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ULTRASONIC PLATE WAVES FOR FATIGUE CRACK DETECTION IN MULTI-LAYERED METALLIC STRUCTURES (PREPRINT)

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Metals, Ceramics & Nondestructive Evaluation Division

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14. ABSTRACT
A representative area of concern for fatigue crack growth in aircraft occurs in multi-layered metallic structures. Ultrasonic plate waves are currently being investigated by multiple initiatives to detect these types of flaws with a minimal number of sensors to enable Structural Health Monitoring (SHM). Previous work has focused on structures with one or two layers, coupled with modeling of the wave propagation within these representative samples. However, it is common for multi-layered structures to have more than two layers in many areas of interest. Therefore, this study investigates ultrasonic wave propagation and flaw detection in a multi-layered samples. The flaws in this study are electric discharge machined (EDM) notches. Preliminary measurements show that EDM notches can be detected by the guided ultrasonic waves, but that the sensitivity to EDM notch location is dependent on the boundary conditions of each layer. The experimental results are supplemented by modeling of the guided wave propagation within the structure using the Finite Element Method. The results of this investigation establish some guidelines for the use of guided waves in multi-layered structures, plus challenges that exist for their use in SHM applications and strategies to address these challenges.

15. SUBJECT TERMS
aircraft structures, cracks, finite element method, guided waves, structural health monitoring

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Ultrasonic Plate Waves for Fatigue Crack Detection in Multi-layered Metallic Structures

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ABSTRACT

A representative area of concern for fatigue crack growth in aircraft occurs in multi-layered metallic structures. Ultrasonic plate waves are currently being investigated by multiple initiatives to detect these types of flaws with a minimal number of sensors to enable Structural Health Monitoring (SHM). Previous work has focused on structures with one or two layers, coupled with modeling of the wave propagation within these representative samples. However, it is common for multi-layered structures to have more than two layers in many areas of interest. Therefore, this study investigates ultrasonic wave propagation and flaw detection in a multi-layered sample consisting of 2 to 4 total layers with fatigue cracks located in only one layer. The samples contain fastener holes configured as would be expected to find on typical aircraft structure. The flaws in this study are represented by electric discharge machined (EDM) notches. Preliminary measurements show that EDM notches can be detected by the guided ultrasonic waves, but that the sensitivity to EDM notch location is dependent on the boundary conditions of each layer. The boundary conditions are changed by applying various loads on the surface of each layer by tightening and loosening the fasteners that hold the sample together. This variation depicts representative conditions found of aircraft. The experimental results are supplemented by modeling of the guided wave propagation within the structure using the Finite Element Method. The primary parameter studied in the modeling effort is the effect of the changes in the boundary condition on the mode and amplitude of the guided wave. The results of this investigation establish some guidelines for the use of guided waves in multi-layered structures, plus challenges that exist for their use in SHM applications and strategies to address these challenges.

Keywords: aircraft structures, cracks, finite element method, guided waves, structural health monitoring.

1. INTRODUCTION

Multi-layered aircraft structure have been investigated to determine the potential to monitor these structures using on-board sensors to determine if damage in the structure can be detected without disassembling the structure. The sensing method typically used in these studies uses ultrasonic plate waves, or specifically Lamb waves [1-2]. A review highlighting these efforts is presented in the next section of this paper. These efforts supplement previous work in the field of Nondestructive Evaluation (NDE) to explore using similar inspection techniques for field and depot inspections with the objective of minimizing the disassembly of the aircraft structure. Note that this type of sensing is also critical for the new methodology of maintaining US Air Force aircraft, which includes performing maintenance when it is required, rather than on a set time-table of periodic inspections [3].

Lamb waves are well known in the NDE research community. These ultrasonic waves are bound to the upper and lower surfaces in the sheet or plate in which they are traveling, which makes them two-dimensional waves [4]. As such, the propagation of these ultrasonic waves is dependent on the boundary conditions of the two surfaces. Therefore, changes in the boundary conditions can change the propagation characteristics of the ultrasonic wave. This is true for all plate modes, including the lowest order symmetric and anti-symmetric modes [5]. The objective of this paper is to present a case study representing typical multi-layered joints in aerospace structures to investigate the effect of changing boundary conditions on guided wave inspection of fastener sites using simulated and experimental studies.

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2. BACKGROUND ON GUIDED WAVES FOR MULTI-LAYER STRUCTURE INSPECTION

Representative two-layered aircraft structures are shown in Figure 1 [6]. At the location shown in this figure, there are only two layers of material. However, this configuration is common only in areas that require a form of reinforcement to support large open areas, such as wing and fuselage skins. In areas of increased stress, it is common to have some form of support stringer in addition to the two layers. Generic representative aerospace joints are shown in Figure 2. The simple lap joint will only have two layers present, as shown in Figure 2(a). However, it is very common for lap joints to have a stringer supporting the joint in this location, as shown in Figure 2(c). Another type of joint commonly seem in aircraft is a butt-joint, shown in Figure 2(b), which typically has at least three layers. The total number of layers in a joint will depend on the number of intersecting surfaces that need to be joined together. A representation of this additional level of complexity is shown in Figure 2(d), which includes a fourth layer in the joint.

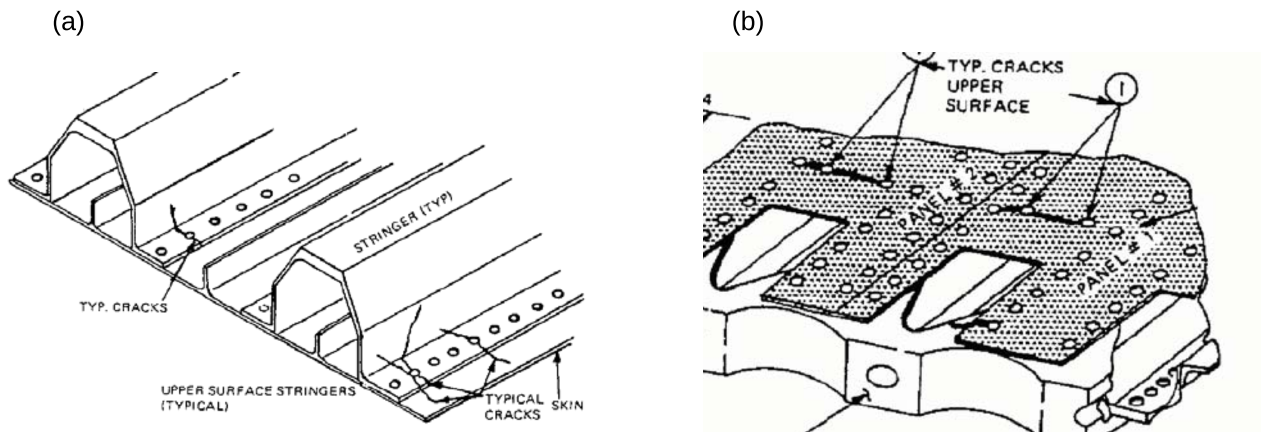

Fig. 1. Complex joints in aerospace wing structures: (a) C-130 hat section, (b) C-130 rainbow fitting.

