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Smart Sensor Phenomena, Technology, Networks, and Systems 2010
[Proceedings], 2010-05-17

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FLEXIBLE ULTRASONIC TRANSDUCERS FOR STRUCTURAL HEALTH MONITORING OF GRAPHITE/EPOXY COMPOSITES

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ABSTRACT

Flexible ultrasonic transducers (FUTs) are presented for structural health monitoring (SHM) and non-destructive evaluation (NDE) of graphite/epoxy (Gr/Ep) composites. These FUTs are fabricated using a sol-gel spray technique to coat piezoelectric films onto 75 μm thick titanium (Ti) or 50 μm thick polyimide (PI) membranes. The main merit of FUTs is their on-site installation capability because they may be glued or attached to a host Gr/Ep structure with planar or curved surfaces. The flexibility of such FUTs is achieved due to the thin substrates, piezoelectric ceramics and electrodes. Tapered Gr/Ep layers bonded onto each side of an aluminum (Al) plate and on a Gr/Ep composite plate with artificial delaminations were investigated. An induction type non-contact method for the evaluation of Gr/Ep composites using FUTs is also demonstrated. Such a non-contact technique may be desired for SHM and NDE of rotating composite components.

1. INTRODUCTION

Composite materials such as Gr/Ep laminates are becoming the materials of choice for aerospace structures because of their high strength to weight ratio. Diagnostic SHM [1 - 4] and NDE technologies [5, 6] for these composites are increasingly being developed by the aerospace industry to enable condition-based maintenance for cost-effective increased safety and eco-efficient designs. Ultrasonic techniques [1 - 6] are frequently used for SHM and NDE purposes because of their subsurface inspection capabilities, fast inspection speed, simplicity and ease of operation. In particular, FUTs and arrays are attractive because they can be used for planar and curved surfaces. Using proper glues, FUTs may have the on-site installation capability which is crucial for SHM and NDE applications.

FUTs have been reported for the SHM and NDE purposes [7 - 10] using PVDF [7, 8], lead-zirconate-titanate (PZT), 1-3 composites [9] and PZT fibers incorporated into composites [10, 11]. In this study FUTs were fabricated using a sol-gel spray technique [12 - 15] on 75 μm thick Ti and 50 μm thick polyimide (PI) membranes as substrates. The center operation frequency of these FUTs during ultrasonic measurements is typically around 8 MHz. All measurements were carried out in pulse/echo mode. This study will further present a current development of an induction type [16] non-contact method for the interrogation of the Gr/Ep

composites using FUTs. Such non-contact technique may be desired for SHM and NDE of rotating composite components.

2. FABRICATION OF FUTS

The detailed fabrication process of sol-gel spray technique can be found from previous publications [12 -15]. PZT submicron size powders were dispersed into a PZT sol-gel solution by the ball milling method to achieve the slurry for spray. Since Ti membranes have high conductivity, they were used as the bottom electrode of the FUT. When insulating PI membranes are used, an approximately 2 μm thick silver bottom electrode layer is coated using a colloidal silver solution sprayed with an airbrush. This silver layer is then cured around 120°C. An airbrush was also used to spray the PZT composite (PZT-c) film and silver coatings onto Ti membranes. Metallic masks were used to serve as the shadow mask during the PZT spray coating. Multiple layers were made in order to reach the desired film thickness leading to proper ultrasonic operating frequencies of FUTs [14, 15]. Poling was then used to obtain piezoelectricity of the PZT-c film. Finally, the top electrode pattern was made by silver paste painting or colloidal silver spraying with a thin plastic mask. This electrode fabrication approach enables to achieve the desired sensor configurations easily and economically. In this investigation FUTs serve primarily as longitudinal (L) wave UTs.

Figures 1 and 2 show fabricated FUTs using 75 μm thick Ti and 50 μm thick polyimide (PI) membrane, respectively. It is noted that the FUTs made on 75 μm Ti membranes shown in Figure 1 have the ultrasonic signal strength close to commercially available broadband UTs in the frequency range between of 5 - 15 MHz [14]. The ultrasonic strength of the FUTs made of 50 μm thick PI membranes shown in Figure 2 is generally 30 dB weaker than that of the FUTs made on Ti membranes because of the upper limitation of the annealing temperature limited by the softening temperature of the PI at 350°C. When PZT-c films are annealed at 650°C, their piezoelectricity is much stronger than when annealed at a temperature lower than 350°C. The merits of the FUTs shown in Figure 2 over the PVDF ultrasonic transducer in [7] are that the operation temperature can be up to more than 150°C and the frequency bandwidth may be larger.

Figure 1. Fifteen FUTs coated onto 75 μm thick Ti membrane. The PZT-c film thickness is 92 μm . Top silver electrodes have a 4 mm diameter.

