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Performance Assessment and Validation of Piezoelectric Active-Sensors in Structural Health Monitoring

Gyuhae Park[†]*, Charles R. Farrar*, Francesco Lanza di Scalea**, Stefano Coccia**

* The Engineering Institute
Los Alamos National Laboratory
Los Alamos, NM 87545

** Department of Structural Engineering
Jacobs School of Engineering
University of California, San Diego
La Jolla, CA 92093-0085

ABSTRACT

A sensor diagnostics and validation process that performs in-situ monitoring of the operational status of piezoelectric (PZT) active-sensors in structural health monitoring (SHM) applications is presented. Both degradation of the mechanical/electrical properties of a PZT transducer and the bonding defects between a PZT patch and a host structure could be identified by the proposed process. This study also includes the investigation into the effects of the sensor/structure bonding defects on high frequency SHM techniques, including Lamb wave propagations and impedance methods. It has been found that the effects are significant, modifying the phase and amplitude of propagated waves and changing measured impedance spectrum. These changes could lead to the false indications on structural conditions without an efficient sensor-diagnostic process. The feasibility of the proposed sensor diagnostics procedure is then demonstrated by analytical studies and experimental examples, where the functionality of the surface-mounted piezoelectric sensors was continuously deteriorated. The proposed process can provide a metric that can be used to determine the sensor functionality over a long period of service time or after an extreme loading event. Further, the proposed method can be useful if one needs to check the operational status of a sensing network right after its installation.

[†] Author to whom correspondence should be addressed. Email: gpark@lanl.gov

1. Introduction

Structural health monitoring (SHM) techniques based on the use of active-sensing piezoelectric materials have received considerable attention in the structural community. One critical aspect of the piezoelectric (PZT) active-sensing technologies is that usually large numbers of distributed sensors and actuators are needed to perform the required monitoring process. In addition, the structures in question are usually subjected to various external loading and environmental condition changes that may adversely affect the functionality of SHM sensors and actuators. The piezoelectric active-sensor diagnostic process, where the sensors/actuators are confirmed to be operational, is therefore a critical component to successfully complete the SHM process. Because piezoceramic materials are brittle, sensor fracture and subsequent degradation of mechanical/electrical properties are the most common types of sensor/actuator failures. In addition, the integrity of bonding between a PZT patch and a host structure should be maintained and monitored throughout their service lives as it modifies the strain and stress transfer mechanism. To the authors' best knowledge, however, the issues associated with long-term reliability of the PZT active-sensors and the methods and metrics that can be used to assess the conditions of piezoelectric active-sensors have not been sufficiently addressed in the literature.

It has been pointed out by Friswell and Inman (1999) that the field of sensor validation has received very little attention in the structural dynamics community compared to the process control of chemical engineering. Here, sensor validation refers to the capability of detecting and isolating a faulty sensor in a sensing network. Subsequently, Friswell and Inman (1999) proposed a sensor validation method based on the comparison between the subspace of the response and the subspace generated by the lower modes of structural modes. Their method was further extended by generating new residuals using the modal filtering approaches (Abdelghani and Friswell 2006). It has shown that these new residuals have an interesting fault isolation property. Worden (2003) relies on an auto-associative neural network, which is known to implement the principal component analysis (PCA), for the detection of sensor failures. Kerschen et al (2005) present a procedure based on PCA, which is further able to perform detection, isolation, and reconstruction of a faulty sensor. However, these studies are usually limited to those sensors used for measuring lower-order global modes or not able to discriminate between a sensor fault and structural damage. Blackshire et al (2006) studied the performance of surface-bonded PZT transducers on operational aircraft environment. The goal of their on-going study is to improve the durability and survivability of PZT active-sensors in typical aerospace environment. Saint-Pierre et al. (1996) and Giurgiutiu et al. (2002) proposed a de-bonding identification algorithm by monitoring the resonance of a PZT sensor measured by electrical impedances. As the de-bonding area between the PZT wafer and the host increases, the shape of the PZT wafer's resonance becomes sharper and more distinctive, and the magnitudes of the host resonances are reduced. This method however requires a high-frequency data-acquisition system because even the first resonance of PZT wafers in SHM applications usually lies in hundreds kHz ranges. In addition, this method is not able to account for the sensor fracture, that may simultaneously occurs with de-bonding, as the sensor breakage would apparently change the resonances of a PZT sensor. Sun and Tong (2003) proposed a closed loop-based de-bonding identification scheme. The premise of the method is to use a sensitive control system that can be destabilized by a slight frequency shift caused by small edge de-bonding in a PZT patch. Although the method shows great sensitivity, 0.1% of de-bonding identification in a simulation study, the issues associated with how to differentiate the frequency shift caused by structural damage from the actuator de-bonding was not fully addressed. Bhalla and Soh (2004) investigated the effect of the shear lag loss on electromechanical impedance measurements. They found that the bond layer can significantly modifies the measured admittance signatures, and suggested the use of adhesives with high shear modulus, the smallest practicable bond-thickness, and small-sized PZT transducers in order to minimize the influence of the bond layer. They also suggested that the imaginary part of the electrical admittance of PZT transducers may play a meaningful role in detecting deterioration of the bond layer. However, by concentrating on the effects of bond layers on the electromechanical impedance spectrums only, the metrics that can be used for the bond quality assessment was not clearly identified, and the ability to discriminate bond failures from structural damage was not thoroughly investigated.

In general, a completely broken PZT active-sensor can be easily identified if a sensor does not produce any meaningful output, or an actuator does not reasonably respond to applied signals. However, if only a small fracture or de-bonding occurs within the materials, the sensors/actuators are still able to produce sufficient performance (with distorted signals after the sensor fracture), potentially leading to a false indication of the structural condition. In order to fully implement current active-sensing systems into SHM practice beyond the proof-of-concept demonstration, the authors believe that an efficient sensor-self diagnostic procedure should be adopted in the SHM process.

This paper describes a piezoelectric sensor-diagnostic process based on electrical admittance measurements. The basis of this process is to track the changes in the capacitive value of piezoelectric materials, which is manifested in the imaginary part of the measured electrical admittances. In addition, through analytical and experimental investigation, it is confirmed that the bonding layer between a PZT patch and a host structure significantly influences to the measured electrical admittance. Therefore, by monitoring the imaginary part of the admittances, one can quantitatively assess the fracture or degradation of the mechanical/electrical properties of the PZT sensor and the integrity of its attachment to a host structure. This paper also investigates the effects of bonding defects (between a PZT patch and a host structure) on high frequency SHM techniques, including Lamb wave propagations and impedance methods. It was found that the effects are remarkable, modifying the phase, amplitude, and shape of propagated Lamb waves and changing measured impedance spectrum, which can easily lead to the false indication of a monitored structure. The rest of this paper includes the brief description of the proposed sensor diagnostic method, experimental procedure and results, and several issues that can be used as a guideline for future investigation.

