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Interaction of Rayleigh Waves Induced by Interdigital Transducer with Fatigue Crack

Jeong K. NA [1], Samuel KUHR [1], and James L. BLACKSHIRE [2]

[1]University of Dayton Research Institute
300 College Park, Dayton, Ohio 45469-0127, USA
Tel: 1-937-904-4689, Fax: 1-937-255-9804, e-mail: jeong.na@sbcglobal.net
[2]Air Force Research Lab (AFRL/RXLP)
Wright-Patterson AFB, Ohio 45433, USA

Abstract

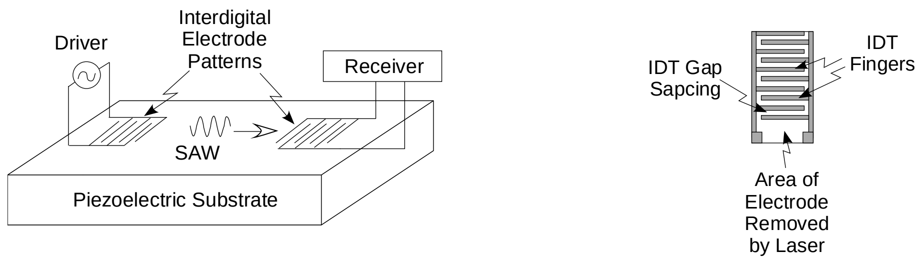
Compared to bulk waves, Rayleigh waves can propagate much longer distances with lower signal attenuation levels, which are nominally proportional to $1/\sqrt{r}$ for a given frequency (r=distance). In addition to the small attenuation, Rayleigh waves are also non-dispersive and sensitive to surface-breaking defects. The surface penetration depth of Rayleigh waves is also approximately one wavelength, which can be beneficial for many NDT applications. However, one major drawback of using Rayleigh waves for nondestructive testing has been the difficulty of generating Rayleigh waves, where the most commonly used method involves the combination of a plastic wedge and a conventional longitudinal mode transducer. Unfortunately, a number of wedges with different angles are needed to generate Rayleigh waves in different materials or at different operating frequencies to satisfy the critical Rayleigh launch angle requirement. In this study, instead of using wedge transducers, we have designed, fabricated, and tested narrow-band Interdigital Transducers (IDTs), where precision electrode patterns were etched on piezoelectric ceramic substrate materials using micro laser machining techniques. These IDTs can be directly applied to the surface of test specimens to generate Rayleigh waves in MHz range. A laser interferometry system was used to characterize the IDT sensors, where a well-defined and directional Gaussian beam profile was observed. Investigations were also made for Rayleigh waves interacting with fatigue cracks in aircraft qualified metallic alloys. It was observed that some of the Rayleigh wave energy can propagate through a tight crack at both normal and oblique incidence.

Keywords: Rayleigh waves, Interdigital transducers (IDTs), Laser interferometry system

1. Introduction

The advantages of using Rayleigh surface waves for nondestructive testing over other types of wave are considered to be their high sensitivity to surface flaws and a longer propagation distance. There are many different ways of generating Rayleigh waves[1]. The most common method is using a wedge device that is made of plastic material. A longitudinal mode transducer launches a compressional wave into the plastic wedge having a critical angle, θ_R, at which the energy converts into a Rayleigh surface wave which propagates with an elliptical particle motion. For different types of test material, the launch angle varies at a given operating frequency. Therefore, it is necessary to have multiple wedges having different launch angles.

In this work, we have developed a standalone, single-element Rayleigh wave transducer that requires no secondary device such as wedges or combs to generate Rayleigh waves. The basic concept is based on the interdigital electrode patterning on a piezoelectric substrate. This type of interdigital transduction method has been used in designing surface acoustic wave (SAW) filters and signal processing devices for communication industry[2-4]. In communication SAW devices, Rayleigh waves propagate through the piezoelectric substrates from one end to another as illustrated in Figure 1(a). Unlike communication SAW devices, we have shaped electrode patterns directly on the piezoelectric plates that are typically used as piezoelectric elements for bulk wave transducers. A schematic drawing of a simple IDT design is shown in Figure 1(b). The resonance frequency is determined by the widths of finger and gap spacing and the Rayleigh wave velocity of the sensor material[5]. The physical dimensions of the sensor are 3 mm x 7 mm with thickness of 0.18 mm.



