Corrosion detection using piezoelectric wafer active sensors

by

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Abstract

In the early 2000's the Air Force was very interested in developing smart structures. Of unique interest was a structure that could be equipped with in-situ sensors that could detect damage under normal operating conditions. The idea was that the United States Air Force could save millions of dollars every year by building aircraft with an inherent way of detecting its own life-cycle damage like stress cracks or corrosion. This would significantly reduce the burden of sending thousands of aircraft to a depot for costly and time-consuming non-destructive evaluations and inspections. This research report focuses on developing an in-situ method for detecting material loss in metal structures using Piezo-electric Wafer Active Sensors (PWAS) and presents a path forward to make this technology operationally viable.

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PWAS:	*Piezoelectric Wafer Active Sensors*

SUMMARY OF RESEARCH

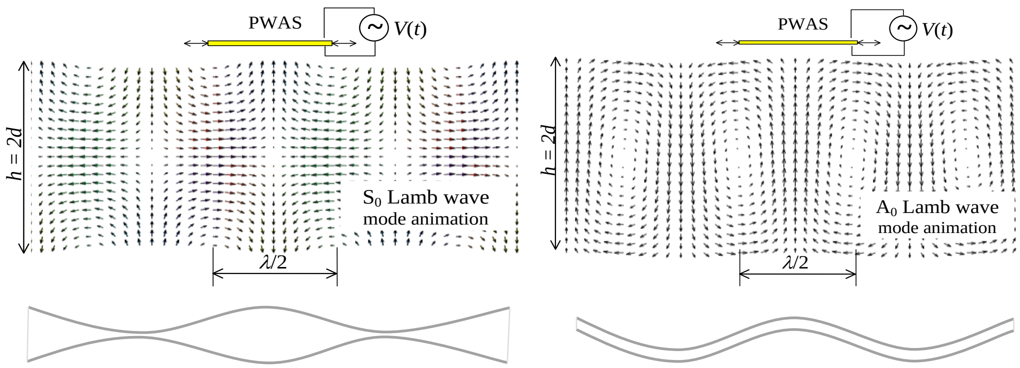
INTRODUCTION

Since the Air Force's aging, legacy fleet is now intended to far exceed their proposed design life, monitoring the structural integrity of those aircraft has become a priority issue. One of the most critical structural problems is corrosion. In the early 2000's the KC-135 cost $1.2 billion a year to find and repair corrosion. This paper demonstrates the use of Lamb waves (named after Horace Lamb who initially described the motion of elastic waves through a thin plate) to detect material loss in thin plates representative of aircraft skins. To detect simulated corrosion, embedded transducers called Piezoelectric Wafer Active Sensor (PWAS) were used in a pitch-catch configuration. Material loss through corrosion was simulated using an acid etching technique that simulated corrosion pits of various depths. The PWAS generated Lamb wave packets that were sent in a pitch-catch mode from one PWAS acting as a transmitter to the other PWAS acting as a receiver. The Lamb wave mode used in these experiments was A_0 since this was found to be more sensitive to changes due to material loss. At the frequencies considered in these experiments, the A_0 waves are highly dispersive. As the Lamb wave travels through simulated corrosion damage, the signal changes in wavelength (due to change in the dispersive properties of the medium) and in signal amplitude (due to redistribution of energy in the wave packet). These changes in the signal can be correlated to the magnitude of damage.

THEORY OF ULTRASONIC LAMB WAVES

By bonding a PWAS transducer to the top surface of a metal plate and exciting it with a harmonic electric voltage $V = V_0 e^{i\omega t}$ (1) elastic Lamb waves are excited inside the structure.

The PWAS induces interfacial shear stress, $\tau = \tau_0(x)e^{i\omega t}$ (2), on the plate which in turn creates propagating waves that can be either symmetric or antisymmetric (Figure).



(a) (b)

Figure 1. PWAS interaction with Lamb modes: (a) symmetric Lamb mode S0; (b) anti-symmetric Lamb mode A0

(Giurgiutiu, 2003) studied the general Lamb-wave response of the plate under PWAS excitation using the space-domain Fourier transforms of the basic Lamb wave equations. The strain-wave response was found in the form

$$\varepsilon_x(x,t) = \frac{1}{2\pi}\frac{-i}{2\mu}\int_{-\infty}^{\infty}\left(\frac{\tilde{\tau}N_S}{D_S} + \frac{\tilde{\tau}N_A}{D_A}\right)e^{i(\xi x - \omega t)}d\xi \quad (3)$$

where

$\tilde{\tau}$ is the Fourier transform of $\tau_a(x)$,

ξ is the wave number, $p^2 = \frac{\omega^2}{c_L^2} - \xi^2$, (4)

$q^2 = \frac{\omega^2}{c_T^2} - \xi^2$, (5)

$c_L^2 = (\lambda + 2\mu)/\rho$ is the longitudinal wave speed (6)

$c_T^2 = \mu/\rho$ is the transverse wave speed, (7)

λ and μ are Lamé constants for elastic material,

ρ is the mass density,

S and A signify symmetric and antisymmetric Lamb modes,

$$N_S = \xi q(\xi^2 + q^2) \cos p\,h \cos q\,h \tag{8}$$

$$D_S = (\xi^2 - q^2)^2 \cos p\,h \sin q\,h + 4\xi^2 pq \sin p\,h \cos q\,h \tag{9}$$

$$N_A = \xi q(\xi^2 + q^2) \sin p\,h \sin q\,h \tag{10}$$

$$D_A = (\xi^2 - q^2)^2 \sin p\,h \cos q\,h + 4\xi^2 pq \cos p\,h \sin q\,h \tag{11}$$

The complete derivation of these expressions can be found in (Giurgiutiu, 2004), pages 609-617. For ideal bonding between PWAS and the metal plate, a closed form solution provides:

$$\varepsilon_x(x,t) = -i\frac{a\tau_0}{\mu}\sum_{\xi^S} \sin \xi^S a \frac{N_S(\xi^S)}{D_S'(\xi^S)} e^{i(\xi^S x - \omega t)} - i\frac{a\tau_0}{\mu}\sum_{\xi^A} \sin \xi^A a \frac{N_A(\xi^A)}{D_A'(\xi^A)} e^{i(\xi^A x - \omega t)} \tag{12}$$

where

$a = l_a/2$ is the half-length of the PWAS, (13)

$a\tau_0$ is the total force transmitted by the PWAS to the structure

The $\sin \xi a$ terms provide opportunities to isolate Lamb wave modes. When the product ξa is equal to an odd multiple of $\pi/2$, the amplitude is at a maximum, and that particular Lamb wave mode is maximally excited. On the other hand, when the product ξa is a multiple of π, that Lamb wave mode is minimally excited.