2. Piezoelectric Active-Sensor Diagnostics and Validation Process

The premise of the proposed sensor self-diagnostic process is to track the changes in the capacitive value of piezoelectric materials, which is manifested in the imaginary part of the measured electrical admittances of the PZT material. In our previous work (Park et al 2006), we theoretically and experimentally demonstrated that the degradation of the mechanical/electrical properties of the PZT sensor and its attachment to the external structure produces measurable and distinct changes in the capacitance of PZT materials. This section briefly describes the sensor diagnostic procedure.

The electrical admittance of a PZT transducer, which is defined as the ratio of the energizing voltage to the resulting current, under a free-free boundary condition is given in the following relation (Sirohi and Chopra 2000).

$$Y_{free}(\omega) = \frac{I}{V} = i\omega \frac{wl}{t_c}\left(\varepsilon_{33}{}^{T}\left(1 - i\delta\right)\right) \tag{1}$$

where V is the applied voltage, I is the electric current, w, l, t_c is the width, length, and thickness of a PZT transducer and δ, ε_{33} is the dielectric loss tangent and the dielectric constant of the PZT wafer, respectively.

When a PZT patch is surface-bonded to a structure, Liang et al. (1994) shows that the electrical admittance, $Y(\omega)$, of the PZT transducer is a combined function of the mechanical impedance of the host structure, $Z_s(\omega)$, and that of the PZT wafer, $Z_a(\omega)$, in addition to the terms in Eq. (1), which is given by;

$$Y(\omega) = i\omega\ \frac{wl}{t_c}\left(\varepsilon_{33}{}^{T}(1 - i\delta) - d_{31}{}^{2}Y_p^E + \frac{Z_a(\omega)}{Z_a(\omega) + Z_s(\omega)} d_{31}{}^{2}\hat{Y}_p{}^{E}\left(\frac{\tan kl}{kl}\right)\right) \tag{2}$$

where Y_p^E is the complex Young's modulus of the PZT patch at zero electric field and d_{31} is the piezoelectric coupling constant. The wave number of the PZT patch, k, is defined as,

$$k = \omega \sqrt{\frac{\rho}{\hat{Y}_p^{\,E}}} \tag{3}$$

where ρ is the mass density of the PZT material. The term, $\frac{\tan kl}{kl}$, is close to 1, when the frequency range of excitation is much smaller than the resonant frequency of the PZT patch. Equation (2) is derived based on an assumption that a PZT patch is attached to one end of a structural system, whereas the other end of the PZT is fixed. This assumption regarding the interaction at two discrete points is consistent with the mechanism of force transfer from the bonded PZT transducer to the structure.

Equation (2) sets groundwork for using the PZT active-sensors for impedance-based structural health monitoring applications (Park et al. 2003, Bhalla and Soh 2003, Giurgiutiu et al. 2004). Assuming that the mechanical and electrical properties of the PZT patch do not change over the monitoring period of a host structure, Equation (2) clearly indicates that the electrical admittance (impedance) of the PZT wafer is directly related to the mechanical impedance of the host structure, allowing for the monitoring of the host structure's mechanical properties using the measured electrical property.

The proposed sensor diagnostic process is based on Eqs. (1) and (2). The electrical admittance is clearly a function of its geometry constants (*w, l,* t_c), mechanical properties (Y_p^E), and electrical properties ($\varepsilon_{33}^{\ T}$, d_{31}, δ,) of a PZT transducer. It is also obvious from the equations that the changes in these properties are manifested more distinctly in the imaginary part of the electrical admittance. Therefore, the breakage of the sensor and the degradation of the sensor's quality can be identified by monitoring the imaginary part of the electrical admittance. The breakage/degradation of the sensor quality would cause a downward shift in the slope of the admittance, as the effective size of the sensor would decrease with the breakage and the values of dielectric constants and piezoelectric coupling constants would decrease with the degradation.

Another significant observation that can be made from Eqs. (1) and (2) is that one can identify the effect of the bonding layer on the measured electrical admittance. The effect of the bonding layer is obtained by assuming the mechanical impedance of a structure is much larger than that of the piezoelectric transducer in Eq. (2), which makes the last term in Eq.(2) is close to zero, then,

$$Y_b(\omega) = i\omega \frac{wl}{t_c}\left(\varepsilon_{33}{}^T(1-i\delta) - d_{31}{}^2 Y_p^E\right) = Y_{free}(\omega) - i\omega\frac{wl}{t_c}\left(d_{31}{}^2 Y_p^E\right) \tag{4}$$

It is clear from Eqs. (1) and (4) that the electrical admittance of the same PZT patch is different if under a free-free condition or surface-bonded (or commonly referred to as blocked) condition. The blocked condition would cause a downward shift in the slope of the electrical admittance (decrease in the capacitive value) of a free PZT with the factor of $\frac{wl}{t_c} d_{31}{}^2 Y_p^E$. The assumption to lead this result is valid, at a lower frequency range, because the mechanical impedance of the structure is usually several orders of magnitude greater than that of a PZT transducer. Even though this derivation does not explicitly consider the parameters of bonding materials (such as thickness or shear modulus), it is obvious from Eq. (4) that the use of a PZT transducer with lower Y_p^E and a smaller dimension, such as a small PVDF patches, will reduce the effect of the bonding layer on the measured admittance, which is consistent with the shear-lag analysis available in the literature (Sirohi and Chopra 2000, Bhalla and Soh, 2004). The importance of Eq. (4) is that the bonding layer also contributes to the overall admittance of PZT patches bonded to a structure.

Figure 1 illustrates the measured admittance of free and surface bonded PZT patches. The 5A PZT materials with dimensions of 20 x 20 x 0.25 mm are used. The admittances of three free PZT patches were measured in the frequency range of 40-20,000 Hz using an Agilent 4294A impedance analyzer. These PZT patches were then surface-mounted to a thick aluminum beam and plate using a super-glue with vacuum bagging to ensure a good bonding condition. The admittance measurements were then repeated.