(a) Interdigital SAW Device (b) Standalone single-element IDT

Figure 1. Difference between the SAW device and the standalone interdigital transducer (IDT).

2. Experiment

2.1 Characterization of IDT

Prior to the investigation for the interaction of Rayleigh waves with fatigue cracks, we have characterized fundamental wave properties of the ultrasound fields generated from the sensor by using a laser interferometry scanning system[6,7]. A block diagram of the setup is shown in Figure 2. The laser head is attached to a two dimensional raster scanner which is mounted on an optical table. The metal plate, on which the IDT is bonded, was kept stationary throughout the test. The surface of metal plate was prepared to have a mirror finish for a good reflection of the laser beam.

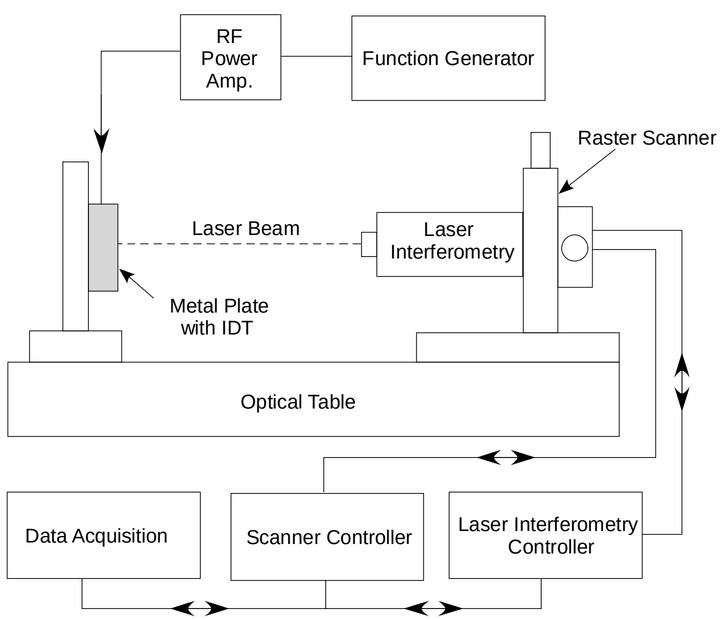


Figure 2. Block diagram of the laser interferometry scanning setup used to characterize IDTs.

A 3.1 MHz sinusoidal tone burst signal, 5 cycles, was generated from the function generator and amplified through the power amp to drive the IDT. The out of plane particle displacements were detected by the laser interferometry and recorded in terms of amplitude. An image of Rayleigh waves produced by the IDT on the aluminum plate is shown in Figure 3 where peak-to-peak amplitude is displayed. It is clear that the IDT generates bi-directional beams with a total beam spread of 21^{o}.

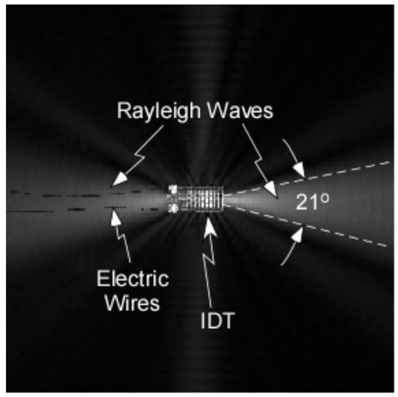


Figure 3. Image of Rayleigh waves generated by IDT on an aluminum plate.

