ON THE DETECTABILITY OF FATIGUE CRACK GROWTH AT FASTENER HOLES USING GUIDED WAVES

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ABSTRACT. The nondestructive detection of fatigue cracks at fastener holes in aircraft structures employing guided waves is studied. Experimentally the first antisymmetric Lamb wave mode A₀ is excited using piezoelectric transducers and the scattered field is measured by means of a heterodyne laser interferometer. The detectability of small defects is investigated and quantified by a parameter study at a model system and using finite difference calculations. The main influence is found to be the ratio of wavelength and defect size. Measurements employing shorter wavelength Rayleigh waves show the predicted good detectability of a small quarter-elliptical fatigue crack.

INTRODUCTION

Guided waves have been successfully employed for the nondestructive testing of a variety of structures [1, 2]. From a single, fixed position of the excitation transducer, a large area can be tested, as the guided wave propagates along the structure and not only through the thickness, as in classical ultrasonic testing (UT). This allows for the rapid inspection of large areas and can be used for the constant monitoring of structures by permanently attached sensors [3]. The practical applicability of guided wave testing for a variety of aircraft components, e.g., helicopter blades, was shown [4], possibly leading to a significant reduction of inspection time and costs. However, the wavelength of the employed guided waves is usually significantly larger than in classical UT, and therefore the interaction of the wave with defects must be studied and the detectability of small defects ascertained.

In cooperation with the fatigue engineering center of RUAG Aerospace (Emmen, Switzerland), the online monitoring of fatigue crack growth was studied [5]. Tensile specimens with a fastener hole were subjected to cyclic tensile loading in a servo-hydraulic testing machine, resulting in fatigue crack initiation and growth at the hole. Exciting the first antisymmetric Lamb wave mode A₀ by means of a piezoelectric transducer, a flexural wave was generated that propagated along the specimen and was scattered at the fastener hole.
The development of a defect changed the scattered field and could thus be detected by monitoring the amplitude of the guided wave at a point close to the hole using a heterodyne laser interferometer. The propagation and scattering characteristics can be described analytically using Mindlin's theory of plates [6, 7], and numerically employing a finite difference scheme [5]. Good correlation between the measured changes and the numerical predictions was found (Fig. 1), allowing an accurate online sizing of the crack length. However, as can be seen in Fig. 1, the measured amplitude changes for small crack lengths are not much larger than the variation of the measurement, making a detection of crack initiation and very short cracks difficult.

This paper presents a study of the detectability of small defects at a fastener hole using a model system and numerical calculations, allowing good control of the different geometrical parameters. The scattering of a flexural wave at a through hole with a notch in a large aluminum plate is studied and the influence of the different parameters investigated. The main influence on the change of the scattered field is found to be the ratio between defect size and wavelength. Therefore a better detection of small defects by using higher frequency excitation, corresponding to shorter wavelengths of the guided wave, is expected. Employing Rayleigh waves with a significantly shorter wavelength, a small quarter-elliptical crack at the side of the fastener hole can be well detected, a significant improvement to previous measurements.

EXPERIMENTAL SETUP

Two types of specimen and modifications of the setup shown in Fig. 2 and further described in Ref. [8] were used. For the detectability study a 1 mm thick aluminum alloy plate with a size of 1 m by 1 m was employed, allowing good control over the geometrical parameters. One hole with a radius of 10 mm was drilled through the plate. Then a notch through the thickness was cut into the plate with a very fine saw blade, resulting in a notch about 0.2 mm wide with a blunt tip. Notches of different length and at different angles relative to the propagation direction of the incident wave were studied. The excitation transducer was a piezoelectric disc (Pz 27) with 10 mm diameter and 1 mm thickness, glued to the plate using two-component epoxy glue.
The tensile specimen used in the fatigue testing was a 3.17 mm thick, 40 mm wide, and 500 mm long tensile specimen, made of Al-7075 PL-T3. A fatigue grown crack at the side of the hole (radius 3.25 mm) was generated by cyclic tensile loading in a servo-hydraulic testing machine. A piezoelectric plate (Pz 27, 40 mm by 8 mm large, 1 mm thick), polarized for thickness extension mode, was glued to the specimen at 50 mm distance from the hole, using a two-component epoxy glue. Voltage proportional to the desired waveform was applied to the piezoelectric transducer. The piezoceramic contracted and expanded, generating a vertical force to the plate surface and exciting primarily the first antisymmetric mode $A_0$, as the applied stress was also antisymmetric. This simple approach was feasible working well below the cutoff frequencies of the higher wave modes, as the mode shape of the other excitable Lamb wave mode $S_0$ has only a very small out-of-plane displacement.

