CHARACTERIZATION OF "KINKED" SURFACE CRACKS USING RAYLEIGH WAVES

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INTRODUCTION

This work combines fracture mechanics and ultrasonics inspection techniques in the non-destructive evaluation of cracks that commonly occur in fretting fatigue. The first part of the study was a fracture mechanics analysis [1,2]. This was necessary to estimate the depth of penetration of the normal stress field under typical 2-D fretting fatigue conditions, which control crack shape and hence served as a guide in the choice of a suitable inspection technique (wave type) and frequency.

In this study, after an initial estimate of the range of crack sizes was obtained, which was from 10 μm to a few mm, an ultrasonic Rayleigh wave method was chosen to characterize the crack and to monitor crack growth. For inspections, initially on aluminum test bars in the laboratory, the aim is to characterize the crack using ultrasonic spectroscopy. An inversion scheme developed which allows the state of the crack to be specified in terms of its growth stage, length and orientation.

FRETTING FATIGUE

Fretting commonly occurs at an interface between two parts where there is relative tangential motion and it results in local stress concentrations which in turn can cause the growth of fretting fatigue cracks. The main feature of this situation is that the influence of fretting is local. The crack propagation consists of three distinct stages as shown in Fig. 1. In Stage I the crack grows inclined to the surface (at about 135°). After some growth

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in this initial phase, the influence of the tangential loading disappears at a depth \((t)\), and Stage II of the growth starts.

The crack then grows normally to the surface and perpendicularly to the principal axis of the repeated stress. These kind of non-planar cracks are often referred to as "kinked" cracks [2]. In stage III, the crack has grown away from the surface and it is almost a simple 2-D crack normal to the surface, since the inclined part is tiny compared with the length of the normal zone.

Most of the existing models of fretting fatigue do not take into account either the sliding mode stress intensity factors or the inclination of the crack in the early stage of its growth. The first part of this study sought to apply a more refined analysis to the crack growth by consideration of the angled crack effects [1,2]. It examined the problem of a rigid or elastic punch pressing onto the surface of a semi-space, where an angled crack grows just under the edge of the punch. The mode-II (sliding mode) stress intensity factors were determined for this configuration and the critical crack length was calculated. Excellent agreement with existing experimental models was found [1]. The geometry involved is shown in Fig. 2.

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**Fig. 1.** Fretting fatigue crack growth stages

**Fig. 2.** Schematic representation of fretting fatigue pad and specimen
INSPECTION WITH RAYLEIGH WAVES

Rayleigh waves are attractive for investigating surface and near surface defects [3]. Their energy is contained within about one and a half wavelengths of the surface, they are non-dispersive in an isotropic homogeneous half-space and will follow gently curved surfaces (when the radius is larger than three wavelengths) for long distances without significant attenuation.

The analysis for the scattering of Rayleigh waves from general crack-like defects does not have a complete analytical solution. For the low frequency (or long wavelength) regime, several perturbation techniques have been implemented to solve the scattering problem. Also for the high frequency (or short wavelength) regime, multiple scattering analysis using ray theory has been developed for normal cracks [4] and for angled cracks in corners [5]. These theories require the scattering coefficients for the corresponding wedges and other canonical problems [6] to be determined by other methods, if the scattered Rayleigh wave field is to be calculated. Finite difference models [7] and hybrid finite difference-finite element models [8] have been applied with considerable success to these problems. The common characteristic of these numerical methods is that they are full field solutions and they allow the visualization of the incident pulse and its ensuing interaction with the slot together with the determination of reflection coefficients. The experimental data are then considered in the context of these theoretical scattering analyses, which facilitate the interpretation of the often complex time domain signals.

EXPERIMENTAL PROCEDURE

The Rayleigh wave speed was measured on the aluminum blocks, in a separate experiment [2,3], to be 2930±10 m/s. Experimental procedures were developed with a view to determining frequency dependent reflection coefficients and comparing them with available data. The experimental configuration employed is shown in Fig. 3. Pulse-echo ultrasonic measurements were made using various combinations of features and transducers. The time-domain signals were digitized using a digital oscilloscope with time-domain samples at 100 MHz (10 ns) and a vertical resolution of 8 bits. The data were then transferred into a microcomputer for signal processing.

