Detection of Radial Bolt-Hole Cracks Using Sampled CW Ultrasonic Doppler-Shift Techniques

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Abstract
Recently there has been considerable interest in detecting radial cracks under fasteners in the wings of C-5A aircraft. Generally, detection is accomplished using the pulse-echo method, reflections from cracks being detected in real time. In the present study, cracks are detected by observing the Doppler-shifted frequency. A sample having a radial crack is mounted on a rotating platform in a water bath. A focused transducer transmits a tone burst such that only the shear mode propagates tangential to the hole in the metal. This transducer receives a Doppler-shifted reflected signal whenever a moving crack is in the field of view of the incident beam. The received signal is heterodyned, filtered, and displayed on a low-frequency spectrum analyzer. Merits and limitations of the technique are discussed.

Keywords
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DETECTION OF RADIAL BOLT-HOLE CRACKS USING SAMPLED CW ULTRASONIC DOPPLER-SHIFT TECHNIQUES*

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ABSTRACT

Recently there has been considerable interest in detecting radial cracks under fasteners in the wings of C-5A aircraft. Generally, detection is accomplished using the pulse-echo method, reflections from cracks being detected in real time. In the present study, cracks are detected by observing the Doppler-shifted frequency. A sample having a radial crack is mounted on a rotating platform in a water bath. A focused transducer transmits a tone burst such that only shear mode propagates tangential to the hole in the metal. This transducer receives a Doppler-shifted reflected signal whenever a moving crack is in the field of view of the incident beam. The received signal is heterodyned, filtered, and displayed on a low-frequency spectrum analyzer. Merits and limitations of the technique are discussed.

Several ultrasonic techniques1 have been used to detect and measure the size of cracks—scattered wave amplitude methods, bulk-wave timing methods, and spectroscopic analysis. This paper deals with the use of a Doppler-shift technique to detect and measure the size of radial bolt-hole cracks. The Doppler effect refers to the change in frequency of an ultrasonic wave reflected from a crack that is moving relative to the incident ultrasonic beam. The technique is outlined schematically in Fig. 1 which shows the ultrasonic beam intersecting a flaw as the sample is rotated. It should be noted that (1) the spectral width of the reflected wave is due to the radial distribution of velocity along the crack, and (2) the crack is only in a position to reflect the incident wave for a short time during the rotation of the sample (Fig. 2). The Doppler shift $f_D$ due to the rotating crack is given by

$$ f_D = \frac{4\pi v}{c} f_0 \sin i $$

(1)

and the total broadening of the Doppler peak by

$$ \Delta f = \frac{\sqrt{2} f_0}{r} + \frac{2\pi^2}{T \cos^2 \frac{\pi}{\gamma}} $$

(2)

where $r$ is the radius of the hole, $a$ is the crack size, $T$ is the period of rotation, $f_0$ is the frequency of the ultrasonic beam, and $i$ is the angle of incidence. The first term in Eq. (2) is due to the aforementioned velocity distribution, and the second term is an instrumental broadening due to the short reflection time.

The experimental setup is shown schematically in Fig. 3. A focused transducer transmits a 35-μsec-long tone burst of 11.65 MHz at a repetition rate of 10 kHz. The transducer is placed such that only shear waves are transmitted tangential to the bolt hole in the sample. The received signal is heterodyned with the incident and then fed to a low-pass filter, the output of which—the Doppler shift—is displayed on a spectrum analyzer.

In the present study, Doppler-shifted data were taken on various Al 6061-T6 disks containing different size EDM notches or real cracks. Figure 4 shows a typical plot of amplitude vs frequency. The Doppler shift has a sine dependence upon angle of incidence (Fig. 5) and is linearly dependent upon both reference frequency (Fig. 6) and the angular velocity of the notch (Fig. 7). The analysis of the broadening of the Doppler peak yielded values of $0.044 \pm 0.006 \text{ in.}$, $0.054 \pm 0.011 \text{ in.}$, and $0.078 \pm 0.012 \text{ in.}$ for $0.040$-, $0.600$-, and $0.800$-in. EDM notches, respectively. From analysis of the data on the EDM notches of known radial depth, it seems that the radial sizes of these notches can be estimated to within 20%. Data taken on radial fatigue cracks at the bolt holes in rectangular plates are shown in Fig. 8. Analysis of the broadening of the Doppler peak for one of these samples yielded a radial-crack size of $0.117 \pm 0.012 \text{ in.}$ Examination of the sample under an optical microscope (Fig. 9) revealed the actual size of the crack to be $0.106 \text{ in.}$

There is a close agreement between the predicted and measured size of the cracks at the bolt holes. It has been demonstrated that Doppler-shift techniques are useful for detecting and sizing the radial cracks. The method is free from the uncertainties in the amplitudes of reflected waves from cracks. However, because of the small Doppler shift, the sampling time is large and the method is, at present, relatively slow. The adjustment of the direction of the incident beam is quite important for avoiding spurious peaks due to eccentricity.

REFERENCES

Fig. 1 Amplitude of the backscattered ultrasonic wave vs time. Crack is in view only for a fraction of the period of rotation of the disk. During this time the crack rotates 2π radians.

Fig. 2 (a) Detailed geometry of the ultrasonic beam and the rotating crack. (b) Top view of the disk and ultrasonic beam.

Fig. 3 Experimental setup for the Doppler-shift studies of radial cracks.

Fig. 4 Doppler-shift frequency f₀ vs angle of incidence. Note the sine dependence of f₀ upon the angle of incidence.
Fig. 5 Doppler-shift frequency $f_D$ vs frequency $f_0$ of the incident beam. Note the linear dependence of $f_D$ upon $f_0$.

Fig. 6 Doppler-shift frequency $f_D$ vs angular speed of the crack. Note the linear dependence of $f_D$ upon angular speed of the crack.

Fig. 7 Amplitude of the backscattered beam from the rotating radial EDM notch vs the Doppler-shift frequency $f_D$. The broadening of the Doppler peak is related to the radial size of the EDM notch. The spikes are due to the sampling. Only one spike appears per revolution.

Fig. 8 Amplitude of the backscattered wave from the rotating radial fatigue crack vs the Doppler-shift frequency $f_D$. Note the close agreement between the experimental and theoretical crack sizes.

Fig. 9 Optical micrograph of the fatigue crack used to obtain the Doppler data in Fig. 8. The hole is the darkest area at the lower left-hand corner, with the fatigue crack running diagonally across the micrograph.