A plot of the frequency response curve for the output signal from the IDT is shown in Figure 4. The laser interferometry was kept stationary at a location 1 cm away from the front tip of the IDT while the driving frequency was changed from 100 KHz to 5 MHz. The resonance frequency was found to be at 3.1 MHz. This is slightly higher than the predicted resonance frequency of 3 MHz. The pass band width, at which 50% of peak amplitude was measured, was 1.1 MHz. Less than 20% of peak amplitude was measured at frequencies below 2 MHz and above 4 MHz.

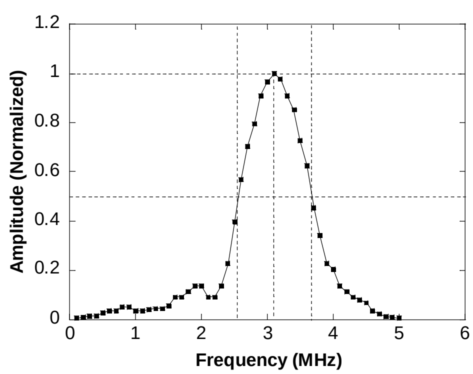


Figure 4. Frequency response of the output signal of the IDT at a distance 1 cm away from the sensor.

At the same distance of 1 cm away from the IDT, the laser beam was scanned across the ultrasound field, perpendicular to the wave propagation direction, to measure the beam profile. The frequency was kept at 3.1 MHz, the resonance frequency of the IDT. A graph in Figure 5 shows the result of the beam profile. The main lobe between ± 5 mm of the transverse distance exhibits a Gaussian shape. No significant side lobes were observed.

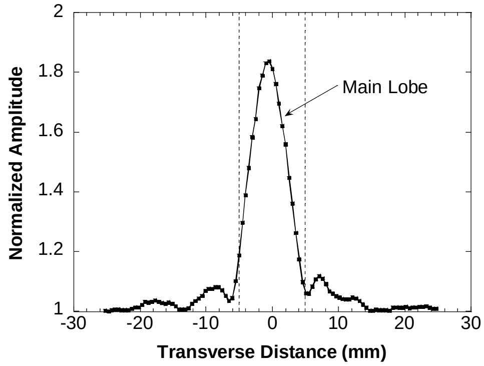


Figure 5. Beam profile at a distance of 1 cm from the IDT.

2.2 Interaction of Rayleigh wave with fatigue crack

The same IDT was used to investigate the interaction of Rayleigh waves with a through the thickness fatigue crack. An aluminum test specimen, that had a fatigue crack induced on an MTS frame, was used. A magnified optical image of the crack is shown in Figure 6.

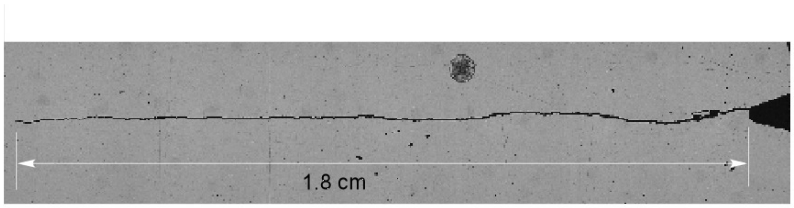


Figure 6. A magnified image of the fatigue crack (image is rotated 90 degrees).

Three different locations were selected to observe the interaction of Rayleigh waves with the fatigue crack. Figure 7 shows the three locations; one normal incidence and ± 30^o launch angles. The sensor locations were chosen to be on a circle whose origin is the tip of the fatigue crack and the diameter of the circle is 11.5 cm. That way the center line of the beam can be assured to pass through the crack tip at the difference launch angles.