Fig. 3. Test block geometry and experimental configuration
Test Blocks

The experimental study of the problem of Rayleigh wave interaction with 2-D fretting fatigue cracks can be investigated using scale models for the three crack stages (shown in Fig. 1.) with dimensions defined in terms of the \( d/\lambda \) ratio, where \( \lambda \) is the Rayleigh wave length and \( d \) the defect length.

A half-space was modeled by an aluminum alloy block with a thickness of 25 mm chosen in order to secure plain strain conditions. This thickness is adequate for the frequency range of the Rayleigh wave transducers used in this study which were between 1 and 5 MHz. The corresponding wavelengths are in the range 0.6 to 3 mm.

A series of test blocks were designed where the length of the test piece and the distance of the transducer from the slot were chosen so that the targets would be just outside the near-field of the transducers [3]. A distance of ten wavelengths should be adequate to ensure distance independent reflection coefficients, so, assuming a 3 mm wavelength for a 1 MHz Rayleigh wave, a transducer-feature distance of 30 mm is needed.

To simulate the three stages of crack growth (Fig.1.) samples with scaled dimensions were prepared. The slots were cut in aluminum alloy test block using a wire-cut Electric Discharge Machine (EDM) with a 0.1 mm diameter cutting wire. A length of 2 mm was chosen for the angled zone, so that for the frequency regime from 1 to 5 MHz, (or the wavelength regime from 0.6 to 3 mm), the ratio \( \alpha/\lambda \) is in the range from 0.66 to 3.33. For Stage I conditions a slot inclined at 135° to the surface (2 mm long) was made. For stage II conditions three samples were prepared, with the angled part (\( \alpha \)) made 2 mm long and inclined at 135° to the surface. The normal zone was then given lengths defined as a ratio of the second (normal) part (\( \beta \)) over the first (inclined) part (\( \alpha \)) were 1:1, 2:1, 6:1 respectively. Stage III conditions were then simulated by one slot where the ratio of the lengths of the two zones was 20:1, with an angled part of 1 mm and a normal part of 20 mm.

Data analysis

The spectral response of every slot was calculated using a Fourier transform. Standard deconvolution procedures were then employed to remove system characteristics by using a reference reflection from a 90° sharp corner.

The steps undertaken for the implementation of the signal processing were:

(a) The transducer transfer function was obtained from the backscattered echo of a reference scatterer. The reference spectrum was taken from a sharp 90° edge, where the reflection coefficient is frequency independent [7].

(b) The ultrasonic backscattered spectrum of the feature to be measured was obtained, which was convolved with that of the interrogating system. The return amplitude is very
sensitive to the orientation of the transducer relatively to
the slot; the error in phase was estimated at 0.4 radians
for 1 to 5 MHz and it requires a degree of skill and
patience to optimize the signal. The typical problems that
occur in contact measurements, associated with the couplant
thickness, surface finish, pressure on the transducer and
the distance of the transducer from the target, among
others, are well known. However, they should not amount
more than ±1 dB of the measured quantity [3,9]. It must
borne in mind that ultrasonic spectroscopy is more suitable
for determining the location of peaks and nulls along the
frequency axis than for amplitude measurements.

(c) The two scattering signals, one from the flaw and the
other from the reference, were deconvolved in the frequency
domain (4096 point complex FFT). The cut-off point was
chosen at -6 dB.

RESULTS AND DISCUSSION

Generally, three scattering regimes (Fig.1.) can be
distinguished, depending on the relative magnitudes of the
wavelength and defect.