For the experiment, a 1 mm thick 2024-T3 aluminum plate was used. By plugging the constants for 2024-T3 aluminum into the equations above, the maxima and minima can be tuned as shown below. Notice that the A_0 mode is almost solely generated below 100 kHz with the S_0

mode being only minimally excited. The next step was to analyze the dispersal characteristics in this region.

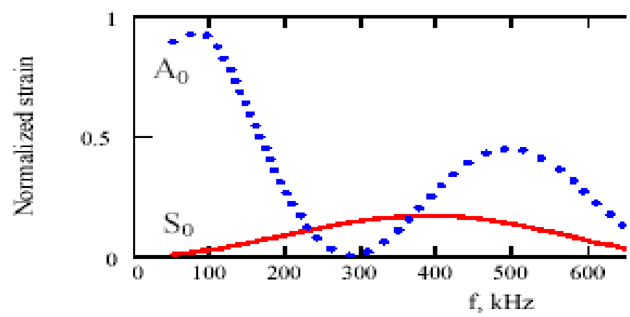
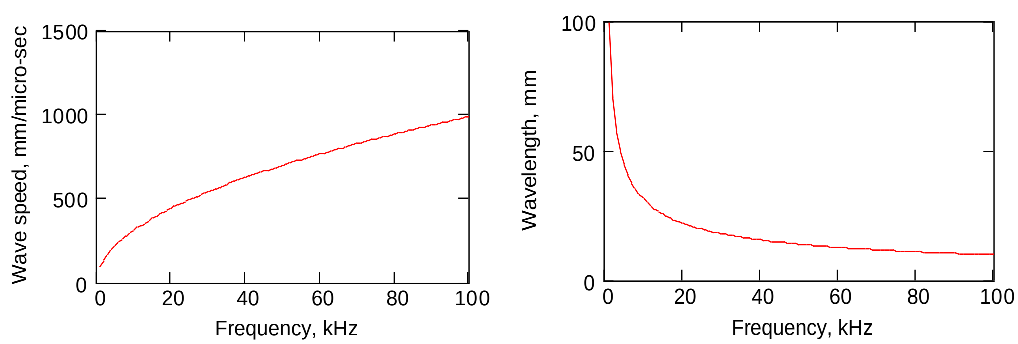


Figure 2. Lamb wave amplitude in 1-mm 2024 T3 aluminum.

In addition, A_0 Lamb waves are very dispersive at low frequencies, meaning that frequency region will be sensitive to small changes in plate thickness, as expected during the corrosion process.



(a) (b)

Figure 3. Dispersion characteristics of A_0 Lamb wave mode in 1-mm 2024-T3 aluminum plate: (a) A_0 wavespeed vs. frequency; (b) A_0 wavelength vs. frequency

Figure 3 shows the calculated dispersion characteristics of the A_0 Lamb mode in a 1-mm 2024-T3 aluminum plate in the 1 to 100 kHz band. Notice that the wave speed and wavelength vary a lot with frequency in this low frequency band. Tuning for a 10-mm PWAS requires a 20-mm wavelength. 3b indicates that a 20-mm wavelength of the A_0 mode would be encountered at 30kHz.

The dispersive nature of the A_0 Lamb-wave mode was analyzed using the Fourier transform method. Figure 4 presents the simulation of the A_0 mode response at the PWAS source, $x = 0$, and at distances $x = 250\sqrt{2}$ and $x = 500\sqrt{2}$ mm from the PWAS source. As the distance from the source increases, the dispersion of the A_0 mode Lamb wave packet also increases.

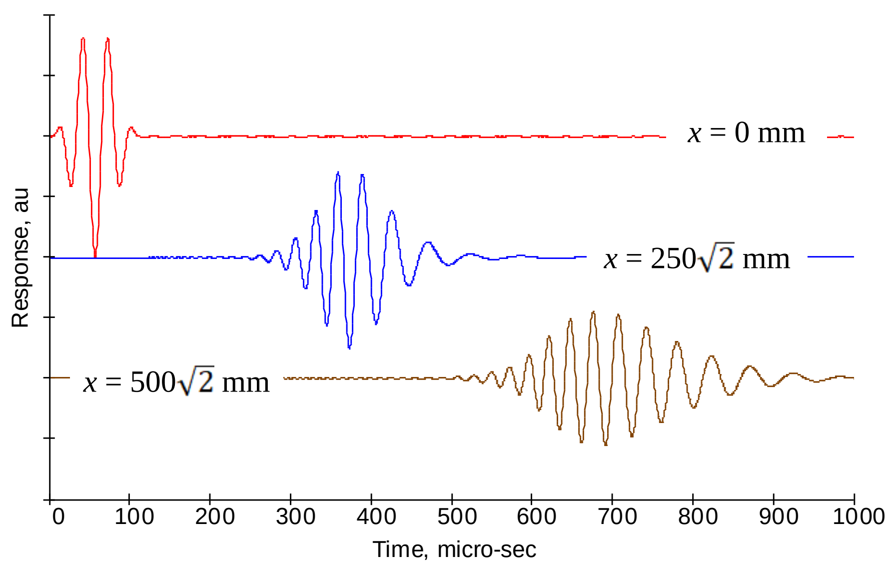
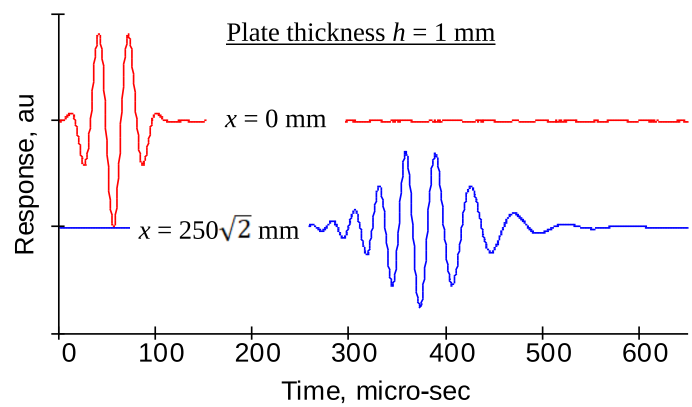


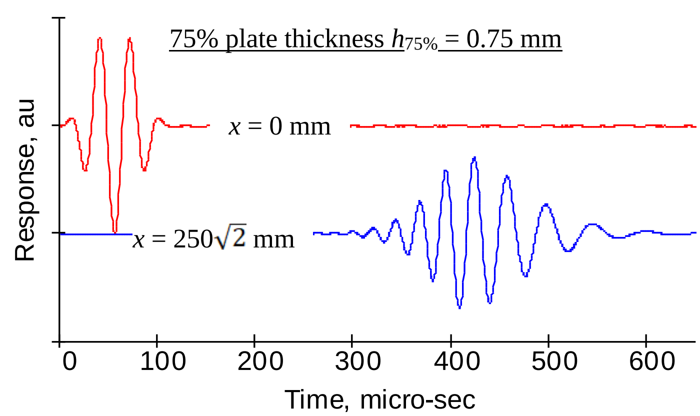
Figure 4. Simulation of A0 mode Lamb wave response at $x = 250\sqrt{2}$ and $500\sqrt{2}$ mm from the PWAS source placed at $x = 0$ mm (3.5-count smoothed tone burst of 31.5 kHz, plate thickness $h = 1$ mm)