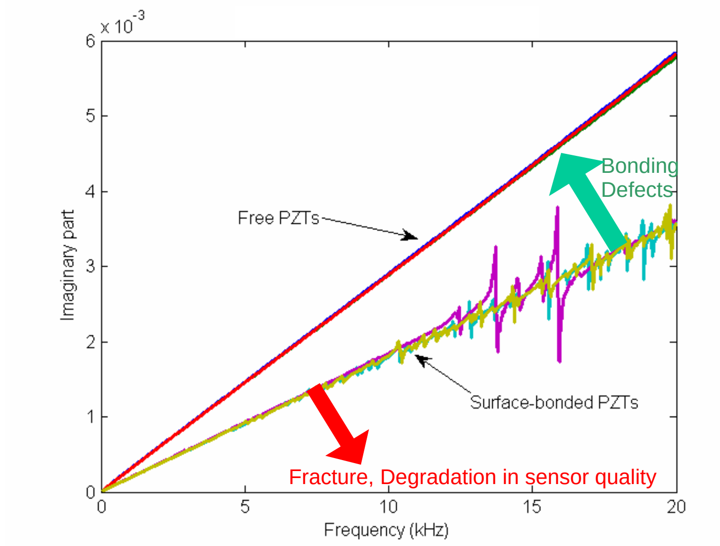


Figure 1: Electrical Admittance Measurement from PZT patches under free and surface-bonded conditions

As can be seen in Figure 1, the downward shifting effect of the bonding layer is remarkable. The slope of the imaginary part, which is the capacitive value of the PZT material, was changed from 29.1 nF to 18 nF, resulting in a 38 % reduction. The slopes of the admittance (capacitances) measured from three bonded PZT patches are about the same, confirming that the bonding conditions of three PZT sensors are approximately identical. In addition, the figure demonstrates that bonding defects would also affect the measured admittance and can be identified by monitoring the slope of the admittance. Contrary to the sensor breakage, bonding defects would cause an upward shift in the slope of the imaginary part of the electrical admittance. Therefore, the sensor functionality including the sensor breakage and the degradation of the bonding condition can be assessed by monitoring the imaginary part of the admittances (capacitance) of the piezoelectric materials. Figure 1 also graphically describes the effects of sensor failures, both the sensor fracture and the bonding defects, on the measured electrical admittance.

3. Experimental Investigations

A series of experiments was performed to demonstrate the effectiveness of the proposed sensor diagnostics. First, an impact test was performed on a composite plate with surface-bonded PZT transducers to assess the performance of the proposed sensor diagnostics method. Then, the sensor diagnostic process is applied to confirm the operational status of a piezoelectric sensing network right after the installation on an aluminum plate and a bolted-washer. The effects of installation defects, in particular the bonding defects, on Lamb wave propagations and electromechanical impedance measurements were also investigated.

2.1 Composite Plate under Impact Loadings

Controlled projectile impact experiments were conducted on a graphite/epoxy-fiber-reinforced composite plate with surface-bonded PZT transducers. These impacts could be considered as similar to operational conditions in real-world applications, such as in unmanned aerial vehicles (Farrar et al 2004).

The test structure is shown in Figure 2. The dimension of the quasi-isotropic composite plate is 609 x 609 x 6.35 mm. The lay-up contains 48 plies stacked according to the sequence [6(0/45/-45/90)]s using 60% Toray T300 graphite fibers in a 934 Epoxy matrix. Two pairs of piezoelectric (5A) and Macro-Fiber Composite (MFC) patches are mounted on one surface of the plate, as shown in Figure 2. The sizes of the PZT and MFC patches are 25.4 x 25.4 x 0.254 mm and 25.4 x 12.7 x 0.254 mm, respectively. The MFC patches are a relatively new type of piezoelectric sensors that are more flexible than the conventional PZT transducer (Wilkie et al 2000). The Young's Modulus of a flexible MFC is 15 GPa, only a fifth of traditional piezoceramic materials (5A, 66 GPa). The MFCs are expected to be less affected by the shear lag loss or bonding defects than traditional PZT transducers because of the lower value in Y_p^E, as described in the previous section.

A total of 14 baseline admittance measurements with the PZT and MFC patches were recorded to capture environmental variability before the impacts were introduced. The baselines were measured under different ambient and temperature conditions over a three week period. Before the impact, two cables were attached to two sides of the plate so that the plate could hang from the test frame in a nearly free-free condition. Impact loading was then introduced to the plate by firing a small projectile out of a gas gun. A gas gun is used to propel a 192.3g steel projectile with a spherical nose at the composite plate. The impact was given on the left side of the plate at 39.93 m/s, and the location is shown in relation to the PZT and MFC transducers in Figure 2. The admittance measurements were then repeated after the impact to asses the condition of the PZT and MFC transducers. Figure 2 also shows the imaginary part of admittance measurements of the PZT 1 and PZT 2 before and after the Impact in the frequency range of 0-20 kHz.

