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Integrated Plate Acoustic Wave Transducers Using Mode Conversion

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I. Motivation/Background

Structural health monitoring is a major concern of the aerospace community when considering aging aircrafts whose growing maintenance costs can reduce their economic life extension. Also emerging new airplanes are increasingly required to be equipped with intelligence for improved diagnostics of the health condition of the critical parts and structures. Therefore, there are demands for miniaturized light weight integrated in-situ sensors and associated techniques for local and global damage diagnostics. In this investigation two techniques to fabricate integrated transducers for plate acoustic waves (PAWs) which propagated many tens of centimeters along thin (~2 mm thick) aluminum (Al) and stainless steel (SS) plates for defect detection were developed.

II. Statement of the Contribution/Methods

Firstly thick films (>50μm) piezoelectric ultrasonic films were directly deposited onto the end edges of these plates as integrated PAW transducers using a sol-gel spray technique. These thickness vibration film ultrasonic transducers (UTs) were used to excite and detect various PAW modes in pulse/echo mode from room temperature up to 150°C without the use of ultrasonic couplant. Novel mode conversion mechanisms from the thickness vibration mode of film UTs were use to efficiently generate and receive symmetric, anti-symmetric and shear horizontal PAWs with proper mode conversion angles. Secondly flexible thick film (>50μm) piezoelectric UTs were glued to the edges of the above mentioned plates as integrated PAW transducers. These flexible UTs used 50μm thick polyimide films as membrane substrates.

III. Results/Discussion

The propagation lengths of symmetrical, anti-symmetric and shear horizontal PAWS reached more than one meter in frequencies of several MHz in these nearly 2mm thick plates. Line defects of 1mm, 1mm depth and a half of the plate width were clearly detected from room temperature up to 150°C. Theoretical calculations of conversion efficiencies from the longitudinal wave of film ultrasonic transducers (UTs) to the symmetric, anti-symmetric and shear horizontal PAWs with respect to the mode-conversion angle were carried out and compared to experimental results. Discussions on advantages and limitations of these above mentioned two approaches to integrate film UTs at the end edges of the plate will be given.

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Abstract—**Integrated (IUTs) and flexible ultrasonic transducers (FUTs) have been used to generate and receive plate acoustic waves (PAWs) for long distance (up to more than 1m) structural health monitoring applications. These IUTs and FUTs were made by sol-gel spray techniques and thickness vibration longitudinal wave transducers. Using mode conversion techniques these transducers located at the edges of the plates could excite and detect symmetrical, anti-symmetric and shear horizontal types of PAWs in pulse/echo mode. IUTs were directly deposited and FUTs were glued onto the edges of the plates. In 2mm and 6.35mm thick plates line defects of 1mm width and 1mm depth were clearly detected at temperatures up to 150°C. Results indicated that for 2mm thick aluminum plates shear horizontal PAWs were the best for the line defect detection.**

Keywords-Integrated ultrasonic transducer; flexible ultrasonic transducer; nondestructive testing; structural health monitoring; plate acoustic waves; thick piezoelectric ceramic film; polyimide; sol-gel spray; mode conversion

I. Introduction

Structural health monitoring (SHM) [1, 2] is a major concern of the aerospace community when considering aging aircrafts whose growing maintenance costs can reduce their economic life extension. Also emerging new airplanes are increasingly required to be equipped with intelligence for improved diagnostics of the health condition of the critical parts and structures. Therefore, there are demands for miniaturized light weight integrated in-situ sensors and associated techniques for local and global (long distance) damage diagnostics [3]. In this investigation two approaches using IUTs and FUTs to generate and receive PAWs [4-6] which propagated many hundreds of mms along 2mm and 6.35mm thick aluminum (Al) plates for global line defect detections will be developed. These IUTs and FUTs will be fabricated at the end edges of the plates by a sol-gel spray techniques [7-9] and are thickness vibration longitudinal modes transducers. Therefore mode conversions techniques [6, 10-12] will be used to use such IUTs and FUTs to excite and detect symmetrical, anti-symmetrical and shear-horizontal types of PAWs. Discussions on advantages and limitations of these above mentioned two approaches to integrate film UTs at the end edges of the plate will be given.