Figure 5 presents the effect of plate thickness on the wave packet dispersion. At x = 0 and arriving at location $r = 250\sqrt{2}$ (Figure a) while traveling through pristine plate. Also displayed is $r = 250\sqrt{2}$ (Figure 5b) while traveling through corroded plate that has experienced a 25%

thickness reduction across the whole path of travel. Comparison of Figure 5a with Figure 5b reveals that the packet traveling through the pristine region reaches its peak amplitude at around 280 micro-sec, while the packet traveling through the region with 25% material loss reaches its peak at 320 micro-sec. This 40 micro-sec delay represents an average increase of 12.5% in travel time. While this 12.5% difference in arrival time is very noticeable, the difference is so large because the thinning occurs across the whole length of wave propagation.



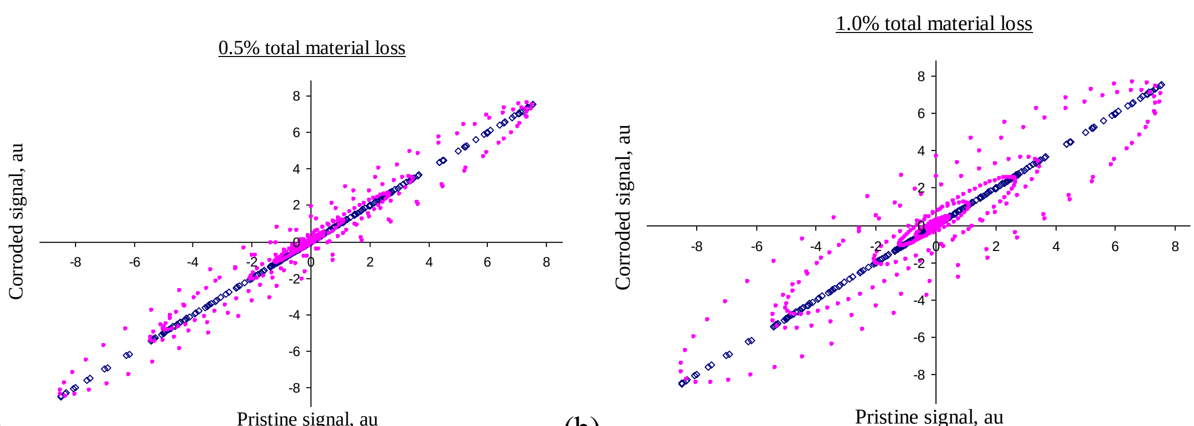
(a)



(b)

Figure 5. Simulation of A0 Lamb wave mode response at $x = 250\sqrt{2}$ mm from the PWAS source for two plate thickness values: (a) h = 1 mm; (b) h75% = 0.75 mm (3.5-count smoothed tone burst of 31.5 kHz)

A_0 Lamb-waves are dispersive at this frequency, making cross plots an convenient way to compare propagation differences between plate thickness (Figure 6). These plots are very sensitive to small shifts in signal phase. Two charts are presented, one for 0.5% total material loss (Figure 6a) and one for 1.0% total material loss (Figure 6b). In each chart, two plots are made: first, a plot of the pristine signal on itself, which results in a straight 45° line; second, a plot of the corroded signal against the pristine signal. This second plot results in an ellipse. By comparing Figure 6a with Figure b we observe that the width of the ellipse correlates with the simulated corrosion intensity. For mild corrosion (0.5% total material loss), the ellipse is relatively slim (Figure 6a). For more intense corrosion, (1.0% total material loss) the ellipse is much wider. These results indicate that the signal cross plots can be effectively used to identify the signal phase shifts and dispersions due to the presence of corrosion.



(a) (b)

Figure 6. Cross plot between the pristine and corroded signals: (a) 0.5% total material loss; (b) 1% total material loss

The previous two methods of measuring material loss (arrival time and phase) were modeled for the whole length of wave propagation. However, in a real structure, corrosion will not likely occur uniformly across the whole plate. The amplitude of a signal could then also provide useful in detecting material loss. Due to the velocity decreasing through a damaged area, a lensing effect at the damage location might be seen. The energy of the wave is focused as if through a lens, thereby increasing the amplitude and creating troughs to the sides of the damaged region (Figure 7). This can be shown theoretically by Snell's law:

$$\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_2}{c_2} \qquad (14)$$

where

θ is the incident angle of the wave with the corrosion damage,

c is the speed of the wave.

By using Snell's Law, a simple ray model can be made to show the effect of material loss as shown below. The denser the rays are packed together, the greater the amplitude of the wave. As the wave propagates away from the source the amplitude drops off by $\frac{1}{r^2}$. The orange box in the middle is the area of material thinning. As the rays pass through the thinned area, the waves become more closely packed together, thereby increasing the amplitude.

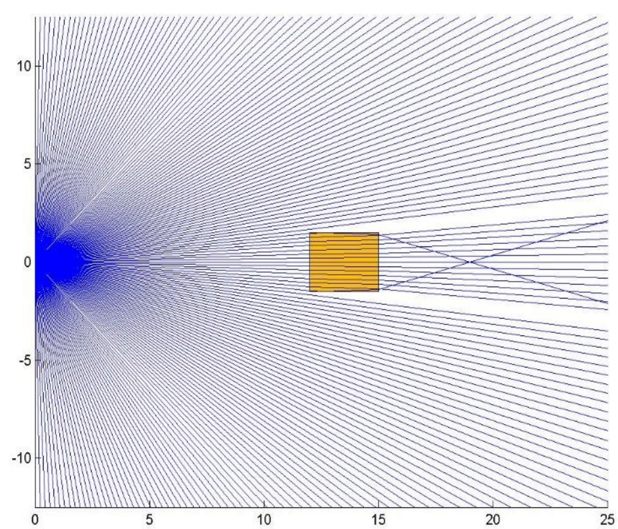


Figure 7. Lensing effect caused by reduced thickness as represented by looking down on the plate

EXPERIMENTAL SETUP

The use of PWAS generated asymmetric Lamb waves to detect material loss was demonstrated by laboratory experiments. A plate of aluminum alloy 2024 that was 750mm x 750mm x 1mm was instrumented with two 10-mm diameter 0.2-mm thick PWAS (American Piezo Ceramics, APC-850) along the diagonal line of the square plate.