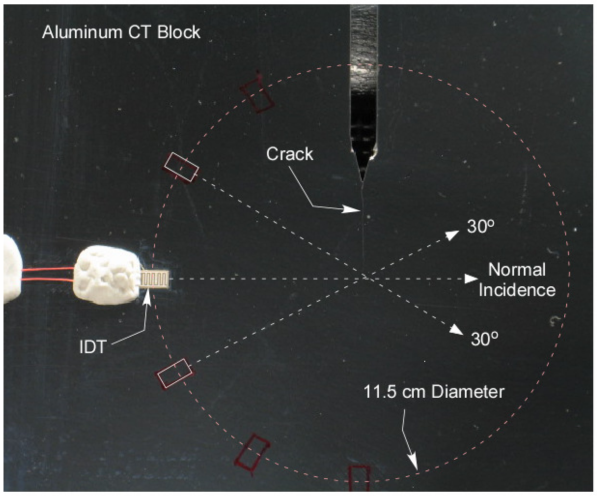
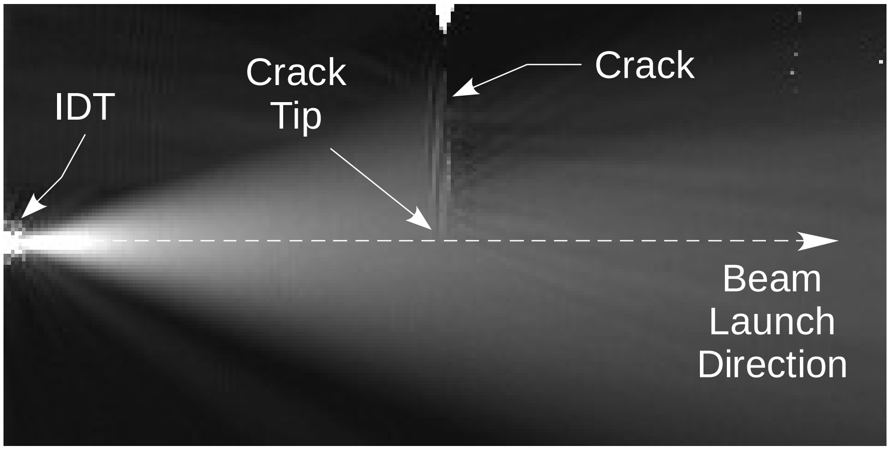
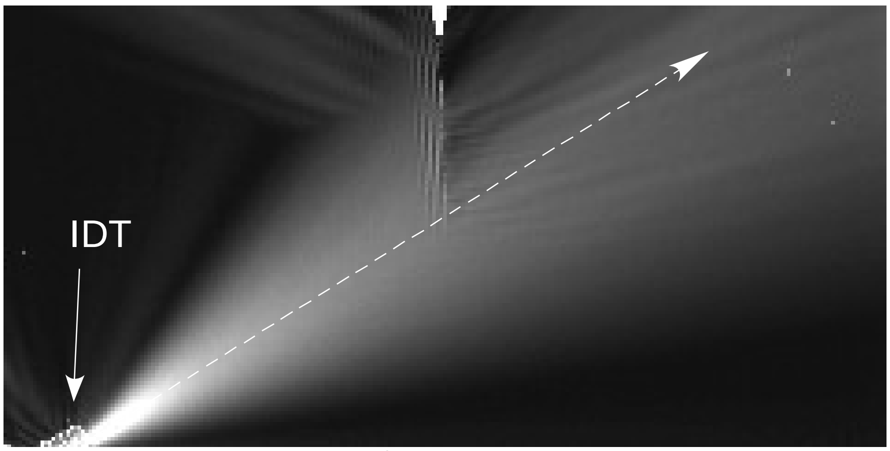


Figure 7. Three different beam launch locations for interaction of Rayleigh wave with fatigue crack.