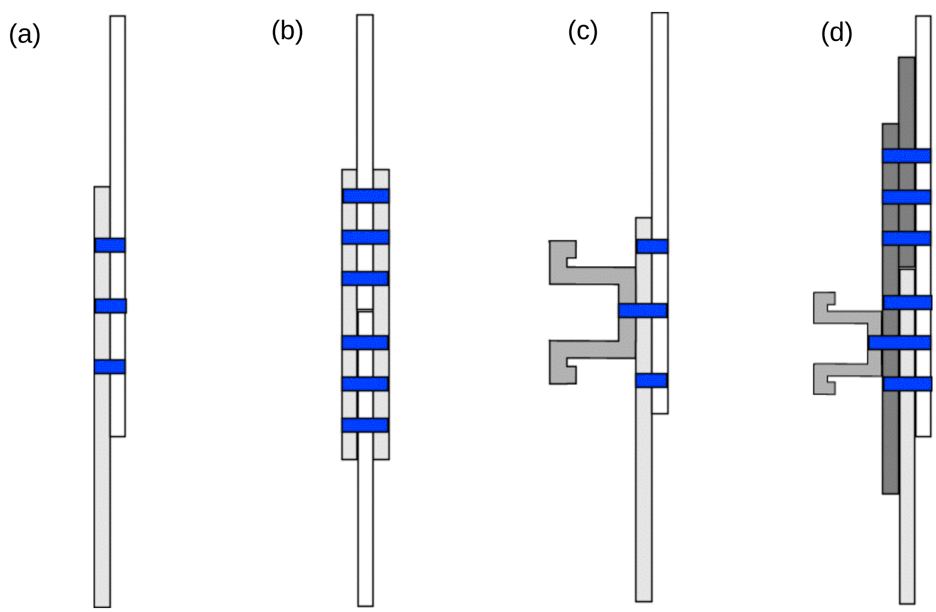

Fig. 2. Typical multilayer joints in aerospace fuselage structures: (a) simple lap joint, (b) three layer splice joint, (c) lap joint with stringer, (d) lap splice joint with stringer and additional reinforcements.

This brief overview of aerospace joint configurations demonstrates that many joints of interest typically have more than two layers. This is especially true for structures that experience significant loading and stress during operation of an aircraft. It is these areas that typically need to be inspected for fatigue cracks, which is why it is important to consider the effect of constraining the boundary of the layers when inspecting an internal layer in these components using plate wave techniques.

The majority of prior work on aircraft joints concerns the use of Lamb waves to evaluate the quality of adhesively bonded aerospace components. Rokhlin developed analytical models for incident A_0 and S_0 mode guided waves at a finite region between two plates under rigid or slip conditions [7]. Through analytical and experimental studies, sensitivity to the bonded region state was demonstrated through changes in Lamb wave transmission and mode conversion at bond edges (for select frequencies and modes). Early experimental work also studied the practical application of lamb waves for detecting disbonds at lap splice joints [8] and T-peel joints [9]. Lowe and Cawley studied the dispersion relations for two plates with an adhesive layer [10]. Alternative inspection configurations using laser ultrasonics [11] and in situ magnetostrictive sensors [12] have been investigated for disbond characterization. A promising application of in situ sensing concerns adhesively bonded composite structures. Recently, Matt et al studied guided wave monitoring for a composite wing skin-to-spar structure through simulated and experimental studies [13]. Best sensitivity to defects was identified as the mode coupling point between the S_0 and A_1 carrier modes. In experimental work, the degradation of the bond was found to increase the transmission of guided waves across the region. However, in experimental studies, poorly cured bounds were found to transmit more energy than fully disbonded joints.

Interface conditions for metallic joints can vary widely across aircraft in commercial and military aviation. Fastened joints are often attached with sealant layers or even adhesive bonds; however, the uniformity and quality of the thin layers between aircraft panels may not be consistent. Fastened metallic joints have been studied for the inspection of corrosion and fatigue cracks using guided waves. Sun and Johnston studied the interaction of Lamb waves across a joint with rivet rows for the detection of corrosion via thickness loss [14]. Experimental results demonstrated a high sensitivity of the technique to frequency, hole separation and pattern, hole size, plate thickness, and rivet tightness. Dalton et al have extensively studied the challenges for using guided waves for large area coverage of aircraft fuselage structure [15]. The finite element method was used to simulate the dynamic response at a joint for both sealant and adhesive layer cases. Incident S_0 mode guided waves (at 1.0 – 1.5 MHz) were found to be attenuated by the presence of the adjacent layer, and exhibit a high sensitivity to joint length due to wave interference in the overlap region. Thus, limitations in the practical application of guided waves across multiple joints were highlighted. Although lower frequency studies at 100 kHz representing an acoustic emission event were demonstrated with the potential to propagate across multiple joints, resolution limitations for the technique are present. Recently, Giurgiutiu has demonstrated the design and application of guided waves from embedded sensors for the detection of cracks in lap splice joints [16].