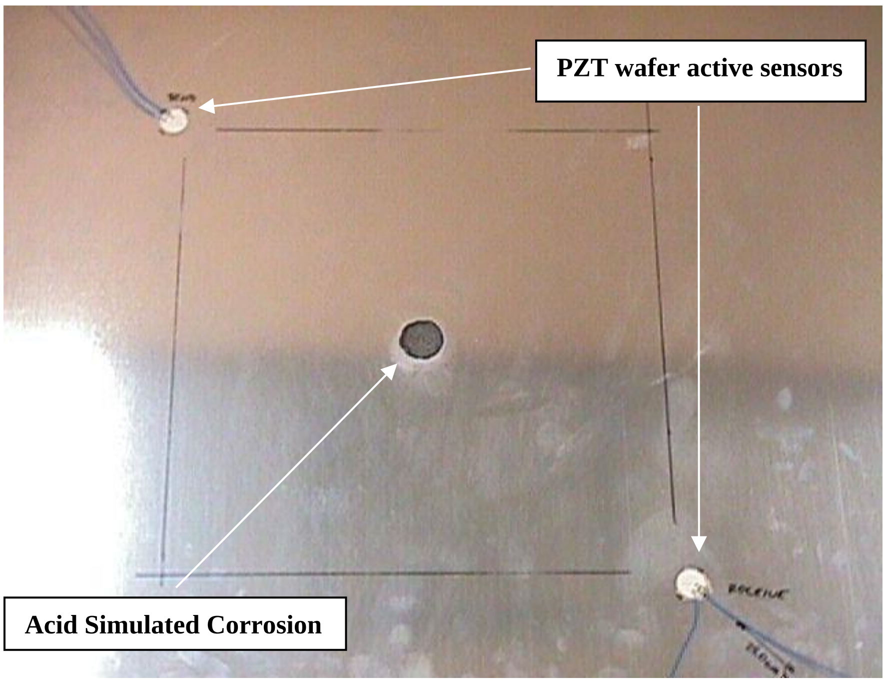


Figure 8. Experimental Setup Showing Simulated Corrosion

The simulated corrosion damage was created on the aluminum plates by using hydrochloric acid, which was confined to a particular area of the center of the plate. Depth of the corrosion area was controlled by time and then measured using a depth micrometer. The dimensions and depths of the damage are in Table 1 below.

Trace Number	Cumulative Time (min)	Total Depth (mm)
1	10	0.04
2	20	0.09
3	30	0.11
4	40	0.18
5	50	0.24
6	60	0.28
7	70	0.33
8	80	0.36

Table 1. Corrosion depth by time

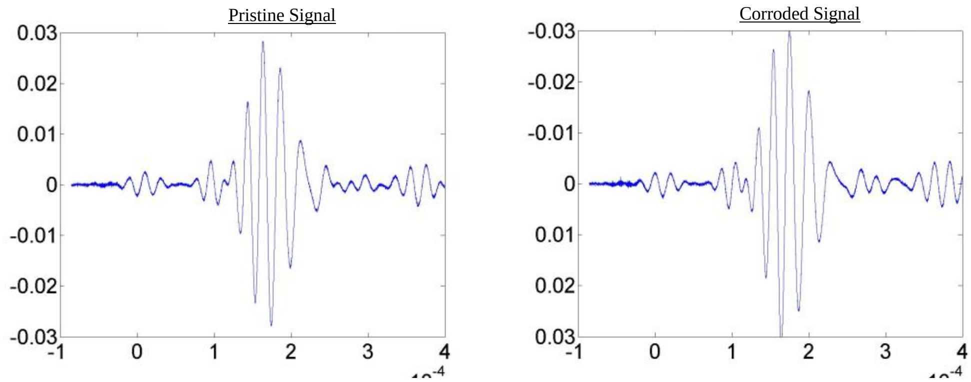
Two different plates with different depths of corrosion were created as seen in Table 2 below.

Plate Number	Diameter of Corrosion (mm)	Total Depth (mm)
1	15	0.14
2	15	0.26

Table 2. Total corrosion depth of sample plates

RESULTS

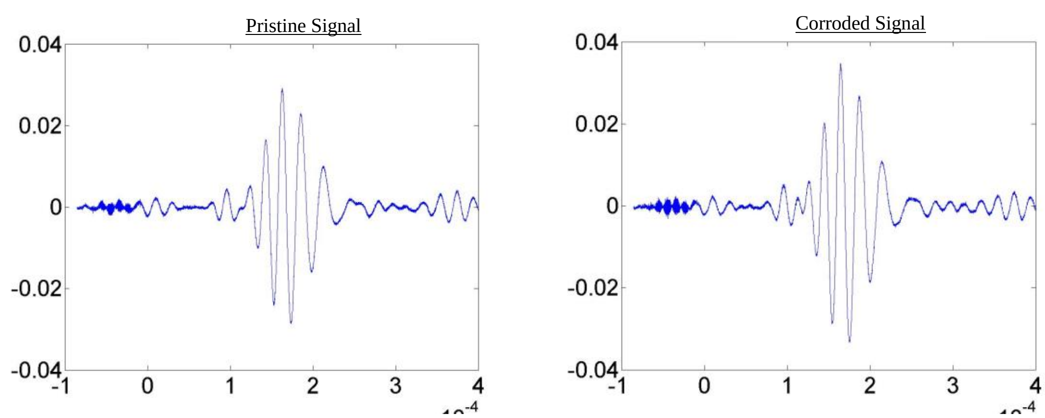
Figure 9 presents data acquired from plate 1 before and after it is damaged. As expected from the theoretical analysis, the damaged signal has a greater arrival time and is more dispersed. The time difference is measurable, but it is very subtle and might be within the noise range. However, two other effects are easier to observe. With the presence of damage, the A_0 wave packet increases in amplitude and there is a significant measurable phase shift.



(a) (b)

Figure 9. Received signal comparison for 0.14mm corrosion sample, amplitude in Volts on the y-axis and time in seconds on the x-axis: (a)Pristine Plate; (b) Corroded Plate

Figure 10 shows pristine and corroded signals for plate 2. Plate 2 has nearly twice as much thickness loss as plate 1. Upon a quick glance there is a larger change in amplitude from pristine to corroded in Plate 2 than Plate 1, which is as expected. However, there does not appear to be as large of a change in the arrival time or dispersion. Since the very small arrival time differences are difficult to measure, especially for a dispersed wave, the dispersion itself would be more useful to measure.



(a) (b)

Figure 10. Received signal comparison for 0.26mm corrosion sample, amplitude in Volts on the y-axis and time in seconds on the x-axis: (a) Pristine Signal; (b) Corroded

To observe the amplitudes for the A_0 mode, the envelope of the signal was taken using a Hilbert transform. In comparing the amplitudes of the pristine envelope to the small thickness loss envelope and the larger thickness loss envelope the data suggests a linear relationship.

