Adhesive disbond detection using piezoelectric wafer active sensors

William Roth*, Victor Giurgiutiu**

University of South Carolina, 300 Main Street, Columbia, SC, USA 29208

ABSTRACT

The aerospace industry continues to increase the use of adhesives for structural bonding due to the increased joint efficiency (reduced weight), even distribution of the load path and decreases in stress concentrations. However, the limited techniques for verifying the strength of adhesive bonds has reduced its use on primary structures and requires an intensive inspection schedule. This paper discusses a potential structural health monitoring (SHM) technique for the detection of disbonds through the in situ inspection of adhesive joints. This is achieved through the use of piezoelectric wafer active sensors (PWAS), thin unobtrusive sensors which are permanently bonded to the aircraft structure. The detection method discussed in this study is electromechanical impedance spectroscopy (EMIS), a local vibration method. This method detects disbonds from the change in the mechanical impedance of the structure surrounding the disbond. This paper will discuss how predictive modeling can provide valuable insight into the inspection method, and provide better results than empirical methods alone. The inspection scheme was evaluated using the finite element method, and the results were verified experimentally using a large aluminum test article, and included both pristine and disbond coupons.

Keywords: EMIS, PWAS, disbond, detection, structural health monitoring, adhesive, adhesive joint

1. INTRODUCTION

The aerospace industry has been using adhesives to create efficient joints and laminated materials since the early 20th century. Adhesives have been used for wood, metal and composite construction; however, its use has been limited on primary structures or in joints whose failure would lead to the loss of the aircraft. This has been driven by several factors. Initially, this could be attributed to the low fracture toughness of early brittle epoxy adhesive; however, the adhesives industry has made great progress in creating toughened epoxies with increased fracture toughness. These toughened epoxies, along with a better understanding of the stress distributions in joints, has led to the design of adhesively joined members who fail in the substrate long before the adhesive. There is one caveat to this statement, which is that if the interface between the adhesive and the substrate is weaker than the cohesion of the adhesive, then this will lead to a failure at a considerably lower fracture energy. This can be prevented with the proper surface treatment and handling of the substrates. Thus, the limiting factor to the expansive use of adhesives for primary structures is not the inability to design or manufacture a durable joint, but in the inability to provide a repeatable and reliable means for ensuring the strength of the joint. Conventional ultrasonic inspection techniques can be used to look for voids and disbonds on the manufacturing floor, or at scheduled inspection intervals. Nonetheless, weak interface bonds can fail unexpectedly with an unstable crack propagation. Currently, this issue is addressed with the use of mechanical fasteners in addition to adhesive for critical joints. Also, fasteners or other design features can be placed at the edges of joints, where large normal stresses arise, to provide an additional path for the peeling stresses and prevent or delay the critical mode I fracture of the joint. However, these fasteners provide new stress concentrations and introduce damage, which will create additional crack initiation zones. Not to mention the increase in weight, cost and manufacturing time for the joint.

This paper explores the use of permanently bonded piezoelectric wafer active sensors (PWAS) along with electromechanical impedance spectroscopy (EMIS) to detect the size and location of adhesive disbonds in situ. By monitoring the joint during operation, the disbonds could be detected at an early stage before they reach an unstable crack propagation state. This would lessen the dependence on mechanical fasteners, and lead to increases in joint efficiency and decreases in manufacturing time and cost.

The EMIS method has been used successfully with PWAS for detecting damage^{1, 2, 3, 4, 5, 6, 7}, and has been shown to be effective at detecting adhesive disbonds⁸. This paper expands on the previous work in two ways. First, this paper uses a

*rothww@email.sc.edu; (803) 777-1535; www.me.sc.edu/research/lamss

**victorg@sc.edu; (803) 777-8018; www.me.sc.edu/research/lamss

physics based approach to lay the groundwork for a methodology to determine the size and location of adhesive disbonds. Second, this paper explores this methodology through a case study in detecting corner disbonds in an adhesively bonded aluminum doubler.

2. ELECTROMECHANICAL IMPEDANCE SPECTROSCOPY

Electromechanical impedance spectroscopy (EMIS) is a local vibration technique for detecting damage in a structure. It has its origins in the coin tap and hammer tests that were developed through the past century, and has similarities with the modern mechanical impedance methods. The primary advantages that this method has over conventional NDT methods is that it can be performed in situ and the very small headspace of the sensor allows it to be placed in low clearance areas. The fundamental idea behind this method is that a measurement of the frequency dependent electrical impedance or admittance of a structurally bonded PWAS will reveal the resonance peaks of the structure. If damage has been introduced into the structure, then the resonances will shift and/or new resonances will appear. This method depends on the PWAS becoming a part of the system through the permanent bonding to the structure, and this is a fundamental difference between this method and the NDT methods.

