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Aircraft components structural health monitoring using flexible ultrasonic transducer arrays

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ABSTRACT

A damage detection capability based on a flexible ultrasonic transducer (FUT) array bonded onto a planar and a curved surface is presented. The FUT array was fabricated on a 75 μm titanium substrate using sol-gel spray technique. Room temperature curable adhesive is used as the bonding agent and ultrasonic couplant between the transducer and the test article. The bonding agent was successfully tested for aircraft environmental temperatures between $-80\text{ }^{\circ}\text{C}$ and $100\text{ }^{\circ}\text{C}$. For a planar test article, selected FUT arrays were able to detect fasteners damage within a planar distance of 176 mm, when used in the pulse-echo mode. Such results illustrate the effectiveness of the developed FUT transducer as compared to commercial 10MHz ultrasonic transducer (UT). These FUT arrays were further demonstrated on a curved test article. Pulse-echo measurements confirmed the reflected echoes from the specimen. Such measurement was not possible with commercial UTs due to the curved nature of the test article and its accessibility, thus demonstrating the suitability and superiority of the developed flexible ultrasonic transducer capability.

Keywords: Flexible ultrasonic transducer, structural health monitoring, nondestructive testing.

1. INTRODUCTION

For several decades, civil and military aircraft operators around the world have encountered increased maintenance costs due to their aging fleets [1]. As a consequence, they continue to seeking ways to reduce the fleet maintenance cost while meeting airworthiness requirements. Structural health monitoring (SHM) is potentially a cost effective emerging area of technology that could enable condition-based maintenance (CBM) in-lieu of the traditional schedule-based maintenance [2, 3]. In our past research, integrated ultrasonic transducers (IUTs) were used on bare aluminum (Al) plates to demonstrate this capability for crack growth monitoring [4]. This capability demonstration did not address aircraft complex environment, such as accessibility, temperature variation, instrumentation etc. In this presented study, simple and complex test articles (planar and the curved structures) are used to demonstrate some of the challenges that may be encountered while implementing SHM solutions for aircraft as well as the suitability of the use of flexible ultrasonic transducers (FUTs) for such application. These FUT are deemed suitable and of choice due in part to their on-site instrumentation flexibility.

2. EXPERIMENT SETUP

2.1 Test article

A complex aluminum (Al) structural component, representative of aircraft structural complexity, was developed and damaged in the form of artificially induced electrical discharge machining (EDM) notches at selected fastener locations as shown in Figure 1. This component was made available, by Defense Research and Development Canada (DRDC), for the evaluation of FUT in damage detection in complex environment. Several EDM notches were introduced in the 6.35 mm thick Al plate (Fig. 1). Notches 1, 3, and 4 are of 2.54 mm long and notches 2, 5, and 6 are of 1.27 mm long. The FUT array is to be bonded on the planar and curved surfaces, as indicated in Fig. 1. Table 1 summarizes the length of the EDM notches and the distance of the notches to the FUT.

Figure 1. The test article – A complex Al structural component.

Table 1. Distance of notches to FUT array.

Notch	1	2	3	4	5	6
Length (mm)	2.54	1.27	2.54	2.54	1.27	1.27
Distance (mm)	15	48	117	135	158	176

2.2 Instruments and equipments

Before the FUTs were bonded on the planar surface at selected locations, a commercial ultrasonic transducer (UT) Panametrics V129-10MHz-0.125 was used to form a reference so that the measurements taken using the FUTs may be evaluated in terms of performance.

2.3 Radiographic inspection

A radiographic inspection was conducted on the test article in order to confirm the locations of the artificially induced EDM notches. The radiographic films and a zoomed-in view are shown in Fig. 2. During the inspection, the X-ray probe needed to be tilted at various angles in order to detect more EDM notches. In addition, it is noted that only the 2.54 mm long EDM notches were identified using this NDT technique. These results will be compared with the ultrasonic technique described in the following sections.

Figure 2. Radiographic inspection of the test article.

3. FUT ARRAY BONDED ON PLANAR SURFACE

Before bonding the FUT array onto the planar surface, pulse-echo measurements using a commercial UT Panametrics V129-10MHz-0.125 were taken at the same locations of that of the FUT. The FUT pre-fabricated on a 75 μm titanium doubler (Ti) substrate was bonded onto the planar surface, as indicated in Fig. 3, using commercial room temperature curable adhesive. In this investigation, the pulse-echo measurements taken using FUT A and FUT B were compared with the ones using the commercial ultrasonic transducer. The distance from the bonding surface to the EDM notches can be found in Fig. 1.

Table 2 summarizes the distance of the bonded FUT to the EDM notches and their associated expected time delay. The plate acoustic wave (PAW) group velocity of 6234 m/s used for calculation of time delay was obtained by dividing the round trip distance 1020 mm, from the bonded FUT to the opposite edge, by the time difference of the two strongest consecutive echoes reflected from the opposite edge of the structure.

The center frequency of the FUT is 10 MHz. The signals obtained from both the commercial ultrasonic transducer V129 and the FUT using the pulse-echo technique were compared at FUT locations A and B, as shown in Fig. 3. All top electrodes have an identical dimension of 3 mm by 5 mm. The pulser/receiver settings used to obtain signals for both commercial ultrasonic transducer V129 and the FUT were the same.

Figure 3. FUT array bonded on planar surface.