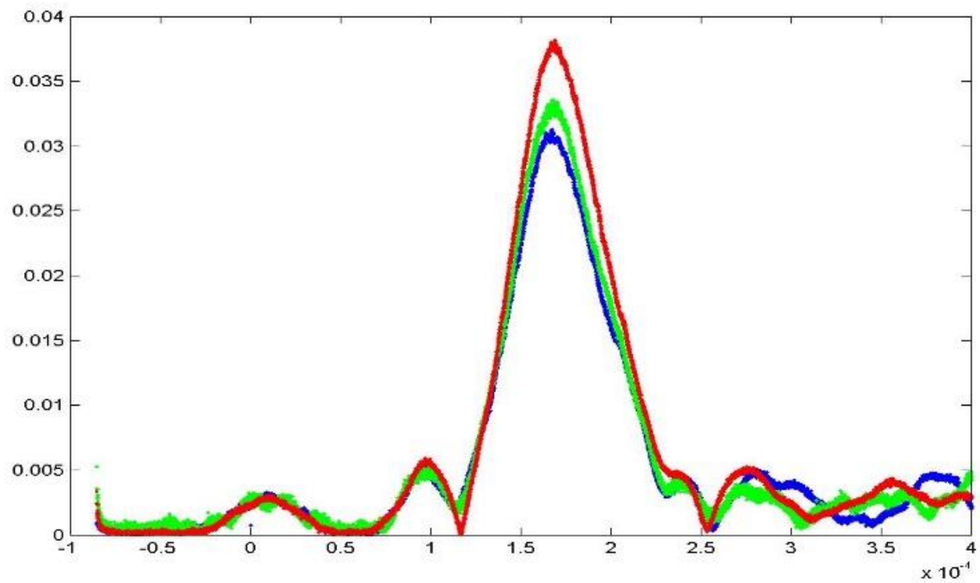
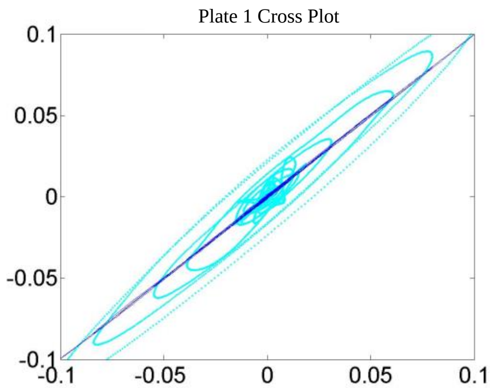
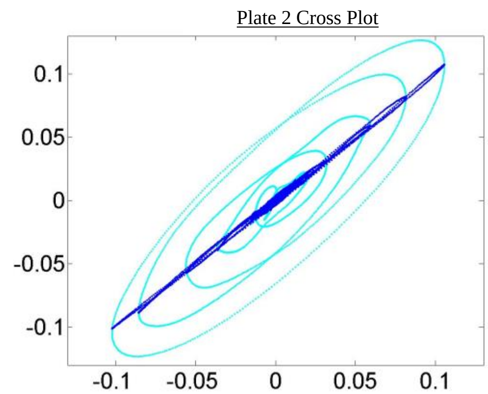


Figure 11. Envelope plot of the pristine and corroded signals, amplitude in Volts on the y-axis and time in seconds on the x-axis: (Blue line) Pristine plate; (Green line) Plate 1 with 0.14 mm corrosion; (Red line) Plate 2 with 0.26 mm corrosion

In order to examine the phase shift, we constructed cross plots as described in the theory section of this paper. As the theory suggests, the ellipse widens with increased corrosion damage. The effect of damage is readily recognizable in the cross-plots and is an easy to process way to identify damage.



(a)

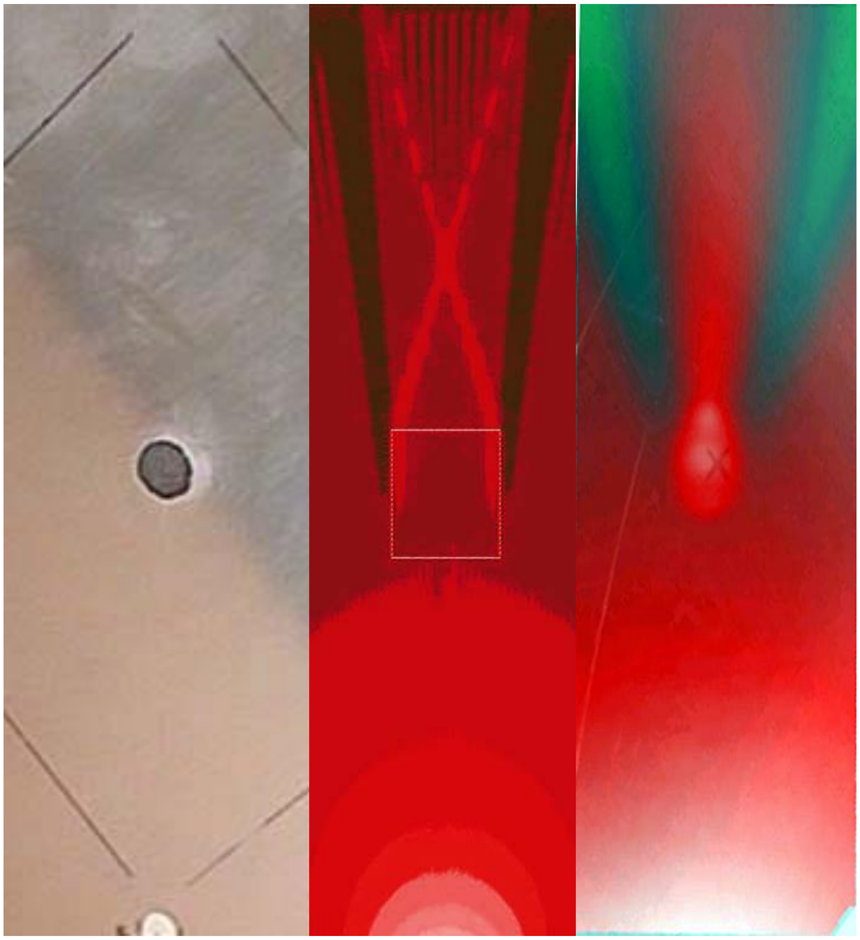


(b)

Figure 12. Cross plot between the pristine and corroded signals, amplitude in Volts on the x-axis and y-axis: (a) Plate 1 with 0.14mm thickness loss; (b) Plate 2 with 0.26mm thickness loss

To measure the effect of lensing created by the corrosion damage, a scanning laser vibrometer was used to measure the displacement of the A_0 Lamb waves as they propagated through the structure. The excitation of the piezoelectric transducer was synced to the laser vibrometer and after each excitation, moved the laser to measure the next point. The results can be seen in Figure 13c below.

A contour plot of the ray model from the theory section was created for comparison to the laser vibrometer image. The image created by the laser vibrometer matches nicely with the model. As expected, the amplitude increases as the wave propagates through the corroded area due to the lensing effect described in the theory section.