The equation for electrical impedance and admittance of a structurally constrained PWAS is determined through the use of the following diagram, which represents the frequency dependent stiffness of the structure as linear springs, Figure 1.

Figure 1. Diagram for a PWAS constrained by a structure

The impedance is then calculated with this diagram and the constitutive equations for a piezoelectric material as Equation 1. This equation assumes that the frequencies remain below the first resonance frequency of the PWAS.

$$Z(\omega) = \frac{1}{i\omega C} \left[1 - k_{31}^2 \frac{Z_{str}(\omega)}{Z_{str}(\omega) + Z_{PWAS}(\omega)} \right]^{-1}$$

$$Y(\omega) = Z^{-1}(\omega) \quad (1)$$

This equation shows that the impedance of the PWAS is highly dependent on the impedance of the structure. This has been proven experimentally by Giurgiutiu¹. This fundamental concept will now be applied in an adhesive disbond case study.

3. TEST COUPON

In order to test the methodology, a set of test coupons were designed and manufactured. The coupon consists of a 500 mm long, 60 mm wide and 1.6 mm thick aluminum host plate, which was bonded to a 100 mm long and 1.6 mm thick doubler plate. The adhesive was an epoxy film adhesive, and the final adhesive thickness was 200 μ m. Figure 2 shows the dimensions of the coupon and the layup diagram for manufacturing the coupon. A strip of Teflon was used to create the disbond. The entire coupon was cured in a hot press, and spacers were used to control the bond line thickness. After curing, the Teflon was removed and a thin razor blade was partially inserted into the disbond region to ensure that the adhesive was fully separated from the host plate.

Both of the test coupons had five PWAS installed in an ordered pattern close to the disbond. The doubler plate was used as the ground and wires were soldered to the top electrodes of all PWAS. The numbering scheme for the PWAS is showed in Figure 3. This figure also shows the disbond in the corner of the doubler.

Figure 2. Test coupon manufacturing diagram

Figure 3. Final test coupons, PWAS layout, and the artificial disbond

Figure 4. Ultrasonic inspection of the disbond region

In order to verify that the triangular area was disbonded, the entire coupon was scanned with phased array pulse echo ultrasonic inspection equipment. The coupon was scanned from the bottom side of the host plate, and water was used as

the couplant. A gate was set up in the time domain to measure the amplitude of the signal in the expected location of the reflection off of the back wall of the host plate. This is shown in the upper left window of Figure 4. The upper right window shows the amplitude of the signal across the width of the coupon. The amplitude is shown as a color scale, and the height is the time scale. The cursor line in this window is located over the disbond. The strong reflection from the top surface of the plate and another strong reflection in the region of the disbond can be seen in this window. This strong reflection is due to the large acoustic impedance mismatch between aluminum and air, which is greater than the aluminum epoxy interface. The lower window in this figure shows the C scan of the plate. The color corresponds to the amplitude within the gate set at the back wall of the host plate. There is a strong reflection over the disbond, which is similar in amplitude to the non-doubler sections of the plate. This is expected because this reflection is also from an aluminum air interface. This inspection has shown that the disbond is as expected.

4. PREDICTIVE MODELING

The EMIS method can detect damage by identifying a change in the electrical impedance or admittance of the PWAS. This change corresponds to changes in the resonances of the inspected structure. These changes could be shifts in the frequency of the resonances as well as the creation of new resonances from changes in the boundary conditions. Since EMIS measures the change in resonance frequency, the first step in understanding how to detect a disbond with this method is to determine how the resonance frequencies change from the pristine to the disbond case. These changes will be driven by the change in boundary conditions from the growth of the disbond. As seen in Figure 3, the disbond creates a new region with a traction free boundary condition. The ANSYS FEA software package was used to perform a modal analysis on the disbond geometry. This analysis calculates the eigenvalues or eigenfrequencies and the corresponding eigenvectors or mode shapes for the structure. The entire coupon was modeled, and the disbond area was simulated by de-tying the nodes between the host structure and the adhesive layer. All exposed surfaces were assumed to be traction free. Figure 5 shows the ANSYS model, along with the de-tied region of the model.