II. Transducer Fabrication

The sol-gel based sensor fabrication process to fabricate IUTs or FUTs using metal substrates [7-9, 13] consists of six main steps [7-9]: (1) preparing high dielectric constant lead-zirconate-titanate (PZT) solution, (2) ball milling of piezoelectric PZT powders to submicron size, (3) sensor spraying using slurries from steps (1) and (2) to produce the thin film, (4) heat treating to produce a solid composite (PZT/PZT) thin film, (5) corona poling to obtain piezoelectricity, and (6) electrode painting or spraying for electrical connections. Steps (3) and (4) are used multiple times to produce optimal film thickness for specified ultrasonic operating frequencies. Silver paste was used to fabricate top electrodes. Such electrode fabrication approach enables to achieve desired sensor array configurations easily and economically. Figure 1 shows a schematic of an IUT directly coated onto the end edge of an Al plate.

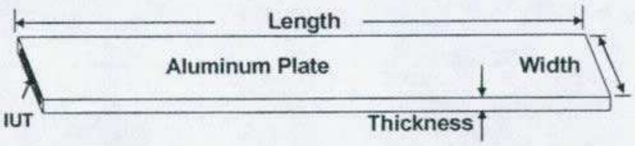

Figure 1. Schematic of an IUT deposited onto the end edge of an Al plate.

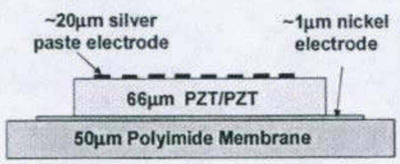

Figure 2. Schematic of a FUT array using polyimide membrane as the substrate.

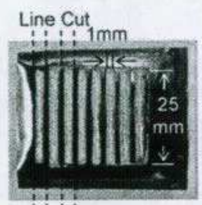

Figure 3. Actual FUT eight-element array using a 50μm thick polyimide

In this study 50μm thick polyimide membranes rather than metal foils [13] are used as FUT substrates. Since polyimide is an insulator, one side of the film is coated with ~1μm thick nickel electrode using electroless plating method. The remaining steps of the FUT fabrication process are the same as those mentioned above. The schematic diagram and an actual flexible UT used for this study are shown in Figs. 2 and 3, respectively. The thickness of the PZT/PZT composite film for the flexible UT shown in Fig. 3 was 66μm. Since top electrode was fabricated using silver paste, array configuration can be achieved with ease. In Fig. 3 each top electrode had a length of 24mm and a width of 1.0mm. Then each FUT is cut and glued onto the edge of the plates to be studied. Such simple FUT

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fabrication process is an excellent alternative to those reported in [14, 15]. In general, the signal strength of the FUT using polyimide film substrate is about 10 dB weaker than the IUT due to the lower fabrication temperature associated with polyimide film substrate [9]. Such FUT can have operation temperature at least up to 150°C which is higher than those reported in [14, 15]. For this study the top electrode size for IUT or FUT was not optimized yet.

III. Mode Conversion Technique

The IUTs and FUTs shown in Figs. 1-3 are longitudinal (L) wave thickness vibration UTs. However, when IUT deposited onto the end edge of a 2mm thick Al plate as shown in Fig. 1 this IUT will generate and receive symmetrical PAWs [4-6].

Recently using mode conversion L wave can be converted into shear (S) waves for nondestructive testing (NDT) applications [10-12]. It is known that there exist shear vertical (S_V) and shear horizontal (S_H) waves in bulk materials [5, 6]. Here using IUTs the analogies of mode conversion from L wave to S_V and to S_H modes have been developed for the mode conversion from L like waves to anti-symmetrical and shear horizontal (SH) PAWs, respectively as shown in Figs. 4 and 5. The mode conversion angles ϕ and θ shown in Fig. 4 and Fig. 5, respectively will be discussed in the latter sections.

Figure 4. Schematic of an IUT deposited onto the end edge of an Al plate to generate and receive anti-symmetrical PAWs.

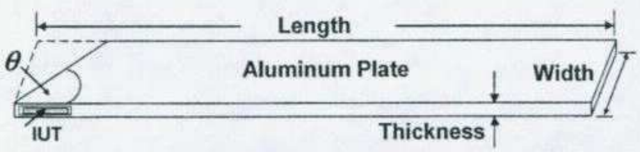

Figure 5. Schematic of an IUT deposited onto the end edge of an Al plate to generate and receive shear-horizontal PAWs.

IV. Ultrasonic Performance

For SHM the ability of PAWs to detect defects in long distances is essential. Therefore the focuses in this section will be to (i) evaluate the propagation distance of symmetrical, anti-symmetrical and SH PAWs excited and received by the developed IUTs deposited and FUTs glued onto the end edges of the Al plates and (ii) the ability of these three types of PAWs to detect artificial line defects at room temperature and 150°C. In order to detect the defect locations pulse/echo mode is chosen although transmission mode can be used.