(a) (b) (c)

Figure 13. Comparison model vs. measured amplitude of Lamb-wave through corrosion, (a) Picture of plate with corrosion damage; (b) Modeled image of waves passing through corrosion; (c) Image of waves passing through corrosion using laser vibrometer.

SUMMARY OF RESEARCH

The experimental data was similar to the theoretical analysis. However, differences in arrival time were difficult to measure. Since the damaged area accounted for only 6% of the total propagation distance and the velocity only decreased by 12.5% through that corroded area, the total difference in arrival time was only 0.75% of the total propagation time. Further complicating the detection of a small difference in time of arrival, this small time difference was masked by the dispersion of the wave. Since a real aircraft structure is much more complex than a simple flat plate, detecting corrosion using the difference in time of arrival is not practical. By the time this method detected any damage on a real aircraft structure, the corrosion would be deep and expansive.

A better way to detect small amounts of material loss was by measuring the dispersion of the wave. This dispersion caused a significant phase shift that was easily identified using a cross plot. In the theoretical section of this paper, the cross plots were shown how they could be used to detect 0.5% and 1.0% material loss across the entire length of the wave's propagation path. In the experimental portion, the corroded section was reduced by 14% and 26% over 15mm of the total 250mm propagation distance. This equates to a 0.84% material loss and a 1.44% material loss respectively across the total distance. The experimental results with corresponding cross plots correlate very well with the theoretical results. For comparison, the combined theoretical and experimental results are shown below in Figure 14.

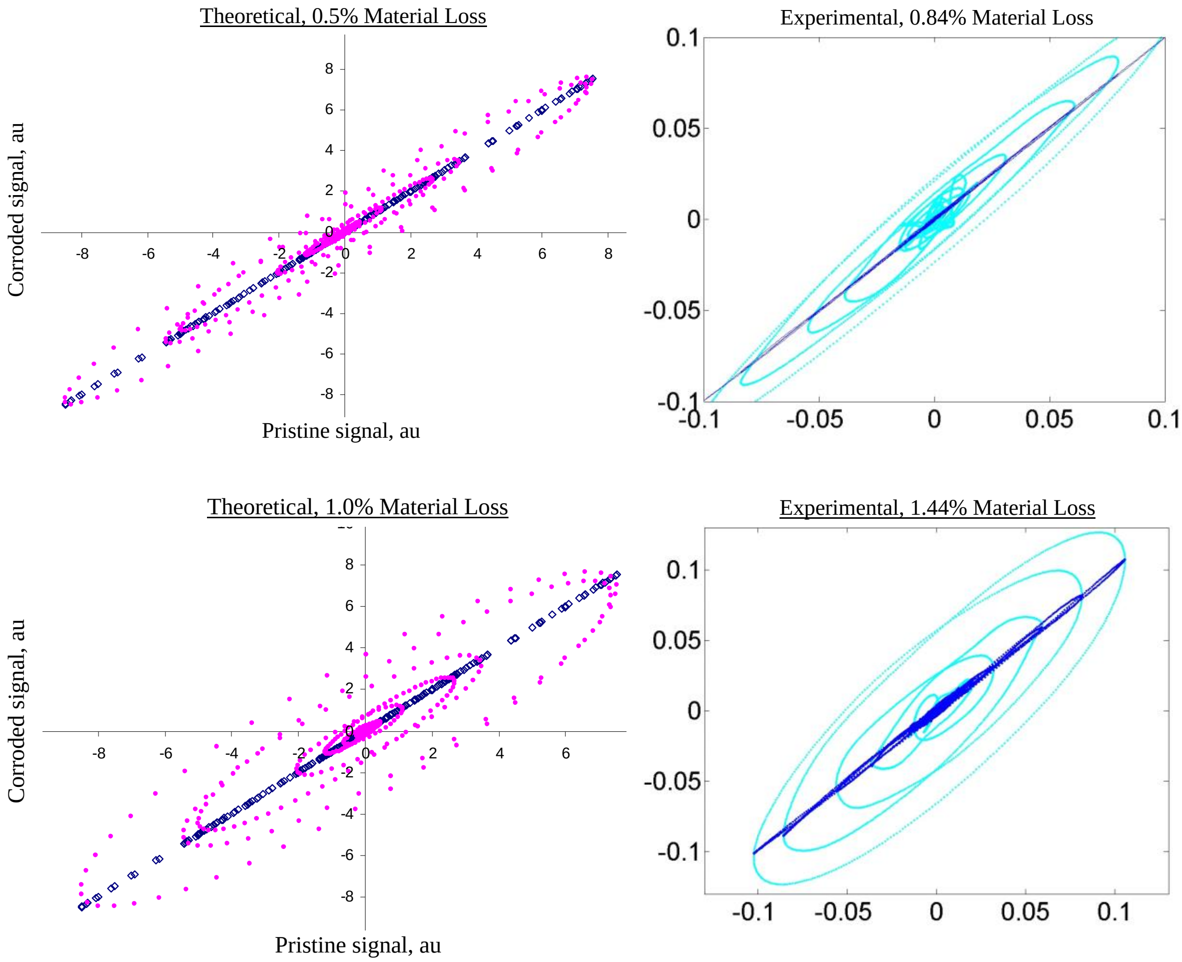


Figure 14. Side by side comparison of theoretical dispersion cross plots with experimental dispersion cross plots.

While the change in velocity did not significantly affect the arrival time, the change in velocity did affect the amplitude of the signal in ways that is easy to measure. Figure 15 shows the increase in amplitude seen by the receiver after passing through the corroded areas. This increase in amplitude is caused by a lensing effect as the waves change in velocity while going through this damaged area. This knowledge could be useful when designing and installing a sensor network in areas most expected to experience corrosion.