The excitation signal consisted of a narrowband tone burst, containing 5 sine cycles multiplied by a Hanning window. Center frequencies $f_0$ of up to 160 kHz were used, resulting in wavelengths of about 10 mm to 30 mm. The incident wave is scattered at the stress-free boundaries of the hole and the defect, generating a scattered wave. In the vicinity of the hole only a single pulse was visible, as incident and scattered wave overlapped in time. The motion of a spot close to the hole was measured using a commercially available heterodyne laser interferometer. For the measurement of the scattered field around the hole, the laser interferometer was fastened to a positioning system and moved on a radial grid (see [9]). The demodulator output was a voltage signal proportional to the velocity of the out-of-plane component of the displacement. The signal was bandpass filtered and averaged over 25 measurements in a digital storage oscilloscope. For each measurement, a time series with 10'000 values was stored. A time windowing was applied to cut off reflections from the specimen boundaries. Fast Fourier transform (FFT) was applied and the amplitude values at the center frequency $f_0$ are extracted.

For the measurements with a higher frequency guided wave, standard ultrasonic equipment was used for the pulse excitation, while the measurement was performed as described above. A standard piezoelectric transducer with a center frequency of 2.25 MHz (Panametrics A408S) was driven by a pulse generator (Panametrics 5800). Employing an angled wedge (Panametrics ABWSL-3039), the correct ratio between in-plane and out-of-plane displacement for the selective excitation of only the Rayleigh was achieved. The wedge was clamped to the 3.17 mm thick tensile specimen and a liquid couplant applied between transducer and wedge, and wedge and specimen (Fig. 8).
MEASUREMENT OF THE SCATTERED FIELD

The plate specimen allowed good control over the experimental parameters. Different geometries with combinations of plate thickness \( h \), hole radius \( r \), wavelength \( \lambda \), defect length \( a \), and angle \( \alpha \) between defect and propagation direction of the incident wave were measured (Fig. 3). Nondimensionalizing, one of the length parameters can be eliminated for the comparison between measurements and the numerical calculations. The scattered field for a circular hole without and with a through notch at the side of the hole was calculated using the finite difference method (FDM) described in Ref. [5].

FIGURE 3. Schematic view of the geometrical parameters for the scattering of a guided wave by a circular hole with a defect; wavelength \( \lambda \), plate thickness \( h \), hole radius \( r \), defect length \( a \), angle \( \alpha \) between defect and propagation direction of incident wave.

FIGURE 4. Measurement and FDM calculation of amplitude (normalized \( U_j = 1 \)) on circle with \( r_M = 11 \text{ mm} \); \( h = 1 \text{ mm}, r = 10 \text{ mm}, \alpha = 315^\circ \), measured: no defect (dashed), \( a = 2 \text{ mm} \) notch (solid); FDM calculation: no defect (dotted), \( a = 2 \text{ mm} \) notch (dash-dotted); a) \( f_0 = 20 \text{ kHz}, \lambda = 22 \text{ mm} \); b) \( f_0 = 50 \text{ kHz}, \lambda = 14 \text{ mm} \); c) \( f_0 = 100 \text{ kHz}, \lambda = 10 \text{ mm} \).
The comparison is shown for one case in Fig. 4, with a 2 mm long through notch at an angle of 45° relative to the wave propagation direction. Good agreement is visible for the measured and calculated amplitudes on a circle (radius $r_M = 11$ mm) around the hole (radius $r = 10$ mm). For increasing excitation frequency, corresponding to shorter wavelength, an increasing influence of the defect on the scattered field is observed, which is modeled well in the calculations. Further measurements for a variation of all geometrical parameters showed a good agreement between measurements and calculations, allowing relying on the FDM calculations for a study of the defect detectability [10].

DEFECT DETECTABILITY

The study on the detectability was performed for a through notch at an angle of 90° to the wave propagation direction, being of relevance for the fatigue crack monitoring. The maximum change in complex magnitude was calculated for a variation of all geometric ratios [10]. The main influence on the scattered field was found to be the ratio of wavelength to defect size, displayed in Fig. 5. Calculations were made for varying excitation frequencies (wavelengths) at a hole with notches of different lengths, and for varying defect size at a different hole geometry for a fixed excitation frequency. The normalized maximum change in complex magnitude depends linearly on the ratio between defect size and wavelength, up to a value of about 0.2. For even shorter wavelength compared to the defect, a variation between the different geometries, but no significant increase in the influence of the defect on the scattered field is visible.