Several efforts have investigated numerical models to study the interaction of Lamb waves with varying contact conditions at joints. Drinkwater et al studied the use of Lamb waves to characterize solid-solid interfaces [17]. A model of the interface as normal and tangential springs was used and the layer stiffness matrix method was applied to calculate the dispersion curves. Although the phase velocity of the guided waves in the glass plate were unaffected by the presence of a rough elastomer, the attenuation of the transmitted A_0 and S_0 modes were found to be sensitive to the elastomer loading condition. The normal stiffness was found to more greatly affect the attenuation of the A_0 mode while the tangential stiffness more greatly impact the S_0 mode. Thus, the use of both modes was proposed to fully characterize the interface condition in terms of normal and tangential stiffness. Good agreement was also found between the Lamb wave measurements of loading condition and the actual measured load using validated normal incidence measurements. Recently, numerical models were investigated by Hosten and Castaings for joints with weak interfaces and good agreement with prior experimental results was achieved [18]. Heller et al has also demonstrated good agreement between the analytical spring model for a bonded layer and experimental results using Lamb waves [11]. In addition, Dalton used FEM models to study the problem of coupling between the two layers and good agreement was found with experimental results for both adhesive and sealant layers [15].

Lastly, Song et al explored the problem transmission and reflection of the A_0 mode at an interface at overlapping panel regions of varying length [19]. A hybrid method incorporating a semi-analytical finite element method (FEM) and boundary element method (BEM) was used to explore the effect of varying frequency and overlap length on the reflection and transmission ratio. Perfect contact conditions between the two layers were assumed. Only very short contact regions with a maximum of 12.7 mm were studied. The response of transmission and reflection coefficients was found to be generally quite complex with many peak and valleys due to the interference of multiple scattered and mode-converted signals within the overlap region. Higher levels of transmission of the A_0 and S_0 modes were found at low frequencies (< 100 kHz) for all overlap lengths.

To build on prior work, this study presents the application of numerical models with experimental studies for multilayer structures. Both lower to higher frequency Lamb waves are considered here for the inspection of the joint between multiple layers. At lower frequencies, the S_0 mode lamb wave source was used. For higher frequency, an angled-beam shear wave inspection with incident angle of 62 degrees was used. The modeling work was performed for two-layered structures to investigate, amongst other items, the effect of boundary conditions at the surfaces of the interface between two layers on the propagation of the ultrasonic signal.

3. SIMULATED STUDIES

Figure 3 presents a diagram of a two layer joint with an ultrasonic transducer for guided wave inspection. The FEM package, FEAP, was used to solve the 2D explicit finite element model for the elastodynamic problem [20]. Integration with Matlab was facilitated using FEAPMEX to implement sophisticated transducer models, consider arbitrary interface conditions between plates in contact, and facilitate parametric studies. In addition, perfectly matched layers were implemented as absorbing boundary conditions to reduce the size of the meshed domain and minimize solution time [21]. A parametric model was constructed to simulated either adhesive or sealant layers between plates as 1) a finite material layer using finite elements, or 2) a stiffness interface modeled using longitudinal (K_L) and tangential (K_T) springs between adjacent nodes. Both low and high frequency guided wave inspections of the joint region are presented using this numerical model.

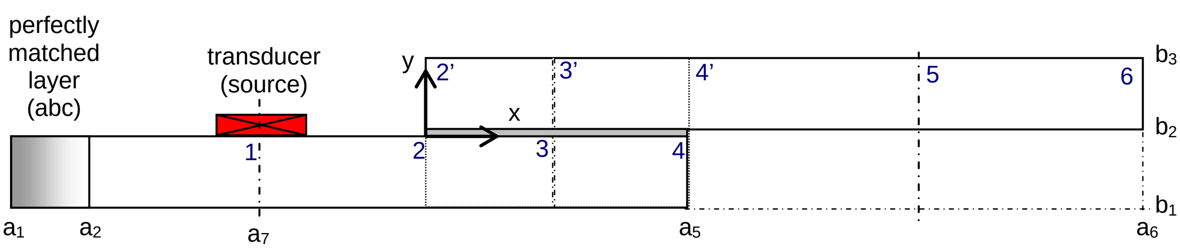

Fig. 3. Diagram of a two layer joint with transducer source and point response locations.

An inspection using low frequency (200 kHz) Lamb waves of S_0 mode generated by piezoelectric wafer sensors was first explored. This frequency-plate thickness combination (f·d = 0.612 mm·MHz) represents a frequency range where the Lamb waves are limited to A_0 and S_0 modes. The corresponding transducer dimensions were tuned for optimal generation of the S_0 mode based on the approach proposed by Giurgiutiu [16]. The model parameter values for the Lamb wave study are as follows: a_1 = -0.229 m (-9.0 in), a_2 = -0.152 m (-6.0 in), a_5= 0.076 m (3.0 in), a_6= 0.229 m (9.0 in), a_7= -0.076 m (-3.0 in), b_1 = 3.06 mm (0.120 in), b_2 = 0.765 mm (0.030 in), b_3 = 3.83 mm (0.151 in), and the material properties of aluminum were used for the two plates.

Transient results are presented in Figure 4 for a baseline case, the 'perfect' interface, where the interface layer material properties were set to aluminum, the same material of the layers. The position for the select point response locations (1,2,2',3,3',4,4',5) can be found in Figure 3. Both the vertical (u_y) and horizontal (u_x) displacements are plotted. Note, S_0 mode Lamb waves have a predominant horizontal (u_x) response at the surface (with no vertical motion at the plate centerline), while A_0 mode Lamb waves have a predominant vertical (u_y) response at the surface (with no horizontal motion at the plate centerline). For the case of a perfect interface, three significant reflections of the incident S_0 are found that return to the source transducer. First, a significant reflection of the incident S_0 wave is observed from the front of the joint (where the top plate begins). Second, a smaller but significant reflection of the incident S_0 wave at the back of the joint (where the lower plate ends). A third significant reflected S_0 wave was observed to propagating through the joint, reflect off of the end of the top plate and return through the joint region to the source transducer location. Mode conversions of the S_0 mode at transition points in the joint are observed; however, at lower frequencies the magnitude of A_0 modes Lamb waves is small.