Figure 2. Nine FUTs coated onto 50 μm thick PI membrane. The PZT-c film thickness is 60 μm . No top electrode is present.

3. GR/EP COMPOSITE SAMPLES AND ULTRASONIC C-SCAN IMAGES

In the last three decades bonded repair technology [17 - 19] has become a cost-effective means of repairing cracks in metallic aircraft structures. One of the objectives of this investigation was to use the above mentioned two types of FUTs to detect disbonds between a simulated Gr/Ep composite patch and an Al planar substrate, thereafter referred to as the “patch specimen”. The patch specimen consisted of six plies of Gr/Ep composite bonded on each side of an Al 6061-T6 plate 406.4 mm long 6.35 mm thick, 50.8 mm wide, as shown in Figure 3. An artificial disbond using Teflon sheet inserts of 0.05 mm thickness, 25.4 mm length and 25.4 mm width was introduced at the interface between the tapered Gr/Ep composite regions and the Al plate. The tapered patch is made of six plies of Gr/Ep composite which covers a total area of 50.8 mm by 101.6 mm. The material properties of Al, Teflon and Gr/Ep composite patch are given in Table 1.

Figure 3. Schematic and an actual Gr/Ep composite patch specimen.

Initially, an ultrasonic C-scan of the patch sample in a water immersion tank was performed. The imaging was carried out by a focused ultrasonic transducer with a center frequency of 7.5 MHz, a focal length of 152.4 mm and a diameter of 19 mm. The scanning step was 0.5 mm in the lateral directions. Figure 4 shows the obtained C-scan image near the side with a Teflon insert indicated as disbond regions. Because the composite patch has the tapered

shape, the immersion UT for C-scan image was chosen to obtain a general image and not the details of each tapered section. It is noted that Teflon was inserted only on one side of the composite patch and the ultrasonic C-scan images obtained for the rest of this sample indicated that there were no other disbonded regions.

Table 1. Material properties of specimens

Material Property	Young's Modulus		Poisson Ratio	Thermal Expansion Coeff.	
	E_1	E_2	ν_1	α_1	α_2
Units	MPa	MPa	N/A	$^{\circ}\text{C}^{-1}$	$^{\circ}\text{C}^{-1}$
Al-6061-T6	68900	N/A	0.33	2.36×10^{-5}	N/A
Teflon	1840	N/A	0.35	2.93×10^{-5}	N/A
Gr/Ep Patch	14200	10300	0.27	N/A	N/A

Figure 4. Ultrasonic C-Scan images of the Gr/Ep composite patch specimen including a 25.4 mm x 25.4 mm disbonded region.

An 8.3 mm thick Gr/Ep composite plate with a stacking sequence of $[0/45/0/-45/90/90/-45/0/45/0] \times 3$ was also made for the experiment. The same size Teflon sheet as used above was introduced into the composite during fabrication to create a simulated disbond. Figure 5 shows the obtained ultrasonic C-scan image near the 25.4mm x 25.4 mm Teflon insert indicated as a disbonded region.

Figure 5. Ultrasonic C-Scan images of the Gr/Ep composite specimen near disbond region.

4. ULTRASONIC MEASUREMENTS OF GR/EP COMPOSITES

FUTs similar to the one shown in Figure 1 were then glued onto two locations of the patch sample and the composite plate. The glue was cured at room temperature for 24 hours. Since the operation temperature of the Gr/Ep composites in aerospace industry normally ranges from -60°C to 100°C , both PZT-c thick film FUTs, together with the glue, have been tested and survived thermal cycles from -60°C to 100°C which is limited by the glue used here.

For the Gr/Ep composite patch sample, a merit of the FUT is that it can be made into different shapes and sizes for specific applications. Because of the step shape of the patch sample, FUTs with a Ti membrane of a size $14\text{ mm} \times 4\text{ mm}$, a PZT-c film size of $10\text{ mm} \times 2.5\text{ mm}$ and a top electrode of $8 \times 2\text{ mm}$ were made and glued at two locations, with and without a disbond, as shown in Figure 6. The measured ultrasonic signals for these two locations are shown in Figures 7(a) and 7(b), respectively. L_c^n is the n th round trip echo through the thickness of the Gr/Ep composite patch. L_{AL}^1 is the 1st round trip echo through the thickness of the Gr/Ep composite patch and that of the Al plate underneath. L_{AL}^2 travels one more round trip via Al plate thickness than L_{AL}^1 . The echoes between the L_{AL}^1 and L_{AL}^2 come from signals travelling through the different thicknesses of the tapered Gr/Ep composite. The center frequencies and 6 dB bandwidths of the L_c^1 echo in Figure 7(a) are 8.5 MHz and 7 MHz, respectively. When a disbond is present at the FUT location, L_{AL}^n disappear due to the loss of the ultrasonic coupling between the Gr/Ep composite patch and the Al plate.