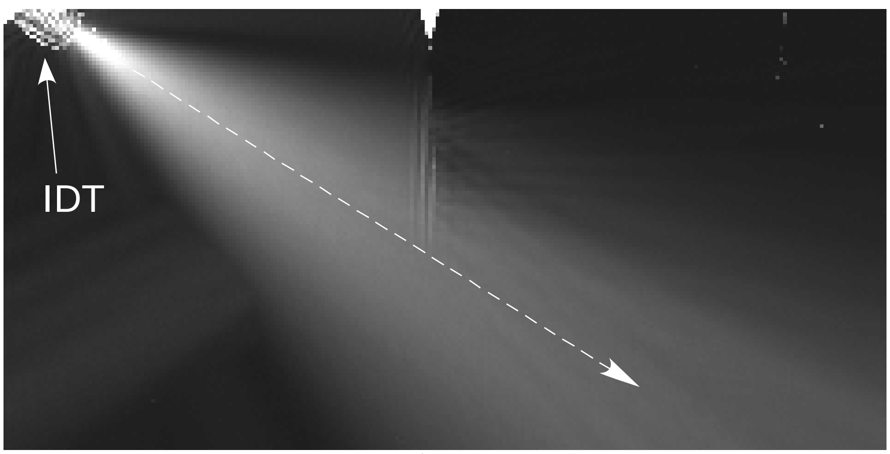
The images of ultrasonic fields interacting with the fatigue crack are shown in Figure 8. For all three launch angles, it clearly shows that part of the Rayleigh wave goes through the fatigue crack. Even though the fatigue crack we had on the aluminum block was a through crack, the images in Figure 8 suggest that there are regions contacting each other inside the crack so that the elastic energy can pass through.



(a) Normal Incidence



(b) 30^{o} count-clockwise



(b) 30^{o} clockwise

Figure 8. Images of ultrasonic fields interacting with a tight fatigue crack at various launch angles with respect to the length of the fatigue crack.

3. Conclusions

A standalone single-element interdigital transducer has been designed, fabricated, and characterized. The electrode pattern was precisely etched off with a laser micro machining technique to form five pairs of fingers having 1 mm width on an ordinary PZT disk (180 μm thick). The beam pattern and beam profile were characterized by using a laser interferometry scanning system. The resonance frequency and pass band width were also measured with the same laser scanning system. It is clear from the symmetrical electrode patterns that the ultrasonic beams launched by the IDT are bi-directional. The beam spread is measured to be $\pm 10.5^{o}$. The measured resonance frequency of 3.1 MHz is very close to the predicted resonance frequency of 3 MHz. The pass band width is found to be 1.1 MHz and the signal output drops sharply at frequencies below 2 MHz and above 4 MHz. The beam profile at the distance of 1 cm from the IDT shows a Gaussian amplitude distribution with small side lobes.

The laser interferometry scanned images also permitted the visualization of the interaction of ultrasonic fields with a tight fatigue crack, where the results suggest that the elastic energy can go through a tight fatigue crack. This means that determining length of cracks with a traditional ultrasonic NDT technique based on either pulse-echo or pitch-catch methods may underestimate the actual crack length due to the possibilities of elastic energy transferring through a crack.

Acknowledgement

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References

[1] I. A. Viktorov, “Rayleigh and Lamb Waves: Physical Theory and Applications”, Plenum, New York, 1967.
[2] R. M. White and F. W. Voltmer, “Direct Piezoelectric Coupling to Surface Elastic Waves”, Applied Physics Letters, Volume 7, Number 12, 1965, pp.314-316.
[3] R. H. Tancrell and R. C. Williamson, “Wavefront Distortion of Acoustic Surface Waves from Apodized Interdigital Transducers”, Applied Physics Letters, Volume 19, Number 11, 1971, pp.456-459.
[4] Melvin G. Holland and Lewis T. Claiborne, “Practical Surface Acoustic Wave Devices”, Proceedings of the IEEE, Volume 62, 1974, pp.582-611.
[5] G. Feuillard, M. Lethiecq, Y. Amazit, D. Certon, C. Miller and F. Patat, “Experimental Determination of the surface acoustic wave properties of new fine grain piezoelectric ceramics”, Journal of Applied Physics, Volume 74, Number 11, 1993, pp.6523-6529.
[6] James L. Blackshire, “Interferometric and holographic imaging of surface wave patterns for characterization of material degradation”, Nondestructive Materials Characterization, Chapter 4, Springer -Verlag, New York, 2004, pp.113-141.
[7] James L. Blackshire and Bradley D. Duncan, “Interferometric and holographic imaging of surface-breaking cracks”, Optical Engineering, Volume 43, Number 6, 2004, pp.1366-1374.