Although significant signals propagating through the joint with limited attenuation provide the means to interrogate joints for damage conditions (fatigue cracks, corrosion), one concern is their relative sensitivity to inherent variations in joint interface conditions over time. Although some degradation of the joint in terms of adhesion quality for bonded joints will concern overall structural integrity, inherent variations in metallic contact conditions, thermal loading, curing of adhesive layers, and aging of the sealant layers may cause changes to the measurement signals resulting in unwanted false calls. A basic demonstration is presented varying the stiffness interface between four levels: (a) a very stiff interface ($K_L = K_{L0}$, $K_T = K_{T0}$), (b) a moderate interface ($K_L = 0.1 \cdot K_{L0}$, $K_T = 0.1 \cdot K_{T0}$), (c) a fluid interface ($K_L = K_{L0}$, $K_T = 0.0$) (d) a very weak interface ($K_L = 0.001 \cdot K_{L0}$, $K_T = 0.001 \cdot K_{T0}$). Figures 5 and 6 show the RMS displacement response for the entire joint region for two shapshots in time, when the S_0 wave reaches the end of the joint and when S_0 reaches the end of the top plate respectively. Of particular interest is the fluid interface, which does not promote the transmission of the S_0 mode Lamb wave from the bottom to the top layer. Thus, there is a concern as a firm sealant interface at a joint degrades over time (resulting in weak shear stiffness between the joints) that the use of S_0 mode Lamb waves may not be viable for inspection of multiple layers. Note, relatively weaker A_0 mode Lamb waves do transmit well to the top layer for both moderately stiff and 'fluid' layer joint interfaces.

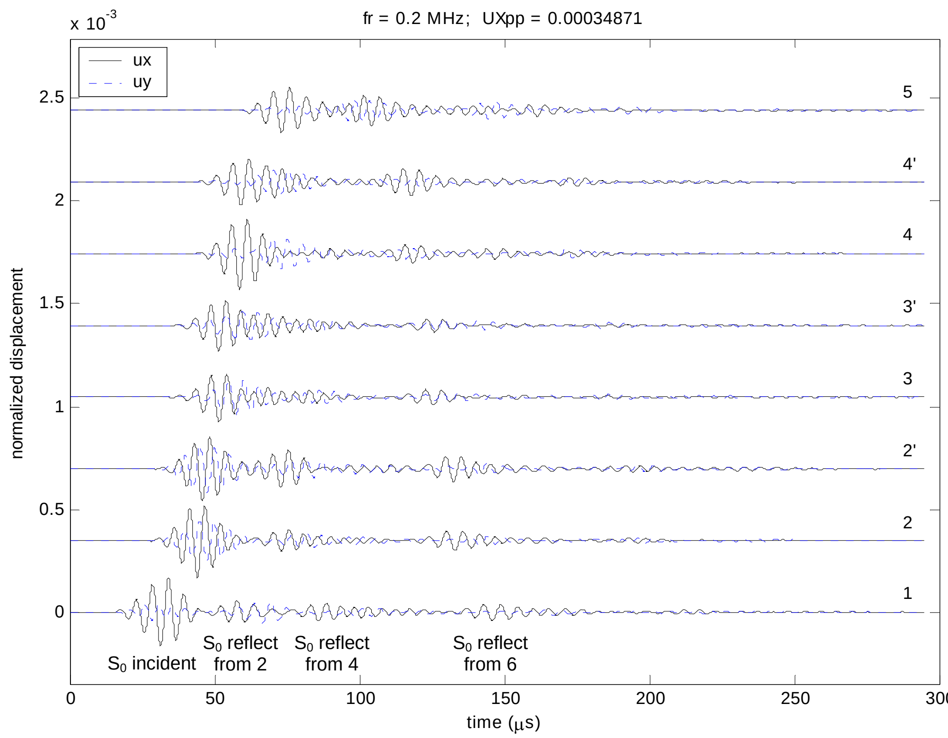

Fig. 4. Displacement response at select points with center frequency at 200 kHz.

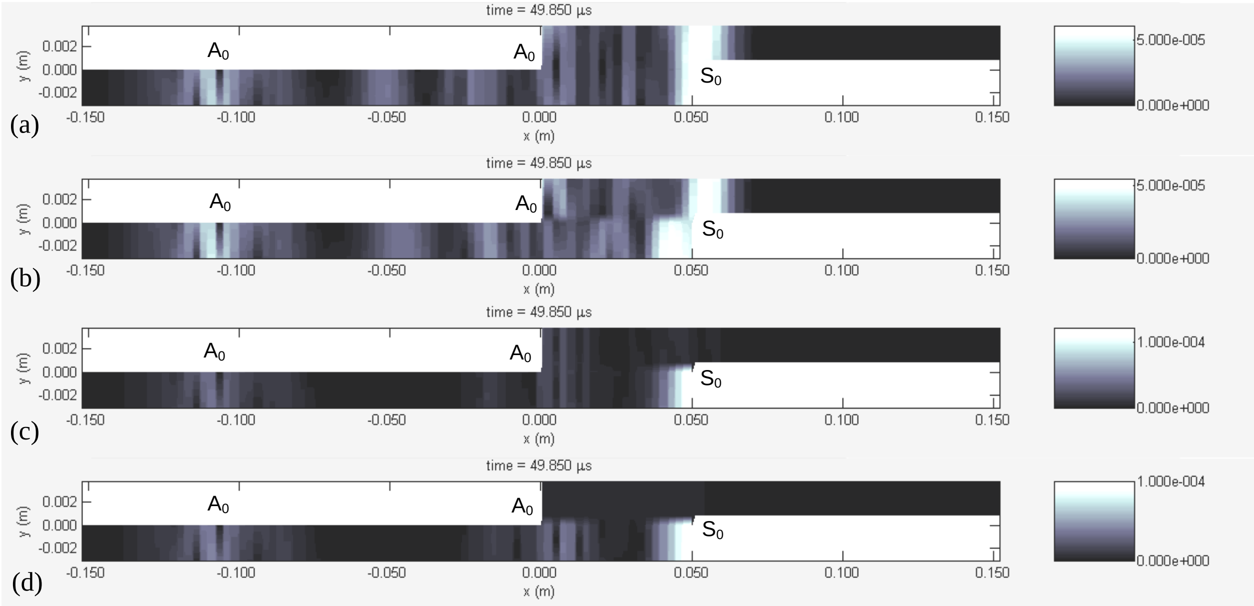

Fig. 5. RMS displacement map for joint region - center frequency at 200 kHz – (a) a very stiff interface, (b) a moderate interface, (c) a fluid interface, (d) a very weak interface.

