GUIDED PLATE ACOUSTIC WAVES TRANSDUCERS FOR STRUCTURAL HEALTH MONITORING

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ABSTRACT

Flexible ultrasonic transducers (FUTs) have been fabricated using a sol-gel spray method. The FUTs consist of 75 \textmu m thick titanium membranes, 135 \textmu m thick lead-zirconate-titanate (PZT) composite films and 10 \textmu m thick silver paste top electrodes. They have been bonded onto metal articles for structural health monitoring and non-destructive evaluation purposes. Two artificial line defects with 1 mm width and depth created on the surface of a 6.35 mm thick aluminum (Al) plate have been successfully detected by such guided wave configurations. In addition, artificial defects perpendicular to the guided plate acoustic wave directions and made on an aircraft representative component were also detected, and the results are confirmed by X-ray techniques. In this investigation the center operation frequencies of the FUTs ranged from 8 MHz to 12 MHz.

\textbf{Keywords:} Structural health monitoring, Non-destructive evaluation, Flexible ultrasonic transducers, Guided plate acoustic waves, Piezoelectric thick films, Sol-gel process.
INTRODUCTION

Civil and military aircraft operators around the world have incurred rising maintenance costs due to their aging fleets. They are seeking ways to reduce the fleets maintenance cost while still meeting airworthiness requirements. Structural health monitoring (SHM) is potentially a cost effective emerging area of technology that enables condition-based maintenance in-lieu of the traditional schedule-based non-destructive evaluation (NDE) [1-3]. Guided acoustic waves (GAWs) are of particular interest in SHM and NDE applications because they provide the ability to conduct large area structural inspections within short period of time using readily available ultrasonic transducers (UTs). For the aerospace industry such sensing tool may be required to operate in an environment where the temperature varies from -80°C to 100°C. In this investigation an approach using newly developed piezoelectric broadband high efficiency flexible ultrasonic transducers (FUTs) bonded to an aluminum alloy (Al) plate structures and on an aircraft representative component to generate and detect GAWs for artificially induced defects. The FUT bonding approach using glue cured at room temperature is a promising on-site sensor instrumentation technique. The center frequencies of such FUTs can range from 3 MHz to 25 MHz [4, 5].

FLEXIBLE ULTRASONIC TRANSDUCERS (FUTs)

The fabrication process of FUTs is based on a sol-gel spray technique [6]. It mainly consists of six steps [4, 5]: (1) lead-zirconate-titanate (PZT) solution preparation; (2) mixing and ball milling of PZT powders and PZT solution to submicron size; (3) spraying of the PZT composite (PZT-c) slurry obtained from step (2) onto 75 µm thick titanium (Ti) membranes; (4) heat treating to produce a thin solid PZT-c ceramic film; (5) corona poling of the PZT-c film to obtain piezoelectricity; (6) top electrode painting using silver paste. Steps (3) and (4) are repeated to achieve desired transducer film thickness that is determined by the desired ultrasonic transducer operational centre frequency and performance. The painting in step (6) provides the convenience of obtaining desired sensor configurations at selected locations. It is noted that the ultrasonic performance of such FUTs on Ti membranes used in this study showed in general 5 to 10 dB stronger signal strength than those reported in [4, 5], whereby FUTs were made onto stainless steel (SS) membranes. The improved signal strength comes from the reduced oxidation of the membrane substrates (Ti over SS) during heat treatment and improvement of the sol-gel spray technique. Figure 1 shows a sample of such FUT with three top electrodes.

![Fig. 1: A FUT with three top electrodes fabricated on a 75 µm thick Ti membrane.](image)
DAMAGE DETECTION CAPABILITIES OF A FUT

Al 6061-T6 Plate Test Article

An Al 6061-T6 plate used as a test article for the developed ultrasonic transducer is shown in Figure 2. A FUT similar to the one shown in Figure 1 was bonded onto the 50.8 mm by 6.35 mm cross section area of the aluminum test article using room temperature cured adhesive as shown in Figure 3. Such bonding method is an excellent sensor installation technique due to its in-the-field potential. All silver top electrodes have identical dimensions (~4.35 mm by 5 mm) with a thickness of about 10 µm as shown in Figure 3. The FUTs have a center frequency of around 10 MHz. Ultrasonic baseline measurements using these FUTs were taken for a virgin article before the introduction of artificial defects (cracks). The edge bonded FUTs will generate and detect the symmetrical-mode like plate acoustic waves (PAWs) [7, 8] propagating along the plate. The guided PAW velocity of 6246 m/s was obtained using the time delay of the strongest first and the strongest second round trip echoes reflected from the end of the plate opposite to the FUTs, at a distance of 406.4 mm.

