, and 14 mm deep notches are similar to the one for 5 mm. They are not drawn. The plateau curve corresponds to the frequency spectrum of the cut off R-wave which is the only major signal for slots of 5 mm and longer. Thus, if the cut off R-wave is removed from all the transmitted signals, the plateau will be removed. The last signal, i.e., the cut off R-wave was digitally zeroed and the frequency magnitudes plotted in Fig. 7. The curves obtained were smooth and showed very clearly that the attenuation of frequency components started from the high frequency end and proceeded to lower frequencies as the slot depth increased. These curves correspond to the frequency magnitude of the undercut R-wave, the diffracted S-wave from the incident S- and R-waves, and mode converted waves. The mode converted signals are very small and clearly do not have a significant effect, except in cases where the undercut R-wave and the diffracted S-wave are weak.

Fig. 5 Schematic of computer hardware.

Fig. 6 Frequency magnitude of the transmitted ultrasonic waves.

Fig. 7 Frequency magnitude of the undercut R-waves and diffracted shear waves from ultrasonic tests.

Figure 7 confirms what previous figures suggested, namely that the frequency attenuation starts from the higher side and moves to the lower side. To correlate this aspect quantitatively, it is necessary to relate a particular point on the curve to the slot depth. One of the points chosen was where the frequency magnitude first goes to a minimum. It is called the 'cut off' point because the frequency components which are higher than the frequency corresponding to this point were "cut off" by the slot. These points on the curves are indicated as \( C_1 \), \( C_2 \), \( C_3 \), and \( C_4 \) corresponding to 1 mm, 2 mm, 3 mm, and 4 mm slots. The peak of the curves also relate to the slot depth. These points are called \( P_1 \), \( P_2 \), \( P_3 \), and \( P_4 \) as shown in Fig. 7. The 'cut off' points and the wavelengths corresponding to the peak and cut off points are tabulated in Table 1 and plotted in Figs. 8 and 9.

<table>
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<th>Slot (mm)</th>
<th>Cut off frequency (MHz)</th>
<th>Cut off wavelength (mm)</th>
<th>Peak frequency (MHz)</th>
<th>Peak wavelength (mm)</th>
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<td>0.93</td>
<td>3.2</td>
<td>0.52</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Table 1
CONCLUSIONS

The property of the Rayleigh wave which relates the wavelength to its depth below the surface has been effectively used to find the depths of slots. Figure 8 shows that the depth of a slot is nearly linearly related to the wavelength. The slope of the line is 0.8. Thus, a slot of 3 mm cuts off all the wavelengths which are less than about 2.4 mm. The theory (2) predicts that the particle motion excited by an R-wave is localized to a depth of 2λ. The results from both photoelastic and ultrasonic tests show that the slot is fairly efficient filter for wavelengths less than 0.8 times the slot depth. The wavelengths in the undercut R-wave and other waves scattered from the slot tip are all longer than 0.8 times the slot depth. Thus:

\[ \text{Slot depth} = 1.25 \times \text{cut-off wavelength}. \]

So in using this technique for inspection purposes the bandwidth of the R-wave should be such that the shortest wavelength (highest frequency) is 0.8 times the shortest crack depth that needs to be inspected. The largest wavelength (lowest frequency) should be longer than 0.8 times the deepest crack that is expected. Increasing the maximum wavelength to one times the crack depth gives a better resolution and should be considered the preferred limit. In doing this the undercut R-wave will be much stronger than the mode converted waves and will thus be affected less by them. Thus, if it is required to size cracks from 1 mm to 10 mm, the wavelengths in the R-wave should be from 0.8 mm to 10 mm.

ACKNOWLEDGMENTS

This research was supported in part by the Director of Energy Research, Office of Basic Sciences, U. S. Department of Energy, WPAS-KC-02-01 and by the National Science Foundation Grant No. ENG77-06970.

REFERENCES


Leonard Bond, Chairman (University College London): As chairman, I will, in fact, make a comment. It's very gratifying to see one's numerical results confirmed by visualization. It's a great relief.

Gordon Kino (Stanford University): We published a paper a year ago on resonances of slots of this kind. I think the basic explanation is that the Rayleigh wave propagates down the slot, so that you get resonance associated with the slot. There is also another resonance associated with the width.

Chris Burger (Ames Laboratory): The resonances are very strongly present. I think we'll talk about those in the next paper which deals with the reflected wave. The transmitted wave does not show strong resonances.

Gordon Kino: You talk about maxima and minima. That's just another word for resonance.

Chris Burger: Yes, let us look at the transmitted wave for a slot where we have fairly good separation. We are only looking at the first portion of the wave. Sort of three cross-over points from the slot. This is the kind of characteristic that you can ask a computer to identify. Look at the wave that follows immediately after the third cross-over point. This is the Rayleigh wave which propagated around the slot. The component which we are looking at in the shear that comes from the tip of the slot together with the cut-off Rayleigh wave. I do not think that there are too many resonances in that portion of the wave.

Volker Schmitz (Battelle Northwest): Are the formulas you showed independent of the transducer? If you change the transducer, would it change the frequency spectrum of your transmitted signal? Would it change the formula?

Chris Burger: The answer is probably yes. We do not know. We only did it with one transducer. I'm not proposing that the formula is a unique relationship of how deep the crack is. There is, however, a clear relationship between the characteristic points in the spectrum and the depth of slot. This kind of approach is worth pursuing.

In fact, I don't see much use for a formula for open slots. We need to progress from here to slots where we have residual stresses at the root to see if the technique is sensitive to such stresses. I hope it's not. Then we can move on to open cracks and to closed cracks. At that point we may be interested in developing more generalized equations that will be of practical value.

Sevig Ayter (Stanford University): In the reduced frequency spectrum, after the first maxima and minima there are a few ripples. Do you try to analyze them?

Chris Burger: Yes, we tried to.

Sevig Ayter: Did you relate it to the resonances?

Chris Burger: Yes, we did get some information, but we were pragmatic at that point. We looked at the main signature, because it contains the most information. We were looking for the strongest indication which relates most directly and unambiguously with crack depth.

Leonard Bond, Chairman: Thank you very much.