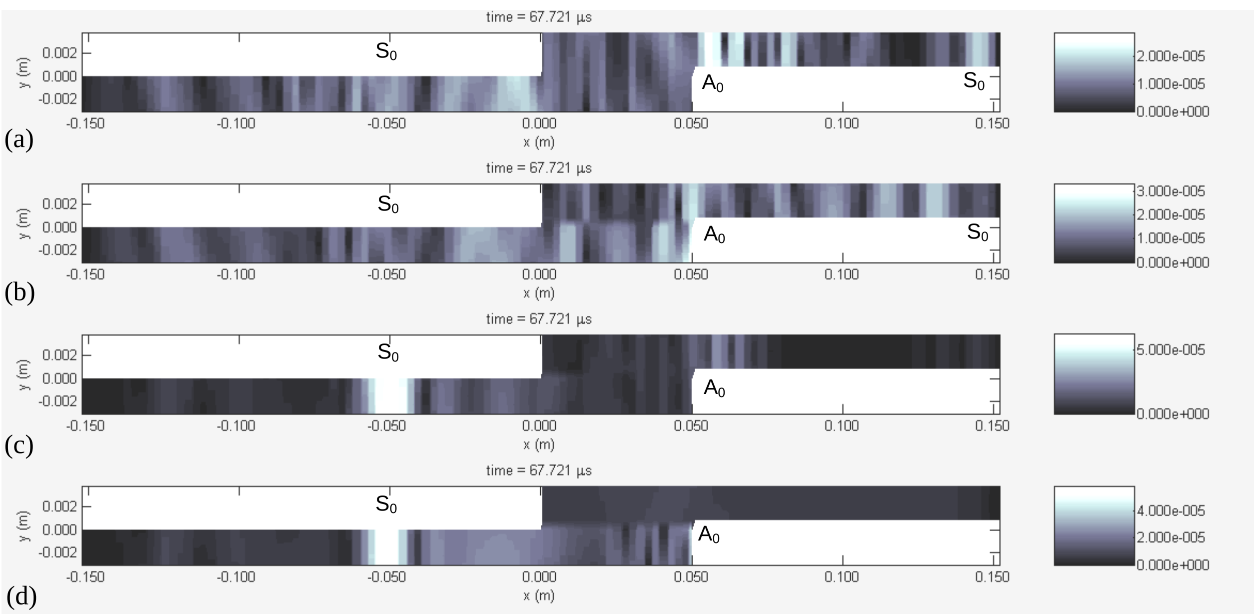

Fig. 6. RMS displacement map for joint region - center frequency at 200 kHz – (a) a very stiff interface, (b) a moderate interface, (c) a fluid interface, (d) a very weak interface.

The numerical model was also used to investigate a high frequency (5.0 MHz) guided wave inspection using an angled beam shear wave source. A diagram of the inspection configuration for the joint using a wedge shear wave transducer is presented in Figure 7. This study represents techniques that have been developed for the inspection of fastener sites in joints with limited transducer accessibility. The model parameter values for the high frequency guided wave study are as follows: a_1 = -76.2 mm (-3.0 in), a_2 = -40.6 mm (-1.6 in), a_5= 25.4 mm (1.0 in), a_6= 76.2 mm (3.0 in), a_7= -25.4 mm (-1.0 in), b_1 = 3.06 mm (0.120 in), b_2 = 0.191 mm (0.008 in), b_3 = 3.25 mm (0.128 in), f = 5.0 MHz (f·d = 15.3 mm·MHz), angle of incident for shear wave in the plate = 62º, and the material properties of aluminum were used again for the two plates. Solution time for the high frequency transient simulation was 16 hours on a Pentium 4 2.53 GHz with 1 GB RAM. Again, to explore the question of measurement sensitivity to joint interface conditions, simulated studies are presented varying the stiffness interface between three levels: (a) a very stiff interface ($K_L = K_{L0}$, $K_T = K_{T0}$), (b) a fluid interface ($K_L = K_{L0}$, $K_T = 0.0$) and (d) a very weak interface ($K_L = 0.001 \cdot K_{L0}$, $K_T = 0.001 \cdot K_{T0}$). Figures 8 and 9 show the RMS displacement response for the entire joint region for two shapshots in time, when incident pulse reaches midway through the joint and when the main reflected pulse (for the very weak joint) is reflected and returns to the source transducer position. For both very stiff and fluid interfaces, as the primary guided wave shear pulse reaches the bonded region, a combination of dispersion, reflection (off of the side walls), spreading and transmission to the top layer is observed. This complex interaction of the high frequency guided wave in joint regions may hinder its practical application for inspection of the lower layer. Similar trends are also observed in the prior work concerning the sensitivity of the magnitude of reflected and transmitted waves as the frequency becomes high (> 1 MHz) [19].

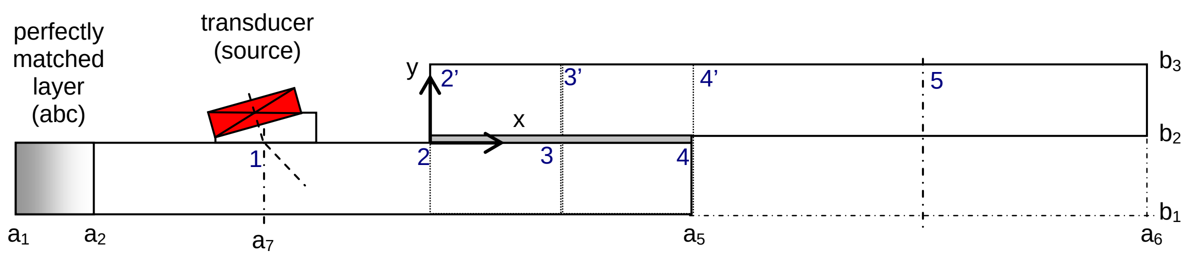

Fig. 7. Diagram of a two layer joint with angled beam shear wave transducer source.