A. Symmetrical PAWs

Figure 6 shows the symmetrical PAWs ($S_{L,1}$) generated and received by the IUT shown in Fig. 1 at 150°C in an 2mm thick, 50.8mm wide and 406.4mm long Al plate . The subscript 1 of the $S_{L,1}$ echo denotes the 1st round trip from the IUT location to the other edge of the plate. It means that $S_{L,1}$ has traveled a total distance of 812mm. The group velocity of the $S_{L,1}$ echo at the leading edge was about 5466m/s which is slower than that of the L wave velocity, V_L = 6364m/s in the Al plate. Therefore it is believed that $S_{L,1}$ consists of many high order symmetrical modes. The same experiment was carried out for a 6.35mm thick Al plate, similar result was obtained except that the pulse width of $S_{L,1}$ is much shorter than that shown in Fig. 6.

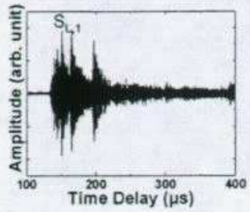

Figure 6. Ultrasonic symmetrical PAW signals obtained in a 2mm thick Al plate using IUT shown in Fig. 1 at 150°C.

To examine the long distance capability of SHM of the symmetrical PAWs two artificial line defects, D1 and D2 with 1mm depth and 1mm width were made onto the Al plate shown in Fig. 1. D1 and D2 had width of 25.4mm and 50.8mm, respectively as shown in Fig. 7. At 150°C the measured symmetrical PAWs are given in Fig. 8. Fig. 6 in which no line defects exist and Fig. 8 in which two line defects present clearly confirm that symmetrical PAWs can be used to perform SHM of defects at 150°C. In Fig. 7 the two line defects were 146.3mm and 223.5mm away from the IUT.

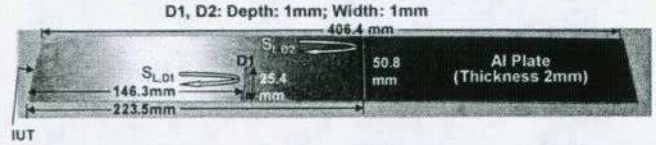

Figure 7. Two artificial line defects, D1 and D2 were made onto a 2mm thick Al plate.

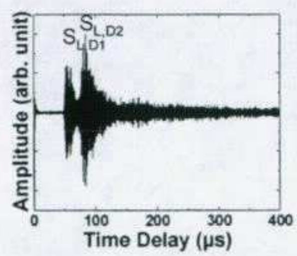

Figure 8. Symmetrical PAW signals detecting two artificial line defects, D1 and D2 in a 2mm thick Al plate shown in Fig. 7 at 150°C.

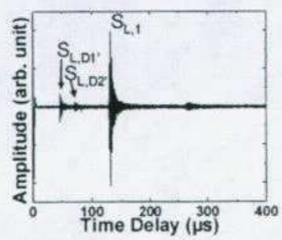

Figure 9. Symmetrical PAW signals detecting two artificial line defects, D1' and D2' in a 6.35mm thick Al plate at 150°C.

A 6.35mm thick Al plate with the same plate width and length as those shown in Fig. 7 was also used as the sample which has same dimensions and locations of two line defects, D1' and D2'. For this 6.35mm thick Al plate the measured symmetrical PAWs at 150°C are given in Fig. 9. The results indicated that two line defects, D1' and D2', can be clearly detected also but with less signal-to-noise ratio (SNR) than those shown in Fig. 8. The main reason may be that in the 6.35mm thick Al plate the defect depth (1.0mm) over the thickness ratio is less than that in the 2mm thick Al plate. However, in Fig. 9 the echo $S_{L,1}$ from the end of the 6.35mm thick plate can be detected as well even with the presence of the two line defects.

In certain SHM situations, accessibility to desired locations of aircraft components is limited for the fabrication of IUTs, thus an alternative approach using FUT may be used. The fabrication of FUTs can be made off-line in a laboratory environment. Thereafter, they can be attached to desired sensor locations using adhesives such as glues that can sustain operational temperatures. Such adhesives can further be used as ultrasonic couplant. Attaching one single FUT obtained from the eight FUT array to the edge location identical to IUT shown in Fig. 1, similar results to those of IUT was obtained but with weaker signal strength due to the lower piezoelectric strength of FUT than that of IUT.