Stage I

When the angled part is much longer than the wavelength
the principles of the geometrical ray theory can be applied
[4]. In Fig. 4, the frequency response curve for an 135°
angled slot is shown, together with analytical results for a
135° down step from [8]. However, it is difficult for this
situation to be achieved in practice, as it requires that
the wavelength must be at least one and a half times smaller
than the smallest dimension required to be resolved. In our
case, the wavelength should be much smaller than the length
of the angled crack, which is very tiny and can be between
10 and 100 μm.

Stage II

When the crack depth (d) is of the same order of
magnitude as the wavelength, the scattered wave pattern is

Fig. 4. Spectral response curve ( ) from a 135° angled
slot. Comparison with numerical data (---) for a
In the "high" frequency regime of Fig. 5. (transducer mean frequency 5 MHz), the normal part of the crack has destroyed the typical modulations that occur for both the angled and the normal slots. Further analysis is required to understand the scattering in this regime.

**Stage III**

In this regime it is the case of the deep slot (ratio 20:1), where the results were almost identical to those of a normal crack (Figure 6). The angled part of the crack is much smaller than the wavelength, and the response is dominated by the normal reflection.

![Spectral response curves from different slots.](image)

**Fig. 5.** Spectral response curves from different slots. The \( \alpha/\beta \) ratios are: \( - - - \) 1:1 (small), \( - - - 2:1 \) (medium), \( --- \) 5:1 (long) and \( \_ \_ \) \( 135^\circ \) slot usually very complicated and very dependent on the features of the defect, such as shape, position, orientation, size, material properties and surface conditions.

![Spectral response curve from a normal down step.](image)

**Fig. 6.** Spectral response curve from a normal down step (ratio 20:1). Comparison with numerical data for a normal down step from [8] (for steel)
Crack characterization-Stages I and II

In terms of the inverse problem, even though the Rayleigh waves follow the crack front face and we cannot easily distinguish in the time domain between angled and normal cracks, when the ray theory holds true \((d/\lambda \geq 1.5)\), the formula \(d = c/2\) or \(d/\lambda = 1/2\) can be applied \([5]\), where \(f\) or \(\lambda\) is the distance between the modulations in the frequency domain.

The dimension \(d\) is equal to \(\alpha\) in the case of an angled crack or to \(\alpha + \beta\) for the kinked crack. The overall reflection coefficients for an angled crack are generally smaller than those for a normal crack (see \([8]\), where they refer to down step geometries) and this can be used to distinguish between the two cases (compare Figures 4 and 6). The fracture mechanics analysis of the first part of this work, where the calculation of the critical crack length was carried out, leads to a method of choice of a suitable range of frequencies, which can be employed for interrogating the crack.

Crack characterization-Stage II

The reflection coefficients shown in Fig. 5, are not easily distinguishable. This means that the scattered wave field is remarkably insensitive to the length of the normal part of the crack. The first 135° zone dominates the scattering, even though its signal becomes coupled with the normal slot effects and produces stronger signature than the 135° angled slot. Figure 7 depicts this effect: the signals from the three slots with quite different slot depths were deconvolved from the signal of a 135° angle and they appear to be identical.

However, one promising phenomenon in this area is the mode conversion that occurs especially at the first zone \([10]\) generating a surface grazing compression wave. Mode conversions seems to provide additional signals for analysis and work on this field continues.

Fig. 7. Spectra from different slots (those of Figure 7), deconvolved from a 135° angled slot
Also, from the insight given by the Rayleigh wave scattering numerical visualizations [8], a linear energy partition model [11] for the reflection from slots is being examined with encouraging results [2,9].

CONCLUSIONS

Following the stress analysis of fretting fatigue an ultrasonic Rayleigh wave scheme has been developed for crack characterization. In essence the scheme involves the composite crack response which is a combination of those for the 135° step and the 90° slot.

In stage I of the crack growth the response is almost that of the 135° step. In stage III the response becomes almost that for a 90° slot. In between these regions the reflection coefficients are between these limiting cases.

It is proposed that in a fretting fatigue test time dependent measurement of the reflected Rayleigh waves would enable crack characterization to be achieved and the length of the two crack sections estimated.

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