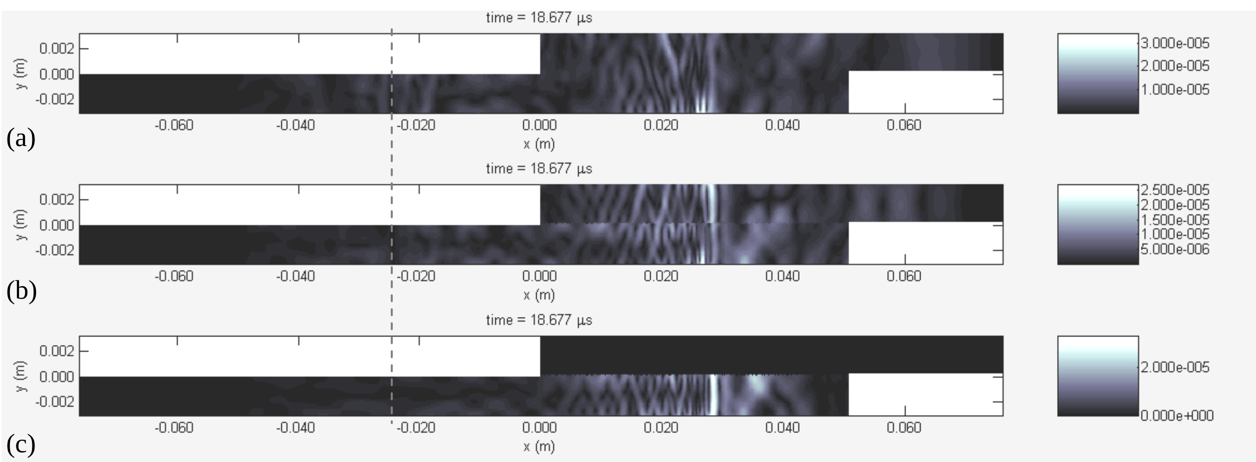

Fig. 8. RMS displacement map at 18.7 µs for a joint region with center frequency at 5.0 MHz for (a) a perfect interface, (b) a fluid interface, (c) a very weak interface.

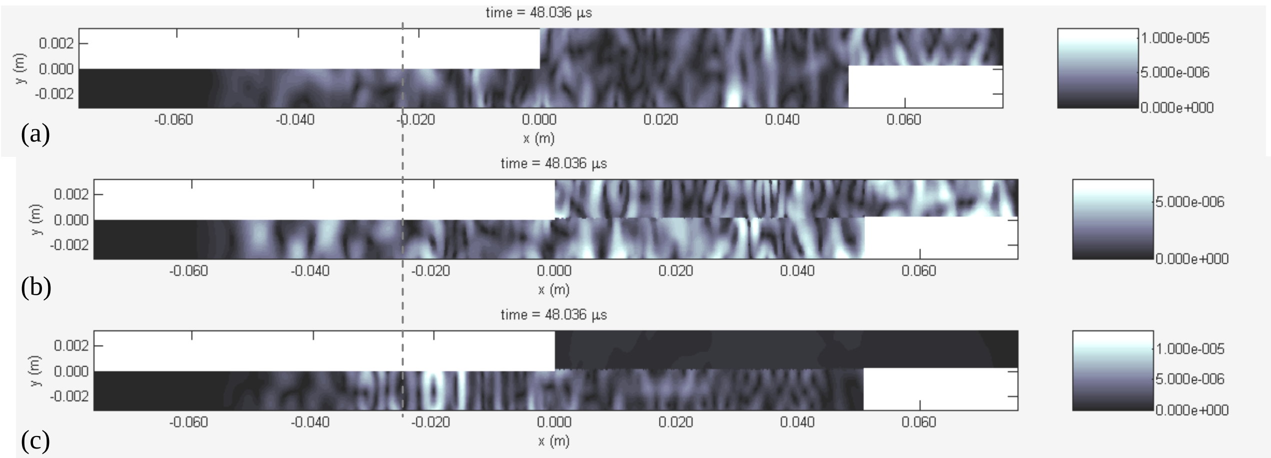

Fig. 9. RMS displacement map at 48.0 µs for a joint region with center frequency at 5.0 MHz for (a) a perfect interface, (b) a fluid interface, (c) a very weak interface.

4. EXPERIMENTAL STUDIES

The samples consisted of an aluminum sheet that was 3.2 mm thick and measured 350 x 50 mm in size. The sample had 10 holes drilled into it that measured 4.76 mm in diameter. The center of each hole was separated by 25.4 mm. EDM notches were placed in the second and seventh hole when counting from the location where the transducer was placed on the sample. The EDM notches were 2.5 mm through wall notches and were oriented in the same direction relative to the hole in the sample, which was perpendicular to the direction of ultrasonic wave propagation. The signal was generated using a commercial ultrasonic spike pulser and detected in a pulse-echo configuration using a 100 MHz sampling digital oscilloscope. It is important to note that all the gain and amplitude settings for the excitation equipment were held constant for all the experimental measurements to insure uniform settings when comparing the results from the different sample configurations and locations of the defects. Additional measurements were performed when a thin sheet of aluminum measuring 1.6 mm thick with no defects was placed on both surfaces of the thicker sheet with no liquid present at the surfaces and with a liquid, mineral oil, at the surfaces. A fluid layer at the interface has previously been used to represent an application of sealant between panel layers and wet installation of fastener sites. Similar measurements were performed with the two outer sheets being 3.2 mm thick and with or without liquid at the interfaces. The amplitude and time scale on the digital oscilloscope was changed as a function of fastener hole or EDM notch location. It is possible to perform a comparison in the amplitude of the reflection from each feature inside the sample as a function of additional layers and liquid between the layers in the samples, but this analysis must include any possible changes in the amplitude and time scales. A photograph of the sample with the two thin sheets and the 5.0 MHz transducer in place is shown in Figure 10.

Figure 10. Photograph of 3.0 mm thick sheet with the transducer located on it, plus the two 1 mm sheets fastened to either surface of the 3.0 mm thick sheet.

Figure 11 shows the digital oscilloscope traces of the reflection from the wall of the first fastener hole under the following conditions, going from left to right and top to bottom: a) single layer free surfaces, b) two thin layers clamped to center layer, c) two thin layers clamped to the thicker center layer with mineral oil at both interfaces, d) two thicker layers clamped to the center layer, and e) two thicker layers clamped to the center layer with mineral oil at both interfaces. Note that the trace in each figure has a time scale on the horizontal axis of 20 microseconds per division except for Figure 11(a) where it is 10 microseconds per division. Also, the vertical amplitude scale is the same for all traces in the Figures, set at 2 Volts per division except for Figure 11(e), where it is 1 Volt per division.