B. *Anti-symmetrical PAWs*

In Fig. 10 a 66μm thick PZT/PZT composite film IUT was coated on top of the Al plate at the edge as shown in Fig. 2. The chosen mode conversion angle ϕ using the analogy of bulk L wave to S_V for this configuration was 63.7° which was obtained from the phase matching angle [12] of the measured bulk L and S wave velocities of the Al plate. In a bulk Al sample the energy conversion rate from the bulk L wave to the S wave at this angle is 83.1%, which is only 0.02% smaller than the maximum conversion rate. Due to this mode conversion configuration the anti-symmetrical modes (A_{SV}) will be excited although the angle ϕ has not been optimized. Because this is a plate (finite dimensions) configuration, the analogy of the bulk (infinite dimensions) material configuration is only used for initial studies. In the future theoretical evaluation to obtain optimal conversion angle ϕ will be performed.

Figure 11 shows the reflected anti-symmetrical PAW $S_{AV,1}$ echoes at 150°C in the time domain. The subscript 1 of the $S_{AV,1}$ echo denotes the 1st round trip from the IUT location to the other edge of the plate. It indicates that $S_{AV,1}$ has traveled a total distance of ~812 mm. It is speculated that $S_{AV,1}$ may be composed of mainly the zeroth order anti-symmetrical PAW [4-6]. Since this Al plate supports multimode anti-symmetrical PAW propagation, some of the higher order modes having traveled faster than the zeroth order anti-symmetrical mode arrived earlier as shown in Fig. 11.

To investigate the thickness effect to the anti-symmetrical PAWs a 6.35mm thick Al plate with the same plate width of 50.8mm as but with a different length of 385mm from the one shown in Fig. 10 was used as a sample. The reflected anti-symmetrical PAWs at 150°C in the time domain are shown in Fig. 12. It demonstrates that in this 6.35mm plate the higher order anti-symmetrical PAWs are not dominant. Since the $S_{AV,2}$ echo denotes the 2nd round trip from the IUT location to the other edge of the plate is clearly seen, it has travelled a total distance of ~1.54m at 150°C. To evaluate the defect detection ability of the current anti-symmetrical PAW configuration two line defects with dimensions and locations away from the IUT nearly identical to those (D1 and D2) for symmetrical PAWs shown in Fig. 7 were created for both the 2mm and 6.35mm thick Al plate. The results showed that these two line defects could be detected but with less SNR than that obtained from symmetrical PAW as shown in Fig. 8. Furthermore, the SNR of the detected line defect signals was lower in 6.35mm than that in 2.0mm thick Al plate.

Figure 10. One IUT coated at the top surface near the edge of the Al plate as shown in Fig. 3 for the generation and detection of anti-symmetrical PAWs using mode conversion.

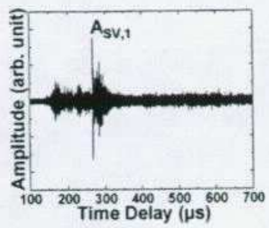

Figure 11. Ultrasonic anti-symmetrical PAW signals obtained using IUT shown in Fig. 10 at 150°C with mode conversion. The Al plate length was 406.4mm.

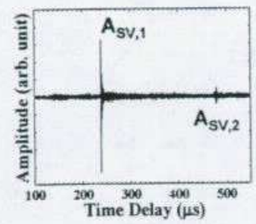

Figure 12. Symmetrical PAW signals obtained in a 6.35mm thick Al plate at 150°C with mode conversion. The Al plate length was 385mm.

Attaching one single FUT obtained from the eight FUT array to the edge location identical to IUT shown in Figs. 2 and 10, the similar results for anti-symmetrical PAWs to that of IUT was obtained but with weaker signal strength due to the lower piezoelectric strength of FUT than that of IUT.

C. *Shear-horizontal (SH) PAWs*

If the IUT is located at the edge indicated in Fig. 3, SH PAWs [5, 6] can be produced and received using mode conversion. In Fig. 13 the thickness of the PZT/PZT composite film was 90μm. For this configuration symmetrical PAW echoes traveled nearly 25.4mm and then converted to SH PAW modes and vice versa. For this configuration the chosen mode conversion angle θ using the analogy of L wave to bulk S_H was 61.7° which was calculated using the phase matching between measured extension mode velocity $S_{L,1}$ and the shear wave velocity of the Al plate. Similar to the mode conversion angle ϕ, θ will be optimized in the future study.