Figure 5. ANSYS model for the modal analysis; de-tied region of the model

This analysis has revealed several mode shapes which appear to be unique to the disbonded coupon. Each of the mode shapes show large displacements in the disbonded region. The mode shapes of this region are similar to those of a plate with one fixed end or a cantilevered beam. Figure 6 shows the mode shape at approximately 18 kHz. The doubler plate above the disbond experiences large out of plane displacements, which are much greater in magnitude than the rest of the model. The motion of this area is very similar to the first resonance of a cantilevered beam. This frequency will help set the minimum frequency in the EMIS measurements. This mode shape can also be referred to as the first damage mode for this shape, location and size disbond. If the length of this disbond was adjusted then the frequency for this damage mode should shift inversely proportional to the size of the disbond.

Figure 6. Mode shape at approximately 18 kHz for the disbond coupon

A second mode shape for the disbond coupon is shown in Figure 7. This mode shape also appears to have a unique motion in the disbonded region, and the mode shape resembles a higher order plate mode. This mode shape will be referred to as the second damage mode.

Figure 7. Mode shape at approximately 36 kHz for the disbond coupon

Lastly, a third mode shape was identified at approximately 66 kHz, which again corresponds to a higher order mode shape with a triangular plate and one fixed end. This is the third damage mode for this analysis and a picture is shown in Figure 8.

The next step in the predictive modeling is to identify the potential PWAS locations for detecting this disbond. A sensitivity study has been performed, as a brute force method for identifying appropriate PWAS locations. This method involves performing a multi physics FEA analysis in order to estimate the electrical impedance of the PWAS. This analysis was performed in ANSYS. The doubler plate was divided into 28 regions, which each contain one square PWAS. The PWAS dimensions are 7 mm square and 0.2 mm thick. The length of the host plate has been decreased in order to make the analysis manageable due to the dense meshing. The disbond was simulated by removing the adhesive in the disbond region, as noted by the gray area in Figure 9. The PWAS were modelled with Solid 226 coupled field elements. The bottom electrode of all the PWAS were coupled and set as the ground. The top electrode of each PWAS was coupled individual and a sinusoidal voltage was applied. In order to quickly acquire results, the first run was performed by exciting all 28 PWAS.

Figure 8. Mode shape at approximately 66 kHz for the disbonded coupon

Figure 9. Modeling scheme for the sensitivity study

This analysis was performed for both the disbond and pristine coupons. The analysis had a minimum frequency of 10 kHz and a maximum frequency of 50 kHz along with a 100 Hz step size. The pristine and disbond spectrums were compared against one another. Figure 10 shows a comparison of the pristine and disbond electrical admittance for PWAS 4. As expected from the modal analysis, there appear to be new resonance frequencies around the 18 kHz damage mode identified earlier in the paper.

In order to compare all 28 PWAS for their sensitivity to the disbond, the root mean square deviation (RMSD) method has been used to determine a single number to rank each PWAS. Equation 2 shows how this RMSD value was calculated. The equation shows that for each frequency the real admittance of the pristine case is subtracted from the disbond case then squared. This value is divided by the real admittance of the disbond case squared which should normalize the values.

$$RMSD = \sqrt{\frac{\sum_N [Re(Y_i) - Re(Y_i^o)]^2}{\sum_N [Re(Y_i^o)]^2}} \quad (2)$$

The RMSD values for each PWAS have been used to create a surface plot, shown in Figure 11. This plot shows that the PWAS locations close to the disbond will have a greater difference between the pristine and disbond coupons. There

appears to be an advantage to PWAS located along the same edge of the disbond. Figure 11 also shows a few admittance plots of different PWAS for comparison.

Figure 10. EMIS spectrum for PWAS 4

Figure 11. Sensitivity map for a corner disbond

This data was used to select the PWAS locations shown in Figure 3. The five closest PWAS to the disbond were chosen. The next step is to experimentally verify these trends.

5. EXPERIMENTAL VALIDATION

The first step in the experimental validation is to measure the impedance and admittance of the five PWAS on each test coupon. This measurement was performed using an HP 4194A impedance analyzer and the results were saved through a LabVIEW VI. Figure 12 shows the experimental setup.

Figure 12. Experimental Setup for measuring the impedance and admittance of the PWAS

Once the results were gathered, they were compared between the pristine and disbond coupons for each PWAS location. The real admittance was used as the metric, and the peaks should correspond to resonance frequencies for the structure. Figure 13 shows the real admittance for PWAS 3. The results are compared for the disbond and pristine test coupon, and the disbanded case is shifted up in order to provide a clear view of both spectra. The circles indicate regions with large changes in admittance, likely corresponding to changes in resonance.