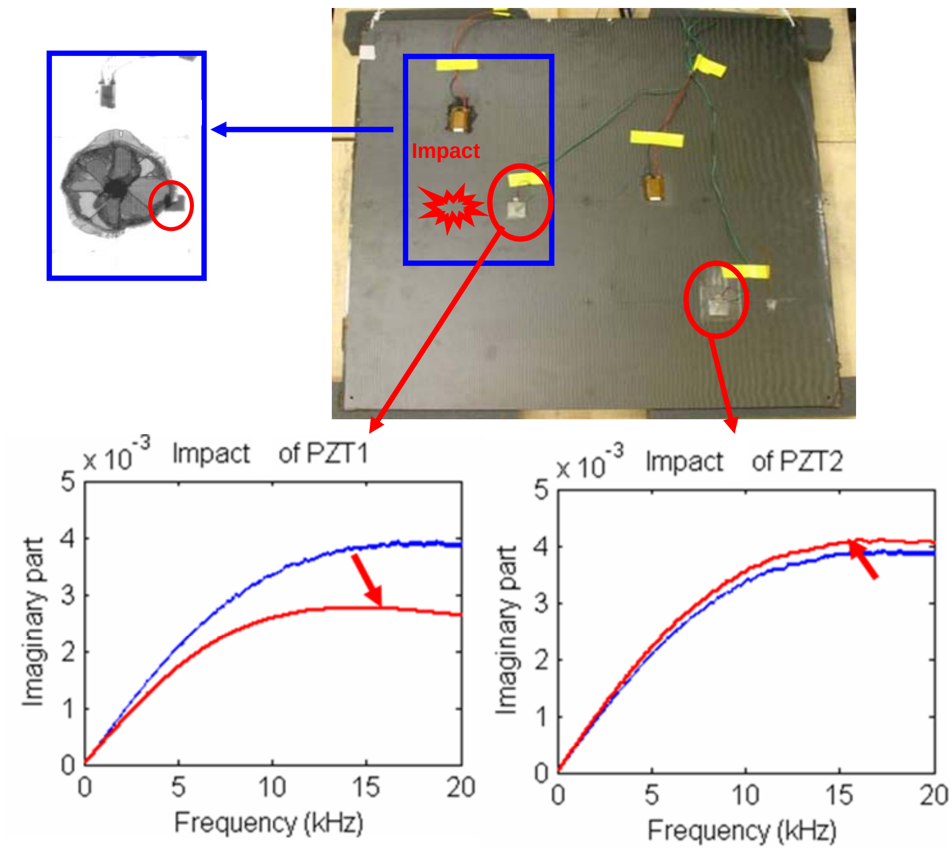


Figure 2: The composite plate used for the test. The Impact causes the downward shift of PZT 1 and the upward shift of PZT 2 in the imaginary component admittance measurements.

The impact produced considerable changes in response of PZT 1, causing a 20% downward shift in the slope, which indicates an internal fracture occurred within the sensor by the proposed procedure. Using an ultrasonic C-scan method, the structural delamination induced by this impact was identified, as shown in the left side of Figure 2. The increasingly dark region shows delamination between different plys, with the darkest area near the surface of the impact zone. This structural delamination was located partially under the PZT 1 (shown in the circle), and it is believed that this delamination caused a partial sensor breakage. For the PZT 2, the impact caused a slight upward shift of the measured admittance slope and this shift could be considered as an indication of de-bonding. Therefore, with the proposed sensor diagnostic method, it can be concluded that the impact causes the internal fracture of the PZT 1 and de-bonding of the PZT 2.

As shown in the figure, the imaginary part of the admittance signature provides a unique feature that can be used for sensor diagnostics. The condition of sensor functionality, including sensor breakage and bonding defects, can be efficiently assessed. It is important to point out that, even with the degraded conditions, the PZT patches were able to produce sufficient sensing and actuation capabilities. The measured responses are significantly distorted partially by the induced delamination on the structure, but the majority of these changes are believed to come from the sensor failure. This type of sensor failure should be identified before SHM data processing, if one wants to avoid a false indication regarding the structural health.

It is also important to point out that the changes associated with the sensor functionality are clearly discernible from those of structural damage. The changes resulting from the structural damage will only cause variations along the imaginary part of the signatures (no change in the slope). On the other hand, sensor failure will result in changes to the slope of the admittance signatures, causing a downward (sensor breakage) and an upward (de-bonding between PZT transducers and the host) shift in the slope.

While PZT patches show considerable changes in the slope of the admittance signatures, neither of the two MFC sensor's integrity was compromised with the induced impacts (Park et al 2006). This flexible sensor certainly provides the advantage of being robust and reliable compared to other available piezoceramic sensors. The MFC sensors are confirmed to be continuously functioning after the impacts and hence, be allowed to monitor the conditions of the structure (Park et al 2005). A more complete description on the experimental procedures and results on this composite plate testing can be found in the reference (Park et al 2006).

2.2 Operational Status Validation of Sensing Network after Installation and the Effects of Bonding Defects on Lamb Wave Propagations

Structural monitoring based on the use of Lamb wave propagations requires relatively large numbers of PZT active-sensors. These transducers can be installed either individually (Kessler et al 2002) or collectively such as smart layer networks (Ihn and Chang 2004), or the sensors (such as PVDF) can cover the entire surface of the structure (Hurlebaus and Gaul 2004). If one sensor inside the network fails, it creates major problems including the failure of the signal processing algorithms, or as a minimum, leaving the large area of a structure unmonitored. The faulty sensors can come from an extreme operational condition, such as an impact, as described in the previous section. However, the sensor failure can also come from the improper installation of the sensors, including imperfect bonding or the accidental sensor breakage during the handling. The proposed sensor diagnostic process can also be efficiently used to determine the operational status of the sensing network right after the installation, as shown in the following example. To the authors' best knowledge, there is no such method or metric available in the literature.

The test structure, shown in Figure 3, is an aluminum plate (1200 x 1200 x 2 mm). Nine circular piezoelectric patches are mounted using super-glue on one surface with a 3 x 3 array of the equal distance. The locations and the numbering schemes of these actuators/sensors are also shown in Figure 3.

The size of the circular PZT patch is 5.5 mm diameter with 0.2 mm thickness. Admittance measurements in the frequency range of 1-20 kHz were made to each PZT patch before and after the installation using an Agilent 4294A impedance analyzer.