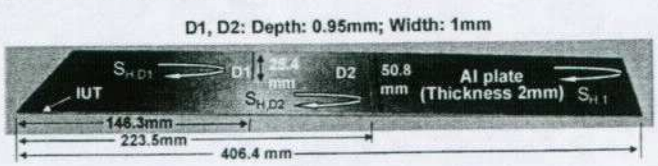

Figure 13. One IUT coated directly onto side surface near the end edge of an Al plate as shown in Fig. 4 with an angle of 61.7° to generate and receive SH PAW using mode conversion.

Using the IUT shown in Fig. 13 the reflected SH PAWs echoes at 150°C without two line defects in time domain is given in Fig. 14. After traveling nearly a distance of 813mm the center frequency of the $S_{H,1}$ echo was 6.3MHz. The subscripts 1 and 2 denote the 1st and 2nd round-trip echo, respectively. $S_{H,2}$ echo traveled a distance of 1.625m. Comparing with the PAW signals obtained for symmetrical and anti-symmetrical modes SH PAW echoes shows the highest SNR. Theoretical calculation results also reveal that $S_{H,1}$ echo mainly comes from the zeroth order SH PAW having the bulk shear wave velocity [5,6]. Also the group velocities of the higher order SH PAWs in the current configuration are slower that that of bulk shear wave velocity and that is why they arrived a little bit later than $S_{H,1}$ echo.

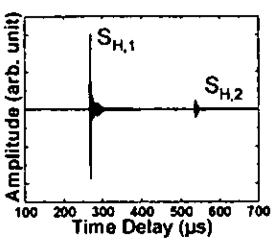

Figure 14. Ultrasonic SH PAW signals obtained using IUT shown in Fig. 13 at 150°C with mode conversion.

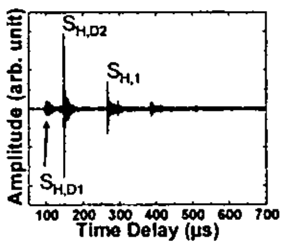

Figure 15. SH PAW signals detecting two artificial line defects, D1 and D2 in a 2mm thick Al plate shown in Fig. 13 at 150°C.

Two line defects with dimensions and locations away from the IUT nearly identical to those (D1 and D2) for symmetrical PAWs shown in Fig. 7 were created in the plate shown in Fig. 13. At 150°C the reflected SH PAW signals are given in Fig. 15. Fig. 14 in which no line defects exist and Fig. 15 in which two line defects present clearly confirm that SH PAWs can be used to perform SHM of line defects at 150°C. In the case shown in Fig. 13 not only SH PAWs can detect the defects which are 146.3mm and 223.5mm away from the IUT, but also travel to the end of the plate and return back to the IUT as indicated by the echo $S_{H,1}$ with good SNR. Therefore for the 2mm thick Al plate SH PAW showed the best SHM capability.

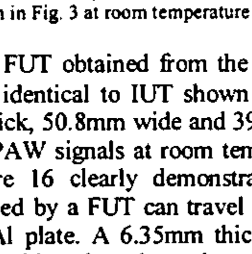

Figure 16. Ultrasonic SH PAW signals obtained using one FUT which replaces the IUT shown in Fig. 3 at room temperature with mode conversion.

Attaching one FUT obtained from the eight FUT array to the edge location identical to IUT shown in Fig. 3 with θ = 61.7° to a 2mm thick, 50.8mm wide and 393mm long Al plate, the reflected SH PAW signals at room temperature are shown in Fig. 16. Figure 16 clearly demonstrates that SH PAW excited and received by a FUT can travel a distance of 1.57m in a 2mm thick Al plate. A 6.35mm thick Al plate with the same plate width and length as those shown in Fig. 13 was also used as the sample which has same dimensions and locations of two line defects, D1' and D2'. The results indicated that two line defects, D1' and D2', can be clearly detected also by SH PAWs but with less SNR than those shown in Fig. 15.

V. Conclusions

Integrated (IUT) and flexible UT (FUT) have been developed using sol-gel spray technique. IUT and FUT located at the edge of a plate can be used to generate and receive symmetrical, anti-symmetric and SH PAWs using mode conversion technique. IUTs were operated in pulse/echo and transmission modes at temperature up to 150°C. The propagation lengths of PAWs could be more than hundreds of mms. Line defects with dimensions of 1mm width and ~1.0mm depth were detected by all three types of PAWs at 150°C. For the samples studied SH PAWs may be the best for in-situ long range SHM.

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