Comparison of the results in these five figures indicates that the amplitude of the reflection from the first fastener hole, which is located 25 mm from the transducer and included approximately half of its travel distance between the clamped layers for the results shown in Figures 11(b) – 11(e), indicate that the presence of a liquid at the interface between the layers has a significant effect on the amplitude of the reflected signal from the fastener hole. This is evident by a decrease in signal amplitude of approximately 50 percent for the two samples with liquid at the interface between the layers. However, analysis of the ultrasonic wave propagation indicates that it is possible for this signal to couple directly into the additional layers and that the signal loss could be due to this coupling. If this is the case, the change in ultrasonic travel path as a function of sealant, which is well known to couple ultrasonic signals form one layer to the next, must be accounted for in the analysis of the results from this inspection configuration. However, to assess the effect of presence of liquid between the interfaces for longer propagation distances, the reflections from the EDM notch

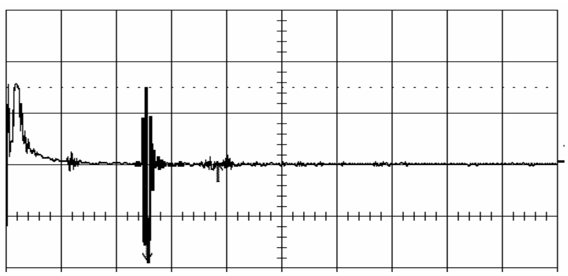

Fig. 11(a). Reflection from first hole with free surfaces.

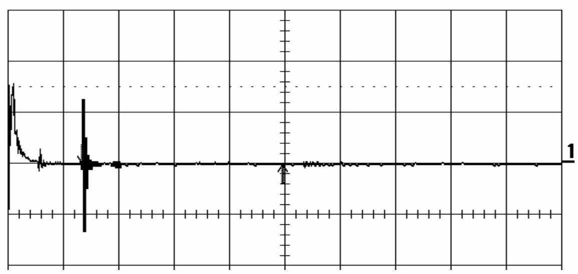

Fig. 11(b). Reflection from first hole clamped by two thin sheets.

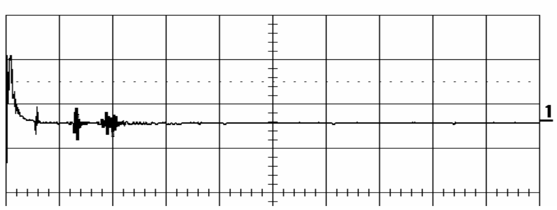

Fig. 11(c). Reflection from first hole clamped by two thin sheets with mineral oil at both interfaces.

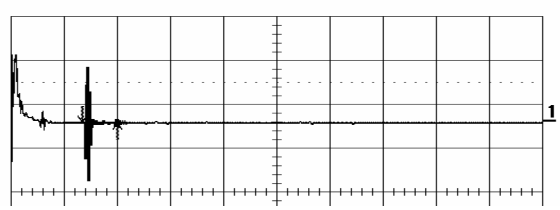

Fig. 11(d). Reflection from first hole clamped by two thick sheets.

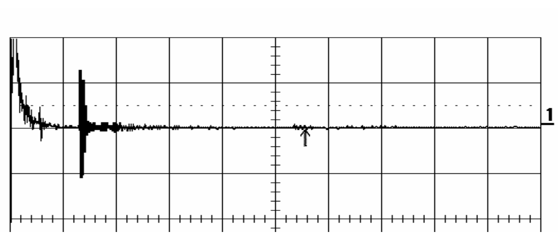

Fig. 11(e). Reflection from first hole clamped by two thick sheets with mineral oil at both interfaces. Note that this is the only figure where the vertical scale is 1 volt per division.

located at the sixth hole are compared for the same five experimental configurations shown in Figure 11. These results are shown in Figure 12, which shows the digital oscilloscope traces from the following experimental conditions, going from left to right and top to bottom: a) single layer free surfaces, b) two thin layers clamped to center layer, c) two thin layers clamped to the thicker center layer with mineral oil at both interfaces, d) two thicker layers clamped to the center layer, and e) two thicker layers clamped to the center layer with mineral oil at both interfaces. Note that the trace in each Figure has a time scale on the horizontal axis of 20 microseconds per division. Similarly, the vertical amplitude scale is the same for all traces in the figures, set at 1 Volt per division.

The results from Figure 12 demonstrate the promise of using Lamb wave based methods to detect fatigue cracks located in multi-layered structures, but also expose some of the considerations that must be included in the analysis of results from this type of inspection. Note that the signal from the EDM notch is readily apparent in the sample without any clamping on the surfaces. The amplitude systematically decreases for the samples with changed boundary conditions with the applied clamping force from the addition of aluminum sheets to the free surfaces of the samples. When a liquid is introduced at the interface between the layers, the amplitude is further decreased. For the signal with thin sheets, there is no evidence of the signal from the EDM notch. A portion of this reduced signal could be due to the manual alignment of the transducer on the sample surface, but all efforts were made to maximize the amplitude of the signal from the EDM notch. Another factor that could affect the amplitude of the signal is localized variations of the clamping force applied to each bolt in each fastener hole. However, these variations appeared to be relatively small when compared to the changes in amplitude induced by the overall coupling of the additional sheets and the addition of a liquid at the interfaces between the layers.

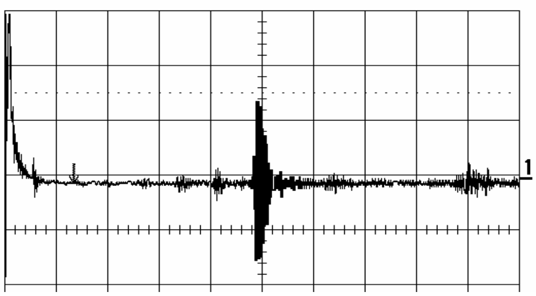

Fig. 12(a). Reflection from the EDM notch at the sixth hole with free surfaces.

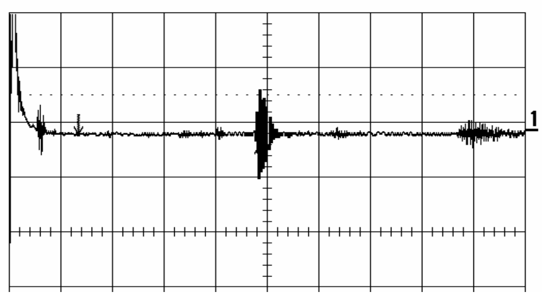

Fig. 12(b). Reflection from the EDM notch at the sixth hole clamped by two thin sheets.