Fig. 2: An Al 6061-T6 plate test article.

Fig. 3: FUT bonded onto the cross section of the Al 6061-T6 plate test article.

Two artificial notches, D1 and D2, of 1 mm width and 1 mm depth were introduced on the Al 6061-T6 plate, as shown in Figure 4. The one way distances from the FUT (at the edge) to the artificial notches D1 and D2 and to the opposite edge E1 are 145 mm, 222 mm, and 406.4 mm, respectively. Notches D1 and D2 have a length of 25.4 mm and 50.8 mm, respectively. Employing the pulse-echo mode and a band-pass filter of 5 MHz to 10 MHz, a comparison between ultrasonic signals measured at transducer A and B in the presence of the artificial defects was made. In Figure 5, GD1, GD2, and GE1 represent the echoes reflected from D1, D2, and E1, respectively. In order to see GD1 and GD2 clearly, the echo GE1 was deliberately made to be saturated in this Figure. The shown result provides a calculated time delay of 46 µs, 71 µs, and 130 µs for GD1, GD2, and GE1, respectively. It is noted that since the PAWs are symmetrical-like modes, the higher order modes form the spurious (trailing) signals [9]
shown in Figure 5. Such spurious signals may affect the accuracy of the arrival time which is closely related to the defect location. Proper choice of the PAWs modes may reduce or eliminate such spurious signals [7, 8, 10]. In Figure 5 (b) only echoes from notch D2 appeared when measured at transducer B. This indicated that for this Al plate of 6.35 mm thick and 50.8 mm wide the guided PAW does not diverge much and this may enable such FUT with array configuration to detect the tip position and propagation of the defect such as D1 and D2.

![Diagram of an Al 6061-T6 plate with transducers and artificial cracks.]

**Fig. 4:** Locations of artificially induced cracks and transducers on the Al 6061-T6 plate.

![Ultrasonic signals measured at sensors A and B.](image)

**Fig. 5:** Ultrasonic signals measured at (a) sensor A and (b) sensor B with the presence of artificially induced cracks illustrated in Figure 4.

**Complex Structural Component**

A complex structural component that is representative of aircraft structural complexity was constructed with artificial cracks at selected rivets locations. This structure shown in Figure 6 is designed to illustrate the structural complexity that could be faced in employing such discussed sensing approach. The length of this structure is 510 mm. Employing electrical discharge machining (EDM) notches were introduced. Notches 1, 3, and 4 are of
2.54 mm long and notches 2, 5, and 6 are of 1.27 mm long. The one way distances from the edge, where a FUT was bonded, to the EDM notches are as identified in Figure 6.

Table 1 summarizes the distance of various EDM notches to the edge bonded FUT and the expected time delay of the ultrasonic echo reflected from the notches using the pulse-echo method. The guided PAW velocity of 6234 m/s used for calculating time delay was obtained by dividing the round trip distance, from the edge bonded FUT to the opposite edge, by the time difference of the two strongest consecutive ultrasonic echoes reflected from the opposite edge of the structure. The actual structure and its FUT edge cross section are also shown in Figure 6.

![Diagram of EDM notches and FUT](image)

**Fig. 6:** Complex structural specimen with artificially induced EDM notches at specified locations.

**Table 1:** EDM notch locations with respect to the edge bonded FUT

<table>
<thead>
<tr>
<th>Notch</th>
<th>Distance (mm)</th>
<th>Calculated Time Delay (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notch 1</td>
<td>15</td>
<td>4.81</td>
</tr>
<tr>
<td>Notch 2</td>
<td>48</td>
<td>15.40</td>
</tr>
<tr>
<td>Notch 3</td>
<td>117</td>
<td>37.54</td>
</tr>
<tr>
<td>Notch 4</td>
<td>135</td>
<td>43.31</td>
</tr>
<tr>
<td>Notch 5</td>
<td>158</td>
<td>50.69</td>
</tr>
<tr>
<td>Notch 6</td>
<td>176</td>
<td>56.46</td>
</tr>
</tbody>
</table>

**X-ray Inspection:** An X-ray inspection was performed on the complex structural component in order to detect the artificially induced EDM notches. An identical schematic to the one in
Figure 6 and the X-ray films are shown in Figure 7. During the inspection, the X-ray probe needed to be tilted at different angles in order to detect several EDM notches. In addition, it is noted that only the 2.54 mm EDM notches were identified using this technique.