Table 2. Distance of FUT array to notches and expected time delay

Notch	1	2	3	4	5	6
Distance (mm)	15	48	117	135	158	176
Expected Time Delay (μ s)	4.81	15.40	37.54	43.31	50.69	56.46

Figure 4 shows the ultrasonic signals, filtered using a band-pass filter 5- 11 MHz and measured at FUT location A. E_{N2} , E_{N3} , and E_{N6} noted in Fig. 4 may be the echoes from EDM notches 2, 3, and 6, shown in Fig. 3, respectively. The actual time delays of the echoes agree well with the calculated values of Table 2. E_{R1} and E_{R2} are the echoes reflected from fastener R1 and R2, which are 82 mm and 94 mm, respectively, from the FUT bonded edge, shown in Fig. 3. It is observed that the signal-to-noise ratio (SNR) of the measurements using the FUT was generally higher than the ones using the commercial ultrasonic transducer V129. Although the EDM notches and fasteners are not in the normal incidence path of FUT A, these features may still be detected due to the fact that ultrasound beam width increases over distance. However, these damage detections cannot be confirmed without being compared with the baseline signals taken before EDM notches were introduced.

Figure 4. Signals measured using FUT A and commercial 10 MHz UT at the same location.

Another set of measurements was taken at FUT location B, shown in Fig. 5. FUT location B is aligned with EDM notch 1. The unfiltered signals are shown in Fig. 5. E_{N1} represents the echo reflected by EDM notch 1 and E_{R3} the echo reflected by fastener R3, as shown in Fig. 3. It is observed that other obstacles that were detected at FUT location A were not detected at FUT location B. This could have been caused by the blockage of wave energy when reflected by EDM notch 1.

Figure 5. Signals measured using FUT B and commercial 10 MHz UT at the same location.

4. FUT ARRAY BONDED ON CURVED SURFACE

It is noted that the planar surface described in the last section may not be accessible on actual aircraft structures. As a result, another approach involving an accessible surface needed to be considered. In this section, the FUT array was bonded onto the curved surface indicated in Fig. 1 and Fig. 6. Under such condition, it may be extremely difficult to use commercial UTs on these small accessible curved surfaces. Here, damage detection capability of the FUT array bonded on curved surface was investigated. Measurements using conventional UT on this curved surface were not taken as the restricted access of 6 mm does not allow placing a conventional UT. In addition, conventional UTs normally are not as effective on a curved surface.

Figure 6 shows the dimension of the FUT to be used. The centre frequency of the FUT is 10 MHz. As soon as the bonding surfaces were cleaned, two pieces of the FUT shown in Fig. 6 were bonded onto the curved surface using commercial room temperature curable adhesive. The curing time of the adhesive is 24 hours at room temperature. The jig and the elastic thin steel plate shown in Fig. 7 were necessary for spring force application in order to achieve uniform pressure across the curved surface during the curing process. Such room temperature curable adhesive has been successfully tested in the temperature range of -80°C to 100°C , which covers the common aircraft operating temperatures.

Once the adhesive was completely cured, colloidal silver was painted as top electrodes on the piezoelectric film in array configuration using a paper mask shown in Fig. 8. Colloidal silver was used because it is easier to manipulate using a brush. The top electrodes having 1 mm width and 1 mm spacing enabled measurements with greater precision. Fig. 9 shows the FUT array bonded on the curved surface. Each top electrode represents a fully functional UT.

The two pulse-echo measurements, shown in Fig. 10, along with the distances 33.7 mm and 5.1 mm, were used to obtain the time delay caused by the measurement equipments and the PAW group velocity through simple algebraic computations. These FUTs were chosen because the line of sights of these FUTs directly intercepts the fasteners. The clear reflected echoes from the fasteners were observed and the time delay was $1.07\ \mu\text{s}$ and the group velocity was 6335 m/s. These results will be used to detect EDM notch for future study.

Figure 6. Curved surface and FUT.

Figure 7. Jig providing spring force for bonding of the FUT on curved surface.

Figure 8. Mask used for top electrode fabrication of FUT array.

Figure. 9. FUT array bonded on the curved surface.

Fig. 10. Pulse-echo measurements taken using FUT 1 and FUT 6.

5. SUMMARY

In this study, damage detection capability of a flexible ultrasonic transducer (FUT) array bonded onto a planar surface and a curved surface was studied. The previously developed integrated ultrasonic transducer (IUT) was not used in this current study due to its lack of instrumentation flexibility (in-situ application and thermal treatment requirement). The test article used was a complex aluminum (Al) component that is representative of aircraft structural complexity. Several notches of different sizes were introduced in the test article in order to simulate the fatigue crack typically found in this type of structure.

The FUT array, fabricated on 75 μm Ti substrate, was bonded onto a planar surface of the test article using commercial room temperature curable adhesive. Such room temperature curable adhesive has been successfully tested in the temperature range of $-80\text{ }^{\circ}\text{C}$ to $100\text{ }^{\circ}\text{C}$, which covers operating temperatures commonly observed in aircraft environment. The FUTs were able to detect fasteners and several notches of up to a distance of 176 mm with sufficient signal to noise ratio. The pulse-echo measurements obtained using the FUT arrays were compared to those obtained with a commercial 10 MHz ultrasonic transducer (UT). Obtained results showed that the performance of the FUT array was as good as the commercial UT. Nonetheless, this is the ideal scenario as the ultrasound beam is almost at normal angle to the induced damage.

Additionally, another FUT array was bonded onto a curved surface of the same test article using the same adhesive. No measurements using commercial UT was conducted due to article complexity and restricted access. Clear signals were obtained at fasteners locations using the pulse-echo mode.

Both planar surface bonded FUT and curved surface bonded FUT arrays successfully demonstrated their potential in damage detection. In addition, experimental results confirmed the potential of the use of FUT array as an additional capability in aircraft structural health monitoring.

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