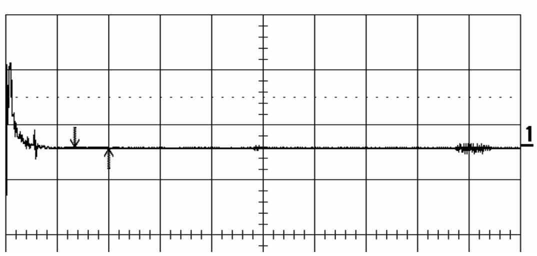

Fig. 12(c). Reflection from the EDM notch at the sixth hole clamped by two thin sheets with mineral oil at both interfaces.

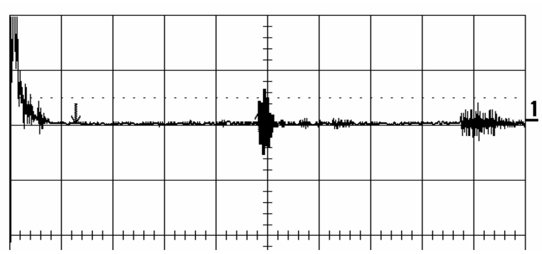

Fig. 12(d). Reflection from the EDM notch at the sixth hole clamped by two thick sheets.

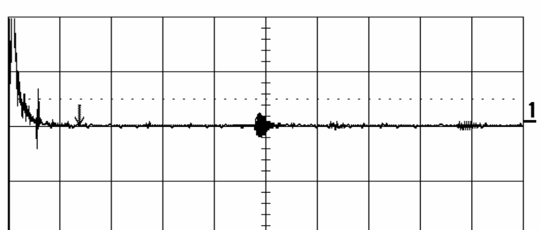

Fig. 12(e). Reflection from EDM notch at sixth hole clamped by two thick sheets with mineral oil at both interfaces.

5. DISCUSSION OF RESULTS

The experimental and modeling efforts indicate that the surface conditions of each layer in a lap joint or other typical multi-layered aerospace structure will affect the propagation of ultrasonic plate waves when this interrogation method is used to detect defects such as fatigue cracks in the layers. Changes in the surface conditions, such as those induced by the presence of fluids and/or loading the surfaces of the sample in which the plate waves are propagating, will vary the boundary conditions which will alter the behavior of the wave propagation. The potential source for these variations in aerospace structures includes the presence of sealant, variations in fastener loading, variations in fastener spacing, and other design/assembly variables that are encountered during the realization of the product.

For an ultrasonic Lamb wave propagating in a plate that has relatively free surfaces, the wave can propagate long distances and be used to detect defects that are located far from the excitation and reception point of the ultrasonic signal. However, when the conditions of the boundary change and the surfaces of the plate are constrained, the wave propagation is altered due to the interaction of the wave propagation at the surface. The results presented here indicate that the potential to use this approach for long distances is limited by the increased energy dissipation as the plate wave propagates along the length of the plate, which results in less sensitivity over areas typically encountered in multi-layered joints. Decreasing the frequency of the ultrasonic signal, which will increase the wavelength of the plate wave, should enable the wave to propagate longer distances, but would decrease the sensitivity of the inspection process to smaller fatigue cracks.

It is worthwhile to note that the modeling and experimental results were performed for only multi-layered structures that includes up to three layers and that all three layers were of the same type of material, namely aluminum alloys. Preliminary measurements performed with other materials, such as using aerospace steel in place of the exterior aluminum sheets in the configuration used in the experimental work, will cause additional changes in the plate wave propagation. In the case of steel plates, the effect appears to be an increase in the attenuation of the ultrasonic signal even without any liquids present at the interface. Other factors that need to be investigated include the effect of additional material combinations, additional number of layers, and changes in the bond condition along the length of the multi-layered structure. For example, if sealant is present between two layers, it is possible that the sealant layer is intermittent, is not continuous, and may have experienced changes in its elasticity as a function of age and environmental exposure. In addition, the loading conditions across a plate can vary as a function of time as a result of the stress experience during flight, thus impacting in situ measurements. Another factor that will be required to be evaluated for the detection of fatigue cracks at fastener holes is the variation in the fit of fasteners in fastener holes. The tightness of this fit can affect the magnitude of the reflected ultrasonic signal from this interface, which can lead to additional scattering and/or absorption of the ultrasonic energy. The resulting attenuation could affect the ability to detect potential flaws located in the region where such changes occur.

The number of potential confounding factors when using plate waves is not trivial. However, the work reported in the literature, including success stories [1], indicate plate wave techniques have significant potential. Additional studies are required to address the various confounding factors for multi-layered structures mentioned in the previous paragraph and the full effect of these factors must be assessed to determine the applicability of these techniques to a variety of potential structural geometry variations that are encountered in aerospace structures. Another factor to be addressed by future work includes the presence of integrated stiffeners, which can be found in areas being inspected, including as components of multi-layered joints. These geometric features will interact with plate wave propagation [21] and must be included as a component of the future research when exploring the use of plate waves for inspecting these structures.

6 SUMMARY

The work described in this paper summarized initial efforts to evaluate the effect of varying the boundary conditions in a simulated multi-layered aerospace structure on the propagation of ultrasonic plate waves. Theoretical modeling was performed using finite element methods and indicates that changing the condition of the interface between the layers affects the ultrasonic wave propagation and the magnitude of energy coupled from one layer to the adjacent layer. Experimental studies indicate that the loading of the surfaces of a plate of aluminum with adjacent plates of the same material can dampen the ultrasonic wave propagation in the center plate. The amount of dampening is increased when a liquid is incorporated into the interface between the plates. The experimental and theoretical work indicates the interface condition between plates, which affects the boundary conditions of the plate in which the ultrasonic wave is propagating, must be evaluated when developing inspection methods using ultrasonic plate waves for multi-layered structures. Additional features to be evaluated that could have similar effects on the ultrasonic plate waves include the material used for each layer, changes in the bond condition between layers, variations in the sealant conditions between layers, and differences in the fastener fit conditions in the region being inspected. Thus, additional research is required before plate wave-based inspection of fatigue cracks can be deployed for SHM, field, and depot based NDE of aerospace structures.

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