Ultrasonic Inspection: The commercial UT V129-10MHz-0.125 from Panametrics was placed at various locations on the cross section shown in Figure 6. The ultrasonic signal measurements were taken using the pulse-echo method. Subsequently, the FUT described earlier was bonded onto the cross sectional surface as shown in Figure 8. The center frequency of the FUT is around 10 MHz. The ultrasonic signals obtained from both the commercial UT V129 and the FUT using pulse-echo method were compared at two sensor locations A and B, separated by 10 mm. Figure 9 shows the ultrasonic signals measured at sensor location A. All top electrodes here have an identical 4×5 mm² dimension. The pulser-receiver settings used to obtain ultrasonic signals for both commercial UT (V129) and the FUT were the same. G_{N2}, G_{N3}, and G_{N6} noted in Figure 9 are the round trip echoes from the EDM notches 2, 3, and 6 that are shown in Figure 6, respectively. The actual time delays of the echoes agree well with the calculated values shown in Table 1. G_{R1} and G_{R2} are the echoes reflected from rivets R1 and R2 between notches 2 and 3, as indicated in Figure 6, respectively. It is observed that the SNR of the signal measured by the FUT is higher than the one measured by the commercial UT V129. Although the EDM notches and rivets are not aligned with sensor location A, echoes from these features may still be seen due to the fact that ultrasound beam width increases over distance.

Another set of ultrasonic signals were measured at sensor location B indicated in Figure 8. In reference to Figure 6, sensor location B is aligned with EDM notch 1. The results are shown in Figure 10. G_{N1} represents the round trip echo generated by EDM notch 1, and G_{R3} is the echo reflected from rivet R3 as shown in Figure 6. The signal measured by the FUT is 8 dB weaker than the one obtained by the commercial V129. For sensor location B, only the first 10 μs time traces are shown as the ultrasonic waves were mostly reflected by EDM notch 1 and other echoes cannot be seen at this level of signal gain.
Fig. 8: FUT bonded onto the 6.35 mm thick section of the complex structural component.

Fig. 9: Ultrasonic signal obtained using (a) commercial Panametrics V129 and (b) bonded FUT at sensor location A indicated in Figure 8.

It has been demonstrated at the two sensor locations that the FUT bonded onto the edge of a plate is capable of detecting defects with high sensitivity, down to 1.27 mm long defects. In addition, the FUT was able to distinguish between rivets and actual defects provided that the rivets and the defects are close to the line-of-sight of the FUT.

CONCLUSIONS AND DISCUSSIONS

Thick composite piezoelectric film sprayed onto 75 µm titanium substrate formed a FUT to excite and detect guided plate acoustic waves. Mass production of the FUT and the potential of ease of on-site installation using room temperature cured adhesive present additional advantage of the technology. The operational temperature of the developed and evaluated FUT is between -80°C and 100°C that is suitable for aerospace structural health monitoring applications. This investigation has demonstrated that the bonded FUTs have
ultrasonic performance as good as commercial ultrasonic transducers while providing additional advantages including their operational temperature range. In addition, the FUT is capable of detecting defects as small as 1.27 mm long in an environment as complex as the one encountered in aircraft structures as illustrated in this document.

**Fig. 10:** Ultrasonic signal obtained using (a) commercial Panametrics V129 and (b) bonded FUT at sensor location B indicated in Figure 8.

The FUTs, having characteristics of flexibility for curved surfaces, light-weight and small profile (< 150 µm in thickness), were bonded onto a cross-section edge of 6.35 mm thick aluminum (Al) plates of 50.8 mm width and 406.4 mm length to generate and receive plate acoustic waves (PAWs). The advantage of PAWs is its ability to perform large area inspections. Artificial line cracks were produced along the Al plate. When pulse-echo technique was used, the guided PAWs generated by the FUTs in array form were reflected by the cracks and then detected by the same FUTs. The relationship between the crack length and the strength of the ultrasonic echoes was studied. Experimental results were compared with theoretical calculations. In addition, a section of an aircraft representative complex structure (L-shaped lap-joint) was instrumented with the FUTs that have center frequency of 10 MHz. The FUTs were bonded onto the edges of the 6.35 mm thick Al sections, and ultrasonic results were compared with those obtained by the X-ray technique.

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