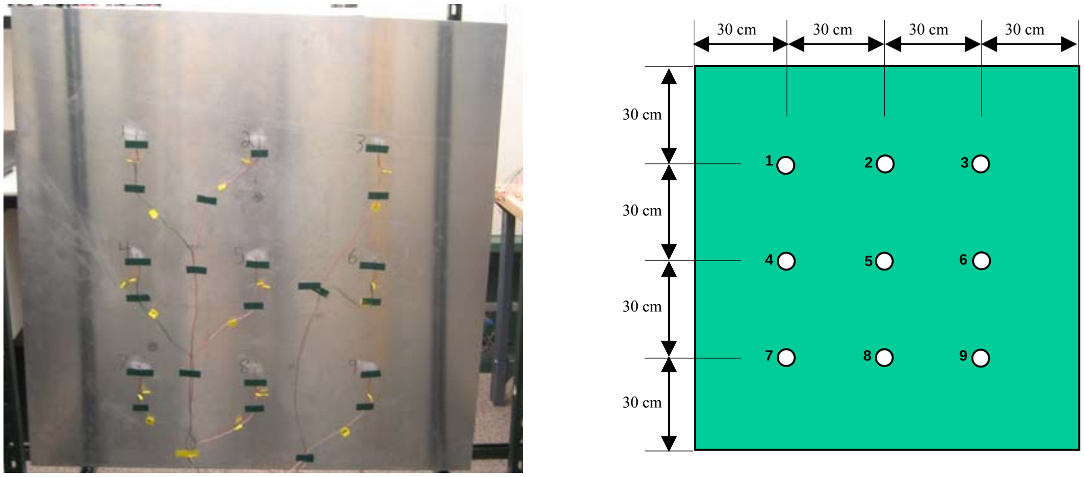
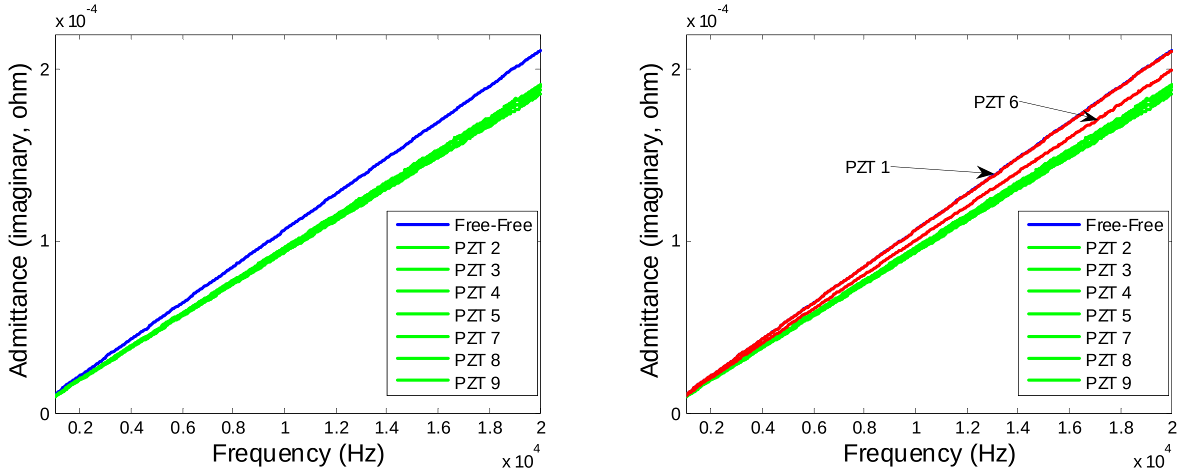


Figure 3. An aluminum plate with PZT transducers attached

The admittance measurements of PZT transducers before and after the installation are shown in Figure 4 (a). For most PZT patches, the downward shifting effect caused by bonding is clearly observable. The slope of the imaginary part, analogous to the capacitive value of the PZT wafer, results in a 4.5 % reduction. However, for the PZT 1, virtually no change in the slope of the imaginary part of admittance was observed, as shown in the Figure 4 (b). Further, for the PZT 6, only 2% change in the slope was observed. As described earlier, the small or almost no change in the slope could be an indication of the imperfect bonding condition. Therefore, these two sensors are classified as a faulty sensor by the sensor diagnostic method. This poor bonding will be very problematic because it can be easily degraded during the operation.



(a) PZT patches under free-free and healthy conditions (b) PZT patches under healthy and faulty conditions

Figure 4. Admittance measurements (imaginary part) from PZT transducers

The effect of bonding defects on the Lamb wave propagation was also investigated. First, the wave propagations (at 100 kHz) from the paths consisting of sensors with the good bonding condition were measured (between PZT 2 and 3, PZT 3 and 5, PZT 4 and 8, and PZT 5 and 9), shown in the figure 5. Because the paths are in the equal distance and through the same materials, the propagated waves show the same characteristics. The arrival of the first So and Ao mode is obvious and they also show the approximately same magnitude. Figure 6 shows the overlapping of the wave propagation in the path between PZT 1 and 5 along the measurement with the healthy paths. PZT 1 was identified as a faulty sensor by the sensor diagnostic process. As one can clearly see, there is a remarkable change in the measured response. There is a clear change in the magnitude, and further, the change in the arrival time can also be clearly observed. It is speculated that, with the bonding defects, there might be a delay in PZT excitation, phase distortion, or the PZT transducer may not be able to efficiently excite the input frequency. Currently, we are investigating these issues for better understanding of the bonding defects. It should be noted that the effects of bonding defects are very similar to those caused by structural damage. If signal processing methods based on the wave attenuation or the time-of-flight information are to be used, and the bonding defect occurs during the operation, these changes can be mistakenly considered as structural damage. Another experimental result, providing the effects of faulty sensors in the path between PZT 1 and 4, are illustrated in Figure 7, along with the Lamb wave propagations of the paths with healthy sensors, including the response between PZT 2 and 3, PZT 4 and 5, and PZT 5 and 8. The same phenomena can be observed and similar conclusions can be drawn from the Figure.