Figure 13. PWAS 3: Real admittance for the pristine and disbond test coupon

It is difficult to distinguish clear peaks with this frequency range; therefore, a new plot was created between 10 and 20 kHz. Figure 14 shows this new plot. The circles mark the new resonance peaks, which correspond to the FEA results that were discussed in the predictive modeling section. Also, the 15.5 kHz peak is labelled in the figure, and the FEA mode shape at this frequency is shown on the right side of the figure. This mode shape is highly localized around the disbond.

Another plot was created from 30 to 40 kHz. Figure 15 shows the new peaks which should correspond to the second damage mode discussed in the predictive modeling section. Again the circles show regions which contain additional peaks when compared to the pristine case.

Figure 14. Real admittance of PWAS 3, FEA mode shape at 15.5 kHz

Figure 15. Real admittance of PWAS 3

In order to compare the five PWAS locations, the RMSD was calculated for each location, see Equation 2. The same method was used in the sensitivity study. The second PWAS on the pristine test coupon had an electrical fault; therefore, the results for this PWAS are not shown at this time. Since the predictive modeling has shown that there are clear damage modes for the coupon, the RMSD can also be applied to a small frequency range near the expected damage modes. This was first calculated for a frequency range between 15 and 20 kHz, and the results are shown in

Table 1. These results show that PWAS number three has the greatest difference between the pristine and disbonded cases. However, the other PWAS can also detect the change in resonance.

Table 1. Experimental RMSD values for 15 – 20 kHz

PWAS #	1	2	3	4	5
RMSD	0.60	N/A	0.72	0.66	0.33

Also, the RMSD was collected for frequencies between 35 and 40 kHz, corresponding to the second damage mode. These results are provided in Table 2. Again the potential detectability of the PWAS is improved through the identification of damage modes and the corresponding frequency range.

Table 2. Experimental RMSD values for 35 – 40 kHz

PWAS #	1	2	3	4	5
RMSD	1.20	N/A	1.23	0.49	0.35

In order to verify that these changes in the admittance of the PWAS do correlate with the damage modes identified through FEA, a second experiment was set up to view these mode shapes. This can be accomplished with the use of scanning laser Doppler vibrometry. This technique measures the out of plane velocity of the structure by utilizing the Doppler Effect. The disbonded test coupon is placed on blocks to maintain the traction free boundaries. Each PWAS will individually be excited with a chirp signal from 10 to 80 kHz. The equipment then scans a section of the coupon and measures the velocity at a point for the entire chirp signal before moving to the next point. In this way a matrix of values for the velocity field is generated for both the magnitude and phase. The experimental setup is shown in Figure 16.

Figure 16. Experimental setup for the scanning laser Doppler vibrometer

The mode shape is then created based on this data and a surface plot is created and superimposed over an image of the test coupon. The mode shape for 17.8 kHz is shown in Figure 17. This mode shape is comparable to the 17.7 kHz mode shape created in ANSYS, as seen in Figure 18. These two mode shapes show good agreement and prove that this change in vibration is the driving factor behind the change in admittance of the PWAS.

Figure 17. Mode shape from the LDV for 17.8 kHz

Figure 18. Mode shape from ANSYS for 17.7 kHz

This has also been performed for the third damage mode. The mode shape from the LDV for 65.1 kHz is shown in Figure 19. This compares well to the mode shape generated in ANSYS for 65.4 kHz, shown in Figure 20. These results verify the predictive modeling methodology for detecting disbonds with the EMIS method.

Figure 19. Mode shape from the LDV for 65.1 kHz

Figure 20. Mode shape from ANSYS for 65.4 kHz

6. CONCLUSION

In conclusion, the EMIS method used with PWAS has been shown to be effective at detecting corner disbonds in an adhesively bonded doubler. A predictive modeling approach for determining the appropriate frequency ranges and PWAS locations was demonstrated. This approach was proven for the test coupon through experimental admittance measurements and scanning laser Doppler vibrometry. This approach should be useful for additional joint geometries, disbond sizes and disbond geometries. It was showed that the PWAS does not need to be directly over the disbond to detect it; however, the ability to detect the disbond decreases with distance. The predictive modeling approach can increase the effective PWAS distance by selecting appropriate frequency ranges based on the identification of damage modes.

Future work will include varying the disbond size to see if this method can be used to quantify the disbond size. This work will also include an exploration of additional disbond location and joint geometries.

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