SURFACE FLAW CHARACTERIZATION USING ULTRASONIC BACKSCATTERED SATELLITE PULSE TECHNIQUE

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INTRODUCTION

Conventionally, part lives of aircraft engine components are determined by empirical and statistical analyses based on fracture mechanics or fatigue crack propagation. Advanced engine design for energy efficiency and improved performance have dictated stringent quality control of components. Small flaws can be critical to the flight safety and service life of those components. It is thus extremely important to characterize the flaw and monitor its growth for better part life management. Eddy current and fluorescent penetrant nondestructive evaluation (NDE) techniques are limited to the detection and sizing of surface cracks. Ultrasonic methods are most commonly used for detection and characterization of subsurface defects; however, some newly developed ultrasonic techniques are gaining popularity for surface flaw detection and sizing.

Ultrasonic forward scattering, backward scattering, and satellite pulse observation techniques have been reported as promising NDE techniques for flaw detection and evaluation by many authors. In this paper, we explore the potential to combine the ultrasonic direct backscattering and satellite pulse technique to characterize flaw depth of surface cracks. The delay time between the main pulse and the satellite pulses of the EDM notches studied is found to be a function of incident angle and linearly proportional to the flaw depth. The ultrasonic wave velocities calculated from the time delay suggests that an interface wave was propagating along the surface of the crack.

BACKGROUND

Backscattering of an ultrasonic wave incident at the Rayleigh angle to a liquid-solid interface was originally reported by Sasaki. The term satellite pulse is introduced by Gruber as the additional pulse accompanied the main flaw signal observed. In this context, the term satellite pulses are more generally defined as all the successive pulses associated with the flaw.

The fundamentals of the direct backscattered satellite pulse technique are similar to that of the satellite pulse observation technique and can
be described by the acoustic ray theory. The operating principle of the satellite pulse technique is to measure the delay time between two or more successive pulses associated with the flaw in the time domain. In the frequency domain presentation, we measure the difference in frequencies of the resonance pattern. In general, the main pulse is generated from the specular reflection or diffraction of the flaw, in which the main pulse has the shortest wave travel path. The satellite pulses are generated by diffracted waves or various waves such as shear wave and Rayleigh wave insonificated from the interaction of the incident wave with the flaw at critical angles.

For spherical and cylindrical types of volumetric defects, the delay time between the main and satellite pulses is found to be

$$\Delta t = \left( \frac{\pi}{2V_R+1/V_S} \right) d$$  \hspace{1cm} (1)

where $d$ is the diameter of the flaw, $V_R$ and $V_S$ are the Rayleigh and shear wave velocity of the material respectively. For the planar defects, the delay time is found to be

$$\Delta t = 2d/V \sin \theta$$  \hspace{1cm} (2)

where $d$ is the crack length, $V$ is the wave velocity of the operating mode and $\theta$ is the incident angle to the flaw.

Based on equation (1) and equation (2), it can be summarized that the delay time $\Delta t$ is linearly proportional to the defect dimension $d$. The relationship can be expressed as

$$\Delta t = 1/K \cdot d$$  \hspace{1cm} (3)

where $K$ is the linear combination of wave velocities propagated in the material and flaw. Equation (3) can also be applied to the study of characterizing surface flaws using the direct backscattered satellite pulse technique. In this case, $K$ is found to be the wave velocity of an interface wave propagating along the water-flaw interface for this study.

**EXPERIMENTS**

The experimental arrangement is shown in Figure 1. A broadband longitudinal ultrasonic pulse was transmitted and received by a Panametrics 5052PR Pulser/Receiver instrument. The return signal was gated, peak detected and displayed on a Tektronix 7D20/R7603 Digital Oscilloscope with cursor time measurements. The stepless time gate delay was adjusted to correspond to the round trip travel time of the pulse from the water immersed transducer to the surface of the specimen. The gate width was adjusted to the width of the first echo from the surface of the specimen. The waveform of the signal was sampled, digitized and analyzed with a Tektronix 4052A desktop computer. The transducer was a 10 MHz broadband Harrisonic I-3 immersion transducer with a 3" focal length. The angle of incidence was varied incrementally from 0° to 40° with a J. B. Engineering BM-120A bottom manipulator.

The sample used in the experiments was a Ti 6Al-2Sn-4Zr-6Mo plate having four sets of 0.005" wide EDM notches with depths of 0.005", 0.010", 0.015", 0.025", and 0.050". These EDM notches in a given set had a particular length to depth ratio ranging from one to four integrally. This
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IV. RESULTS AND DISCUSSIONS

A typical time domain ultrasonic direct back-scattered satellite pulse flaw signal is shown in Figure 3 for the 0.025"x1.000" EDM flaw. Note the occurrence of a delayed satellite pulse signal in pair with the
main pulse signal from specular refraction of the flaw at the surface. The time domain signal obtained from the rest of the flaws displayed the similar feature as shown in Figure 3. It is observed that the delay time increases as the flaw depth increases. The measured delay time versus flaw depth for length/depth = 1 and the linear curve fitting is shown in Figure 4. The other sets of flaws also show the linear relationship between delay time and flaw depth.

![Figure 3](image_url)

Figure 3.—A Typical Example of Time Domain Flaw Signal (Depth = 0.025" and Length = 1.000").