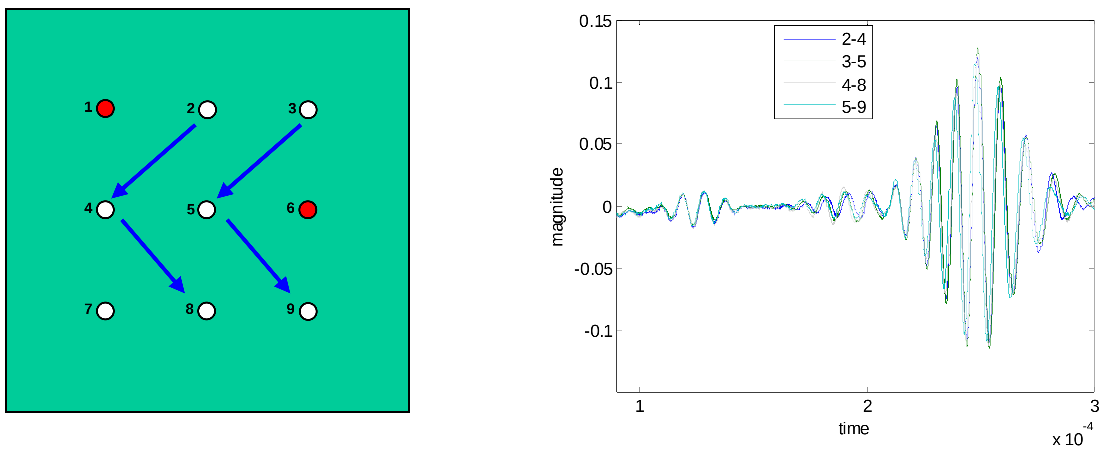


Figure 5. Lamb wave propagations between healthy sensors

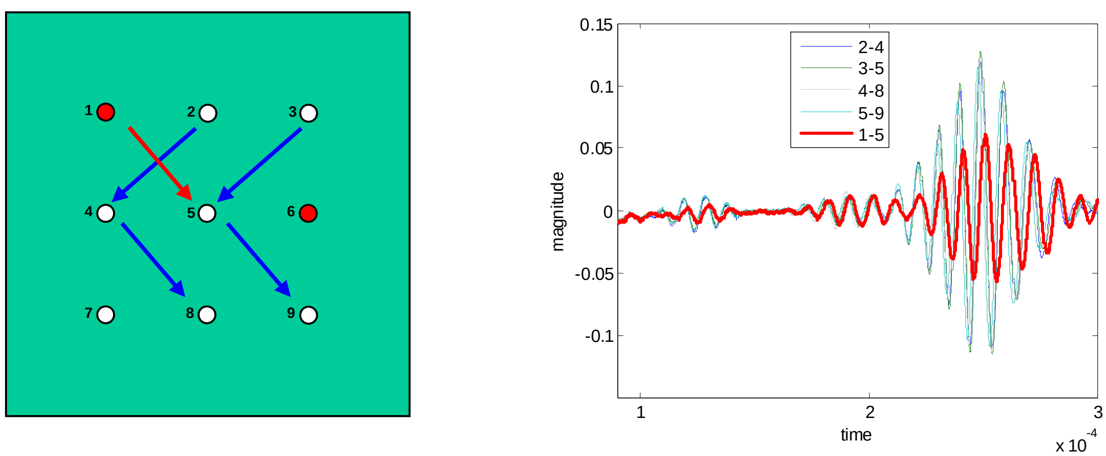


Figure 6. Lamb wave propagations between healthy sensors and faulty sensors

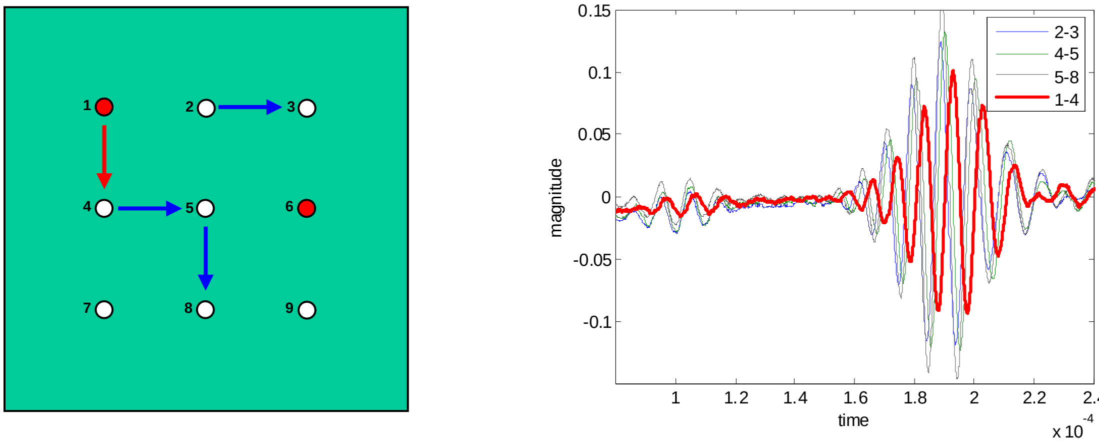


Figure 7. Lamb wave propagations between healthy sensors and faulty sensors

Our next experiment includes the use of larger PZT transducers on the same structure. In the new test, the circular PZT patches of 11 mm diameter with 0.4 mm thickness were super-glued on the same aluminum plate with the same orientation. The piezoelectric transducers that were used in the previous and the new test are shown in Figure 8. For the installation status check, admittance measurements in the frequency range of 1-20 kHz were made to each PZT patch before and after the installation using an Agilent 4294A impedance analyzer.

(a) 5.5 mm diameter with 0.2 mm thickness (b) 11 mm diameter with 0.4 mm thickness

Figure 8. The piezoelectric Sensors used in the testing

The admittance measurements of the larger PZT transducers are shown in Figure 9. In this experiment, three PZT patches (PZT 4, 7, 8) were classified as faulty sensors because they did not show the expected decrease in the slope compared to other transducers. The well bonded PZT patches showed at least 9%

decrease in the slope. The effects of bonding defects are expected to be more significant compared to the previous experiment because the influences of the bonding layer become more significant as the size of the sensor increases (Sirohi and Chopra, 2000, Bhalla and Soh 2004).

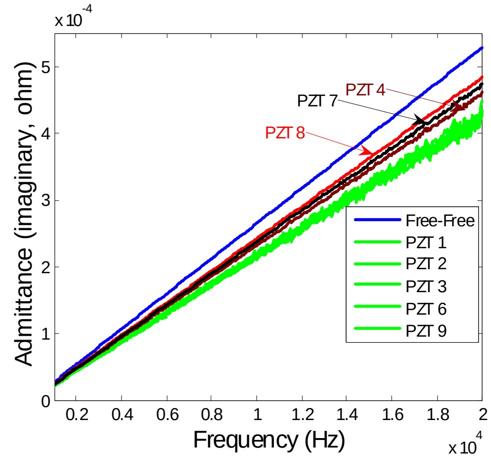


Figure 9. Admittance measurements (imaginary part) from PZT transducers

The effects of bonding defects on these transducers were also investigated. The wave propagations (at 100 kHz) from the paths with the sensors in the good bonding condition were first measured (between PZT 2 and 9, and PZT 1 and 6), then the measurement of the path with a faulty sensor (between PZT 6 and 7) were compared, as shown in the Figures 10 and 11. As expected, the bonding defects induce much more significant impacts compared to the previous test. As can be seen in the Figures, the bonding defects cause the changes in the shape of the propagated wave, rather than merely causing the decrease in the magnitude. The modification in the arrival time was also clearly observed. One obvious reason would be that the faulty bonding condition would make the excitation of PZT actuators no longer linear; the wave may travel with different magnitude or phase in the different directions. The same would be true for the sensing mechanism. Furthermore, because of the faulty bonding condition, a portion of a PZT transducer might not be directly bonded on the surface of the structure; the results would be the multiple excitations from a single piezoelectric source. The propagated waves from these multiple sources would be overlapped, distorting the shape of the propagated waves. Again, these issues are currently being investigated for better understanding of the effects of a bonding layer on Lamb wave propagations. Another result is shown in the figures 12 and 13. The responses from the paths with good sensors (between PZT 1 and 2, PZT 2 and 3, PZT 3 and 6, and PZT 6 and 9) are compared to that of the path with faulty sensors (between PZT 7 and 8). There is a significant distortion in the measured signals as shown in the figures. It could be concluded that the bonding defects do not merely cause the decrease in magnitude. The effect could be the complete distortion of the measured signals. Once again, if this de-bonding occurs during the SHM practice, the change could be registered as structural damage, which points out the importance of the proposed sensor diagnostics in the real-world operation. As can be seen in these examples, the proposed sensor diagnostic method is efficient to monitor the operational status of the PZT transducers right after their installation. Furthermore, the degradation of bonding condition over its service life could also be identified by tracking the changes in the admittance measurements.