**FIGURE 5.** FDM calculation of maximum complex change in magnitude due to notch at $\alpha = 90^\circ$ versus relation from notch length $a$ to wavelength $\lambda$; $h = 1$ mm, $r = 10$ mm, $f = [20 \ 1000]$ kHz, $\lambda = [22 \ 2.3]$ mm: $a = 2$ mm (dotted, circles), $a = 1$ mm (dash-dotted, diamonds), $a = 0.5$ mm (solid, squares); $h = 1$ mm, $r = 1$ mm, $f = 1$ MHz, $\lambda = 2.3$ mm, $a = [0.25 \ 2]$ mm (dotted, diamonds).
FIGURE 6. Dispersion diagram for an aluminum plate; frequency-thickness operation points for the monitoring measurement and the Rayleigh wave measurement marked.

MEASUREMENT USING RAYLEIGH WAVES

The results from the study above show that a significant improvement on the detection of small fatigue cracks can only be expected for higher frequency excitation, resulting in a shorter wavelength. Shown in Fig. 6 is the dispersion diagram for an aluminum plate, with the previous measurements marked as ‘Monitoring’. Significantly increasing the excitation frequency leads into a frequency-thickness region where not only the two first Lamb wave modes $A_0$ and $S_0$ have rather similar mode shapes, but which is also above the cutoff frequencies of the higher Lamb wave modes. Therefore the use of the simple piezoelectric transducer elements, as described above, cannot achieve the selective excitation of the $A_0$ mode, as the other modes also have a large out-of-plane component [3]. It was therefore decided to move even further up in the frequency-thickness spectrum (marked as ‘Rayleigh wave’ in Fig. 6) and employ commercially available wedge transducers with a center frequency of 2.25 MHz for the selective excitation of the Rayleigh wave. The resulting wavelength of 1.3 mm is small compared to the thickness of the tensile specimen ($h = 3.17$ mm).

The scattered field was measured using the heterodyne laser interferometer, as described above. A Cartesian grid with a step size of 0.1 mm in both directions and a sampling frequency of 100 MHz were used. The amplitude of the high-frequency wave was significantly smaller than in the previous measurements, leading to a larger variation visible as graininess in Fig. 8. The amplitude measurement was done at a tensile specimen with a small quarter-elliptical crack of about 2.25 mm length at one side of the fastener hole, and is shown in a grayscale.
For the undamaged left side of the hole, an undisturbed scattering pattern of semi-circles with high and low amplitude can be seen in Fig. 8. On the right side with the partial fatigue crack this pattern is clearly disrupted. Most of the energy of the incident wave is backscattered, leading to a complicated pattern of high and low amplitude above the crack. Below the crack only very low amplitude is visible, the so-called shadow area. From this measurement the short fatigue crack can be clearly detected. The change in amplitude is almost 100% of the amplitude of the incident wave, a significant improvement on the previous measurements at the lower excitation frequency of 160 kHz. Visible in Fig. 1 is a variation in amplitude of only about 20% for the same length of a fatigue crack.

For further monitoring measurements a recommendation for the measurement spot can be made. In contrast to the previous monitoring measurements [5], the amplitude should be monitored at a spot behind the expected location of the fatigue crack. The measurement of a significant reduction in amplitude there will clearly indicate the initiation of a crack, as the shadow area is rather larger and shows a uniform amplitude reduction. Measuring above the crack, a strong local variation in the amplitude due to the complicated scattered field and short wavelength is visible. This could lead to errors in the measurement for a slight sliding of the specimen relative to the laser interferometer during the tensile testing, experienced in previous measurements.

**FIGURE 7.** Photo of the wedge transducer clamped at the tensile specimen.

**FIGURE 8.** Measured amplitude (normalized) of the scattered field by a hole \((r = 3.25 \text{ mm}, h = 3.17 \text{ mm})\) with a quarter-elliptical fatigue crack \((a = 2.56 \text{ mm}, c = 2.20 \text{ mm})\), \(f_0 = 2.25 \text{ MHz}, \lambda = 1.3 \text{ mm}\).
CONCLUSIONS

The influence of a defect on the scattered field of a guided wave by a through hole in an aluminum plate was studied. Exciting the first antisymmetric Lamb wave mode A0 by means of a piezoelectric transducer, the scattered field without and with a defect was measured very accurately employing a laser interferometer. Good agreement with finite difference calculations was found, and the detectability of small defects studied numerically. The main influence on the scattered field was found to be the ratio between defect size and wavelength. Therefore high excitation frequencies, corresponding to short wavelengths should be employed for the early detection of fatigue cracks at fastener hole. For a tensile specimen the good detectability using a Rayleigh wave transducer was shown for a small partial fatigue crack, which was at the detection limit in previous measurements.

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