Figure 6. Gr/Ep composite patch with two rectangular shaped FUTs glued at two locations, without and with disbond.

Figure 7. Measured ultrasonic signals in time domain at room temperature using the FUTs shown in Figure 6 at the location (a) without and (b) with delamination.

Figures 8(a) and 8(b) show the ultrasonic measurement results using an FUT, based on a PI membrane, similar to the one shown in Figure 2 glued onto the regions without and with disbond, respectively. The same signal designations used in Figures 7(a) and 7(b) are applied in Figures 8(a) and 8(b). The center frequencies and 6 dB bandwidths of the L_c^1 echo in Figure 8(a) are 8.9 MHz and 2.5 MHz, respectively. Even though the signal strengths in Figures 8(a) and 8(b) are 30 dB weaker than those in Figures 7(a) and 7(b), the disbond can be detected clearly.

Figure 8. Measured ultrasonic signals in time domain at room temperature using the FUT made of a 50 μm thick PI membrane glued at a location (a) without and (b) with delamination.

5. NON-CONTACT ULTRASONIC MEASUREMENTS

In order to achieve NDE and SHM of rotating components, non-contact ultrasonic measurement approaches are desired. In this study an induction based method [16] is used together with FUTs using Ti membranes. The 8.3 mm thick composite plate of with a stacking sequence of $[0/45/0/-45/90/90/-45/0/45/0] \times 3$ shown in Figure 5 was used for the experiment here. Two FUTs shown in Figure 9 were glued onto the Gr/Ep sample at the locations without and with the disbond for demonstration purposes. Firstly, ultrasonic measurements using the conventional contact method were carried out. Then a flat coil made of a thin lacquered wire served as a main component for induction coupling. The two ends of this coil were connected to the top electrode of the FUT and the Ti membrane which served as the bottom electrode of the FUT. Directly on top of such coil, connected to the FUT, another flat coil was connected to the coaxial cable of the pulser/receiver.

Figure 9. Two FUTs glued onto the Gr/Ep the composite plate of Figure 5 above regions with and without disbands.

At room temperature the measured ultrasonic signals obtained by two FUTs shown in Figure 9 with the contact method are shown in Figures 10(a) and 10(b). L^n is the n th round trip echo through the thickness of the Gr/Ep composite and L_D^n is the n th round trip echo from the FUT to the disbond region. The center frequency and 6 dB bandwidth of the L^1 and L_D^1 echoes are 2.9 MHz and 2.1 MHz, 2.9 MHz and 1.8 MHz, respectively. When a non-contact method is used, the measured ultrasonic signals at the location without and with the disbond are shown in Figures 11(a) and 11(b), respectively. It is noted that the tuning of the electrical impedance matching between the FUTs and the size, diameter and number of turns of the coils has not been optimized. Therefore the measured ultrasonic frequency may be affected by the electrical impedance of the coil. The separation distance between two coils was 10 mm. The ultrasonic signals were 20 dB weaker in non-contact than contact configuration of which the ultrasonic signals are shown in Figures 10(a) and 10(b), respectively.

Figure 10. Measured ultrasonic signals in contact method at room temperature using a FUT made of a 75 μ m thick Ti membrane at a location (a) without and (b) with disbond.

Figure 11. Measured ultrasonic signals in non-contact method at room temperature using a FUT made of 75 μ m thick Ti membrane at a location (a) without and (b) with disbond.

6. CONCLUSIONS

Flexible ultrasonic transducers (FUTs) were presented for SHM and NDE of Gr/Ep composites. These FUTs were fabricated using a sol-gel spray technique to coat piezoelectric films onto 75 μm thick Ti or 50 μm thick PI membranes. The main merit of these FUTs is their on-site installation capability because they can be glued or attached to a host Gr/Ep structure with planar or curved surfaces. Their center operation frequency ranges between 2.9 MHz and 8.9 MHz and FUTs with a Ti substrate are in general 30 dB stronger in signal strength compared to those with a polyimide (PI) substrate. An aluminum plate bonded on both sides with a tapered Gr/Ep composite layer to simulate a patch, including an artificial delamination simulated with a Teflon insert, was fabricated. FUTs with specific small sizes were then glued onto the composite patch and successful disbond inspection performed. An 8.3 mm thick Gr/Ep composite plate was also implanted with an artificial delamination and its detection using both contact and a prototype induction type non-contact method demonstrated. The separation distance between the induction coils was 10 mm and the signal reduction was 20 dB. Such a non-contact technique may be desired for SHM and NDE of rotating composite components.

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