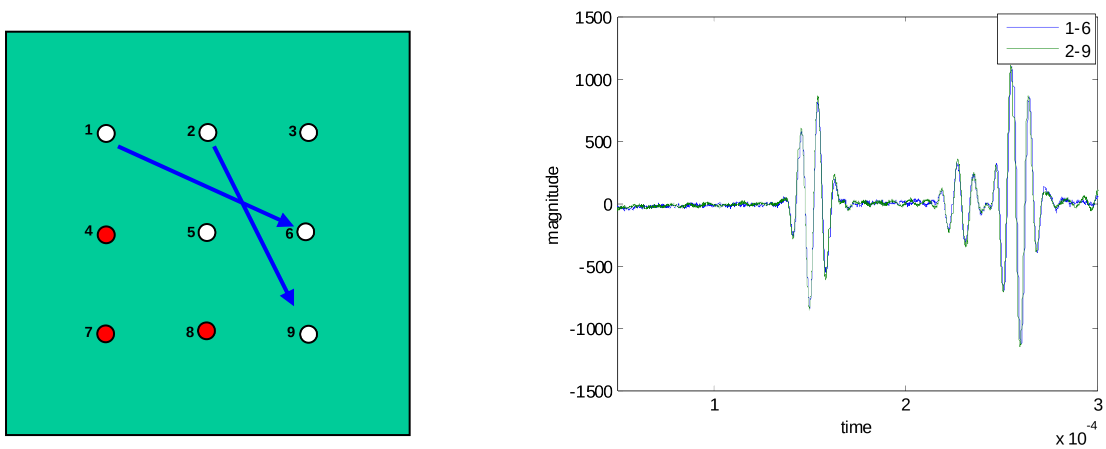


Figure 10. Lamb wave propagations between healthy sensors

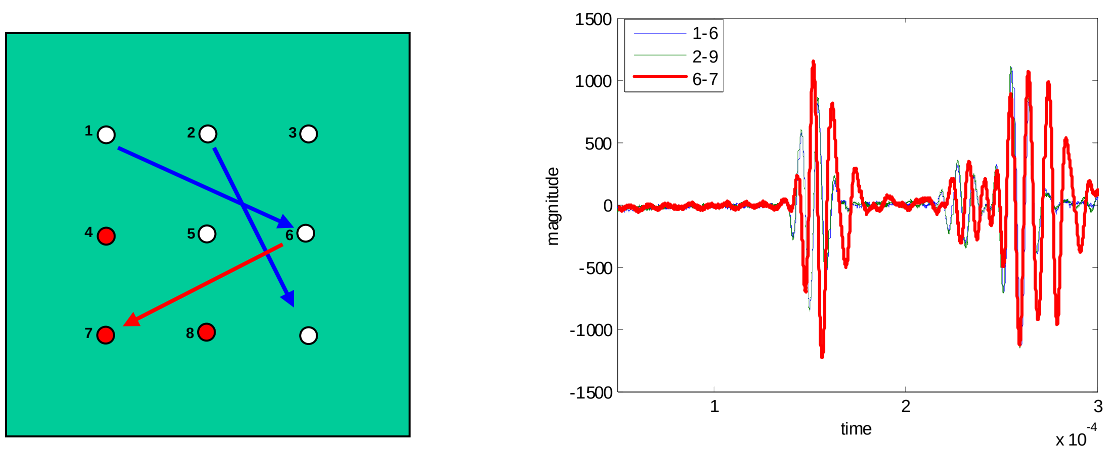


Figure 11. Lamb wave propagations between healthy sensors and faulty sensors

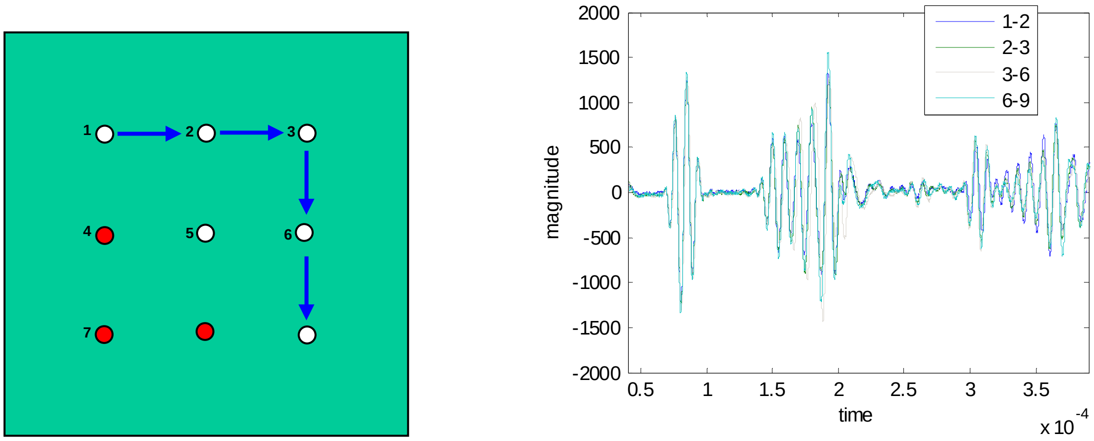


Figure 12. Lamb wave propagations between healthy sensors

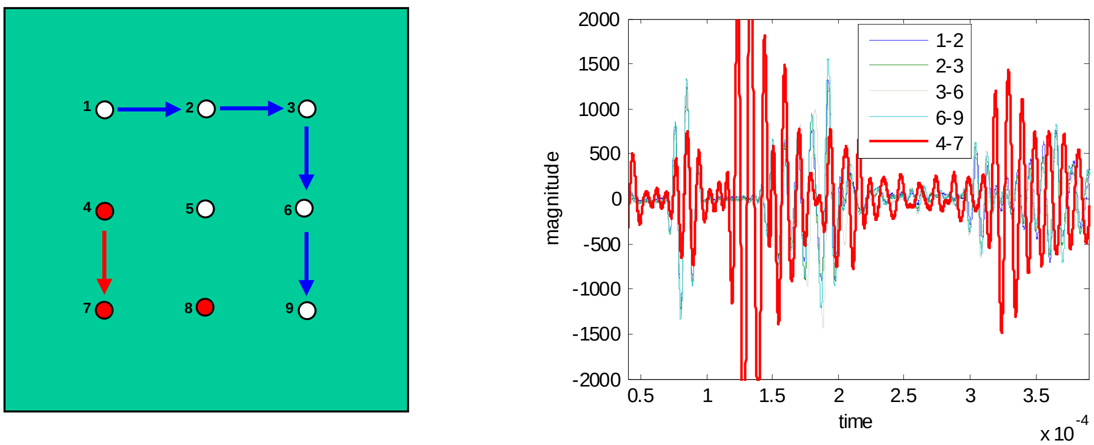


Figure 13. Lamb wave propagations between healthy sensors and faulty sensors

2.3 Bonding Condition Assessment and Effects of Bonding Defects on Electromechanical Impedance Measurements

Impedance-based structural health monitoring techniques (Park et al. 2003, Bhalla and Soh 2003, Giurgiutiu et al. 2004) indirectly measure the mechanical impedance of a structure over selected frequency ranges for SHM. At the lower-order global vibration frequency ranges, several studies (Seeley and Chattopadhyay 1998, Sun et al. 2001) showed that the bonding layer plays a critical role on the measured dynamics, modifying the measured modal frequencies and damping ratio. Because the frequency range of the impedance method lies in much higher frequency ranges, the effects of the bonding layer could be much more significant and should be well understood for this method to be successful in practical applications. Winston et al (2001) investigated the "sensor re-bonding repeatability" of the electromechanical impedance signatures by repeatedly re-bonding a PZT transducer on the same structure. The experiment showed that spectral variations caused by re-bonding the PZT sensors are of the same order of magnitude as those caused by moderate amounts of structural damage. It is believed that the variability introduced by the re-bonding process is solely from the bonding condition changes. Bhalla and Soh (2004) integrated the shear lag effect into electromechanical impedance formulation. They found that the bond layer can significantly modify the measured admittance and incorrectly identify the peak frequencies. However, it can be stated that no experimental investigation in the past has been performed with slight or quantifiable bonding defects on impedance signatures because degradation in bonding is difficult to achieve experimentally, and more importantly, there is no method or metric available to assess the quality of the bonding condition.