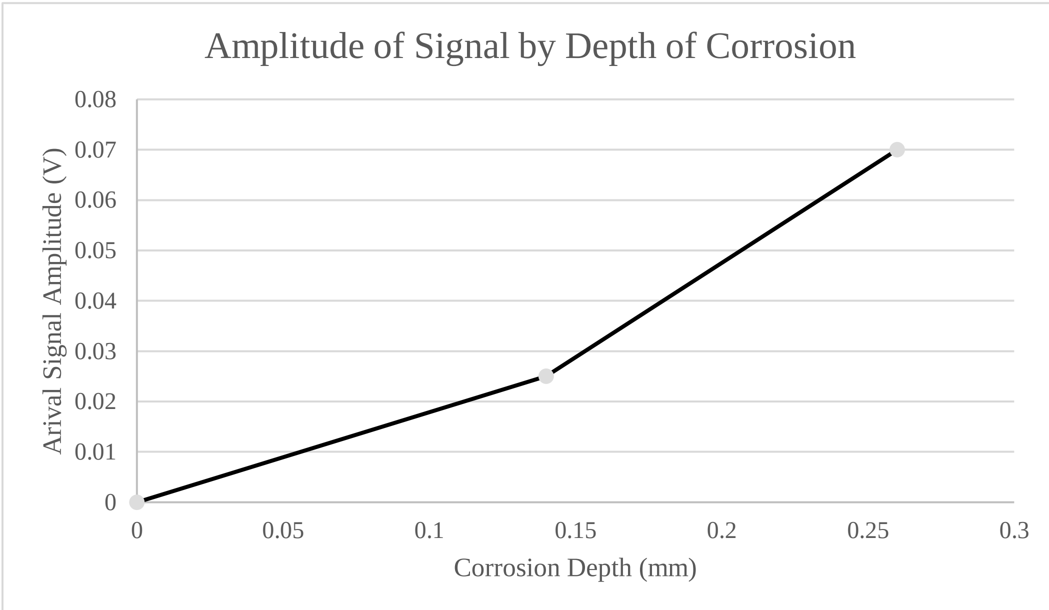


Figure 15. Signal amplitude increase caused by corrosion depth.

Finally, using a laser vibrometer, the plate was imaged to see the amplitude effects on the Lamb waves as they passed through the damage area and was compared to a simple ray model. Because these results match very closely, further investigations should continue using multiple sensor arrays on more complex structures to find a viable solution for using in-situ sensors for detecting corrosion on aircraft.

CURRENT STATE OF THE ART

Prior to work in the early-mid 2000s, many researchers worked with embedded piezoelectric transducers to generate Lamb waves to detect damage in materials. (Keilers C.H., Chang, 1995) were early researchers who experimented with in-situ piezoelectrics for detection of material damage through wave propagation through a composite beam. (Wang, C.S., Chang, 2000) used piezoelectric wafer sensors in other composite structures to detect impact damage in composite structures. (Giurgiutiu, 2003) showed in his work that PWAS configured in an array and operating in the S_0 symmetric Lamb mode could detect and locate cracks through pulse-echo excitation and signal processing.

While not using embedded sensors, (Chahbaz, Ahmad, Mustafa, V, Hay, 1996) demonstrated the ability of A_0 Lamb waves to detect corrosion through material loss. Using a different type of sensors, they showed that Lamb wave modes could detect material thinning that was hidden under lap joints.

Work in this field has continued since after this research was completed in late 2005. Several researchers have used embedded ultrasonic transducers to generate Lamb waves to detect corrosion in metals. The primary areas of research have been in Sensor Improvement and Signal Analysis, Complex Structures, and Sensor Durability.

Sensor and Signal Analysis

(Nagy et al., 2014), using an Electromagnetic Acoustic Transducer, showed that A_0 Lamb waves could be generated while suppressing S_0 Lamb waves by controlling the angle of the transducer and not relying on specialized tuning of the frequency. (Rathod & Roy Mahapatra, 2011) demonstrated PWAS oriented in a circular array could locate corrosion damage outside of the circular array using wavelet coefficients. (Terrien et al., 2007) found that by using much higher frequencies (5 MHz), corrosion could be discovered by mode conversion from S_0 to A_0 while also being able to discriminate from a change in material thickness as in a lap joint. Also, the change in material thickness generated an additional A_1 mode. By detecting the occurrence of different modes, they could detect very small corrosion pitting.

(Zeng et al., 2017) demonstrated a network of sensors adhered to both sides of the plate to detect the location of corrosion. They showed that they could determine between anti-symmetric and symmetric modes by signal addition or subtraction and then single out which mode was being propagated. They could then localize the damage to a particular area. (Hua et al., 2020) took a new novel approach to using PWAS to detect corrosion damage. In contrast to this research of attempting to tune to a specific Lamb mode where a change in speed of travel and dispersal characteristics from a pristine sample were detected, Hua et al. generated signals with lots of modes and measured characteristics in which no pristine sample was needed. They measured ridge curvature, energy distribution ratio and image difference coefficient and used an image probability algorithm to detect damage.

Complex Structures

Boukabache et al. showed some promise in being able to detect and locate corrosion damage in complex structures by not tuning for specific modes (Boukabache et al., 2013). Instead, they used wavelet decomposition to detect the presence of damage in complex structures over large areas. Zhao et al. also showed the ability to detect and locate corrosion damage on a complex wing structure, though the damage was in a non-complex location. (Zhao et al., 2007)

Sensor System Durability

Progress has been made in both understanding of how sensors will degrade over time and how to make the sensors survive longer. Scott et al. provides a good method of self-sensing and calibrating based on sensor adhesive degradation in addition to a new type of ultrasonic sensor. (Scott et al., 2010) Spray on PWAS are beginning to look very promising for increasing survivability (Banks et al., 2016). Not only are they likely to survive longer than bonded sensors, but they can induce more strain into the structure with less power. Pitropakis introduced the concept of pseudo-defects that can be used to calibrate a PWAS suite. These pseudo-defects were simply mechanisms that would change the stiffness of the structure and could be removed. By placing the pseudo-defects in multiple locations, the sensor system could be calibrated. This might also be useful for training a neural net.

OPERATIONAL VIABILITY

Detecting cracks and corrosion damage on aerospace structures is historically a costly and time-consuming endeavor. In-situ structural health monitoring could enable predictive maintenance and avoid catastrophic structural failures. However, several problems need to be solved in order to make this technology viable, including detecting damage through complex structures, durable sensor systems, installation and integration, and cost.

Accurately Sensing Damage on a Complex Structure

The work presented in the previous sections demonstrate the ability to detect corrosion on simple structures. However, as the complexity of the structure increases with lap joints, rivets, bolts, and changing thicknesses, the detection of corrosion becomes more difficult. There are two different ways to deal with structural complexity.

1. Tune for specific Lamb wave modes to isolate for specific characteristics.
2. Embrace the complex structure and subsequent complex signals, using neural networks, statistical learning, artificial intelligence and advanced signal processing.

Both methods will need to be used in conjunction in order to detect, locate, and quantify the damage. Advanced signal processing techniques and statistical learning should prove useful in detecting and generally locating corrosion damage. However, tuning for specific modes of waves should allow for more tightly locating and quantifying the damage.

Durability of Sensor System

If the sensor system is not at least as durable as the structure it is meant to monitor, it would not be of much use. Acellent Technologies has been producing a SMART layer for several years that is focused on providing a sensor system embedded in a dielectric film that can be adhered to a structure. However, at this point, the information to determine how durable the SMART layer is not available.

Intensive testing on the ground and then in flight needs to be accomplished to assess shock, vibration, temperature, and humidity in order to determine the sensor system's life. A sensor system based on Piezoelectric sensors could have many failure mechanisms. Piezoelectric sensors can be easily crushed. The wires can be disconnected from the sensors. The sensors can become dis-bonded from the structure. Therefore, a ruggedized sensor system needs to be developed and extensively tested in order to prove that it can last as long as the structure it is sensing.