The angular dependence of the back-scattered acoustic signal is in general similar to that of Figure 3 except the delay time increases as the angle of incidence increases up to 20° and then remains unchanged with increasing angle of incidence. An example of this phenomenon is shown in Figure 5 for the 0.005"x1.000" flaw. The ultrasonic wave velocity can be obtained either from the inverse slope from Figure 4 or by using the following equation

\[ V = \frac{2d}{\Delta t} \]  

(4)

where \( d \) is the depth and \( \Delta t \) is the measured delay time between the main pulse and satellite pulse signal. The velocities calculated based on Equation (4) are 1.35x10^5 cm/sec, 1.40x10^5 cm/sec, 1.50x10^5 cm/sec, 1.61x10^5 cm/sec, and 1.80x10^5 cm/sec for length to depth ratio of 1 to 4 and the set of length = 1.000" respectively. These wave velocities are compared to 6.10x10^5 cm/sec longitudinal wave velocity, 3.12x10^5 cm/sec shear velocity, 2.79x10^5 cm/sec Rayleigh wave velocity of titanium and 1.49x10^5 cm/sec longitudinal wave velocity of water. It is suggested that the wave was propagating with an interface (Scholte or Stonley waves) velocity along the flaw. The wave velocity versus length/depth ratio is shown in Figure 6. The functional dependence of wave velocity and length to depth ratio is believed due to the size of focal beamwidth which is calculated to be 0.040" in diameter.

The time domain signals were also Fourier transformed for spectral
analysis. An example of frequency domain presentation of the satellite pulse technique is shown in Figure 7 for the 0.005"x1.000" flaw. The spectrum has an envelope that peaked at 10 MHz which corresponds to the transducer frequency. There also was a resonance pattern displayed in the spectrum which corresponds to the depth of the flaw. The resonant frequency \( \Delta f \) (\( = 1/\Delta t \)) decreases as the depth of the flaw increases. We have to point out that although it may be difficult to define the leading edge of the time domain signal for shallower flaws, it is easily measured in frequency domain.
At high angle of incidence, it is observed that a train of satellite pulses generated was from the longitudinal, shear and Rayleigh critical angles as shown in Figure 8 for the 0.005"x1.000" at 40° angle of incidence. It may also be used to determine defect parameters. The ultrasonic signal amplitude versus angle of incidence for the 0.005"x1.000" flaw is shown in Figure 9. There is also a functional dependence between flaw length and signal amplitude. It has shown that an oblique angle of incidence can be chosen to maximize the main and satellite pulse flaw signals and eliminate the surface effects. The results of the analysis of the amplitude data have been reported by the author previously.

In summary, we have demonstrated the capability of characterizing surface flaws using the ultrasonic direct back-scattered satellite pulse
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Figure 8.- An Example of Multiple Satellite Pulse Observed at 40° Angle of Incidence for the EDM Flaw of 0.025" in Depth

Figure 9.- Ultrasonic Backscattered Peak Amplitude of Surface, Main Pulse and Satellite Pulse as a Function of Angle of Incidence

technique. There is also the advantage of eliminating the dead zone of the inspection envelope by using oblique angle direct back-scattered satellite pulse method. Since the single transducer system used in these experiments can also serve in conventional subsurface flaw detection and characterization, one has the potential capability to perform both surface as well as subsurface flaw inspection in one practical ultrasonic NDE inspection system.
REFERENCES


DISCUSSION

G.J. Gruber (Southwest Research Institute): Did you try to do shear wave?

E.J. Chern: This is longitudinal only. I call it the direct back-scattered.

G.J. Gruber: You varied the angle?

E.J. Chern: That's right. 0° to 40°.

G.J. Gruber: Can you produce shear waves also in titanium?

E.J. Chern: I only measured the direct back-scattered signals, I didn't really identify what kind of wave propagated in the material at which critical angles. I positioned the time gate between the transducer initiation and the reflected signal. I don't really care what kind of waves propagate in the material.

G.J. Gruber: But if it is a shear wave, you could double your resolution because from the same crack depth you can get twice the delay time?

E.J. Chern: Yes, I mentioned that in my presentation. There are more shear waves created than Rayleigh waves due to the wide angle range of the focal transducer. I am only starting with direct back-scattered signals at this point, and measuring only the delay time of pulses to calculate defect parameters.
G.J. Posakony (Battelle Northwest Labs): Do you consider the phase influence?

E.J. Chern: There is definitely a phase change, but I have not looked at the phase signal yet. Right now in our business, we are more interested in getting the length and depth information by the simplest method. If we showed we can obtain the information from the time signal, that's sufficient. In the inspection of aircraft engine parts, for the normal incidence inspection, there will be a dead zone within the signal of the surface. This technique is intended to provide a method to eliminate this dead zone of the longitudinal inspection. I am sure there are a lot more parameters we can try and determine more information.

J.H. Pratti (Teledyne CAE): Have you tried this on any real flaws?

E.J. Chern: Yes, sir. We are doing it right now. We can definitely see a delay in time, a measurable delay time with the deep cracks, but the problem right now is not the measurement. We are doing it in a systematic manner. We are trying to correlate the measurements with flaw length and depth. It's not an easy task.

G.J. Posakony: Did you try deconvolution to help you in reading the time delays?

E.J. Chern: Not yet.

G.J. Posakony: You might try that.

E.J. Chern: Thank you.