Installation and Integration

Installation and integration on legacy metallic airframes require dismantling the aircraft, installing the sensor systems, tuning the sensor system, re-mantling the aircraft, and a final tuning of the sensor systems. This procedure could be time consuming and potentially initiate failure modes into the structure. Therefore, sensor systems should be focused on two sets of locations:

1. Locations where mechanical failure could lead to a catastrophic crash
2. Locations that require frequent inspections (especially hard to reach ones)

Whether a location receives an in-situ sensor system depends on different factors. The first type of location should receive sensors if there are high danger locations on aging legacy aircraft that need to extend its overall life. The second type of location should receive a sensor system if by installing the system, if it increases the time between scheduled maintenance, thereby saving money. The method of calculating the cost savings is discussed in the next section.

Another hurdle for integration of the sensor system would be access to the system. Since the most desirable locations to place the sensor system are in difficult locations to administer traditional Non-Destructive Evaluation Techniques, access to the sensor system could be limited. There are two ways of overcoming this hurdle:

1. Install a wireless communications capability along with the sensor system. This would allow a maintainer to access data from the system without physically touching the system. However, the primary problem with this is found in providing power to the sensor system. If this method was chosen, the new hurdle of supplying power is then presented. Banks et al. demonstrated wireless sensors by activating them using induction. However, it is still unclear how to induce these sensors in hard to reach locations.(Banks et al., 2016)
2. Run a data/power line to/from the sensor systems to an access port. With this option, a device could be used to supply power and probe the structure. While this could be a more pragmatic solution, it does not come without its own difficulties. On many aircraft it could be difficult to find a path to run a line from the sensor system to an access panel.

Either method to gain access to the data and supply power to the system would require extensive and costly design and test efforts. Therefore, in order to make sure the system is worth installing, cost must be a driving factor.

Cost

Ultimately, in order to determine whether a sensor system is operationally viable, a cost analysis of expected application and integration of the sensor systems during the life cycle of the aircraft would need to be performed. Several questions must be answered: What is the projected cost of maintenance as currently performed? What is the cost to integrate the sensor system on the aircraft? How much does the sensor system reduce mean time between inspections and scheduled maintenance? What is the expected life of the aircraft?

After answering these questions the overall cost between leaving the aircraft as is or adding the sensors need to be compared by using the following equations.

Total Cost = Cost, sensor system + Cost, sensor integration + Cost, scheduled maintenance (14)

Where the *Cost, scheduled maintenance* is calculated by:

$$Cost, scheduled\ maintenance = \frac{L}{T_{MTSM}} * C_I \qquad (15)$$

Where,

L = *Life left in the aircraft*

T_{MTSM} = *Mean time between scheduled maintenance*

C_I = *Cost of each Inspection*

If the sensor system has a chance to ever become operationally viable, it must buy its way on to the aircraft by creating reduced maintenance costs by increasing scheduled maintenance intervals.

If Not Viable on Legacy Aircraft, Plan for Future Aircraft

The problems that needs to be solved in order to make PWAS operationally viable to detect corrosion on legacy metallic aircraft structures seem daunting. Any one of the above problems could keep PWAS for Structural Health Monitoring as just a promising idea and not a useful technology. However, future aircraft present promising opportunities for overcoming the problems identified above. Here are some ways the problems above could be solved in future aircraft:

Installation and Integration: There has already been substantial research on installing PWAS while building up composite structures and has shown some promise. Also promising are structures made through additive manufacturing. They could be built with embedded sensors with electrical lines built on for easy access.

Accurately Sensing Damage on a Complex Structure: In addition to helping solve the installation and integration problem, they could also solve the problem of complex structures. Additively manufactured structures would already be modeled, leading to the opportunity for additional analysis on ultrasonic wave propagation through the complex structure. These models could help to understand what types of changes in the structure are causing the signals to change over time. By feeding real-world data along with modeled data into a neural network, the ability to overcome the complex structure problem could finally be overcome.

Durability of Sensor System: On an additively manufactured part, durability will still be a main area of interest, both for the sensor system and the part. This needs to be researched in more detail.

Cost: In the case of using additively manufactured parts, the cost problem is not the main driver. While developing a new aircraft, the designer will decide which type of material and manufacturing process to use based on cost and performance. The structural health monitoring system would likely be a minor consideration for the overall design until proven. However, if proven, because the cost of military aircraft continues to increase significantly, the cost of a sensor system may become negligible when compared to the life-cycle maintenance costs of an advanced aircraft. A relatively proven and inexpensive sensor suite could be very appealing to airframe designers in order to drive down expensive life-cycle maintenance costs.

CONCLUSION

This report presents experimental research on corrosion detection on legacy aircraft using embedded PWAS. The theory of Lamb waves to show how A_0 waves are very sensitive to material loss because these waves are highly dispersive at select frequencies. As the A_0 Lamb wave travels through simulated corrosion damage, the changes in velocity, dispersion, and amplitude can be correlated to the magnitude of damage. While the difference in time of arrival of the wave packet was very small and difficult to measure, dispersion and phase shifts were clearly recognizable. This was shown by using simple cross plots where phase shifts due to dispersion can readily be seen with only 0.5% material loss. With more advanced signal processing, much smaller levels of corrosion could be found. Also, increases in the received signal amplitude are a clear indicator of damage due to a lensing effect through the damaged area.

While these experimental results are promising, much work needs to be done in order to make in-situ sensors viable on aircraft. Since this work is several years old, new research was examined for advances. Identified was a few main areas to concentrate because they are believed to be the most needed for these sensors to be installed on aircraft. These were advances in sensor and signal analysis, defect detection in complex structures, and sensor durability. Many advances have been made and the hurdles to achieving an embedded health monitoring system are much lower.

Therefore, using this research and what was learned about the advances made since then, the next steps in making this technology viable were explored. The major technical problems that still need to be addressed were examined. Creating an in-situ structural assessment system would be very challenging, especially on legacy aircraft. However, if a structural damage detection system could increase scheduled maintenance intervals, it could reduce the cost enough to be practical. To increase the maintenance intervals, confidence in the system must be high. Therefore, improvements need to be made in detecting damage in complex structures. Advanced signal processing techniques and statistical learning should prove useful in detecting and locating corrosion damage in complex structures.

While in-situ structural health monitoring sensors may find it difficult to buy their way on to legacy aircraft because installation could be very expensive, these systems could be promising for future advanced aircraft. If the aircraft is designed and built with a corrosion detection system already embedded, it would not face the same problems of integration and installation, making it more cost effective for an advanced aircraft.

With additional advancements, in-situ corrosion detection systems could become a viable way of increasing the reliability of the fleet of Air Force aircraft, driving down the maintenance burden of operating these aircraft, and thereby saving taxpayer dollars.

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