A set of experimental testing was performed with different bonding conditions of the PZT patches. In order to assess the effects of different sensor bonding conditions on measured impedance, an aluminum hexagonal washer (with geometry 25.4 mm high, and 31.75 mm across the flats with a 12.7 mm diameter hole) was instrumented with two circular PZT patches (12.7 mm diameter, 0.2 mm thickness), each on a different face, as shown in figure 14. The patches were attached to the plates using two different bonding techniques to simulate both good and poor bonding conditions. One bonding condition was to use the 3M Thermo Bond film for a temporary (and poor) bonding condition, while the other was to use the superglue for a better bonding condition.

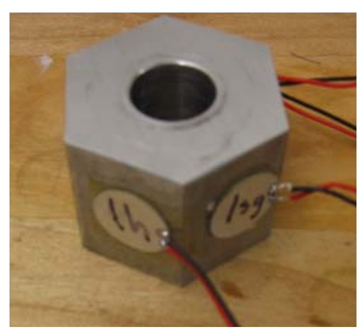


Figure 14. An aluminum washer with two PZT patches installed with different bonding conditions

Figure 15 shows the imaginary part of the admittance of each of the sensors bonded to the aluminum hexagonal washer in the frequency range up to 20 kHz. This plot also includes an admittance measurement for an un-bonded 11 mm-diameter PZT patch. The quality of the bond can be determined based on the changes in the slope steepness of the admittance measurement. From Figure 15, one can see that the super-glued sensor demonstrates the lower slope, and therefore can be considered to have a better bonding condition.

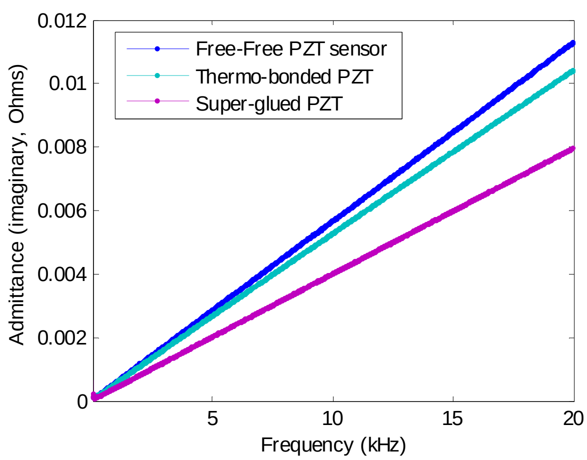


Figure 15: Admittance measurements from different bonding conditions from an Aluminum washer.

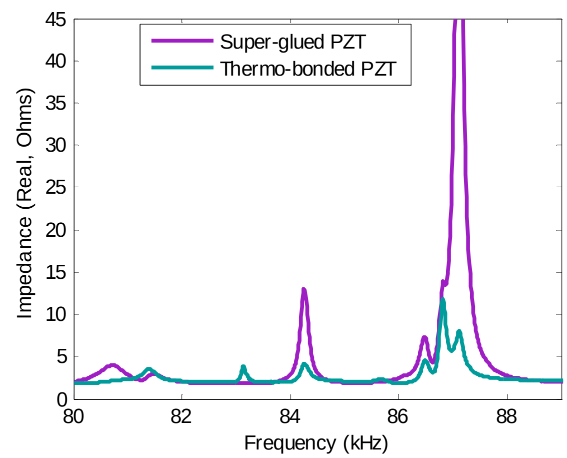


Figure 16: Impedance measurement (real part) under different bonding condition

The impedance measurements (the real part) under the different conditions are shown in the figure 16. It is obvious from the figure that the PZT bonded with the superglue shows the resonances near 84 and 87 kHz much clearer, at least an order of magnitude greater, than the sensor bonded with the thermo film. From the measurements, it once again confirms that the magnitude of the resonance is affected by the bonding conditions. The poor bonding condition may result in erroneous or misleading results as the stress/strain transfer mechanism is modified by the changed electro-mechanical interaction between the structure and PZT patches. Furthermore, near the frequency range at 83 kHz, the PZT active-sensor with the thermo bonded condition exhibits a new resonance of the structure. Therefore, it can be concluded that, as the bonding condition changes, the identified resonances and associated magnitudes are significantly affected. It is very clear from this figure that the bonding condition significantly influences structural identification and health assessment if not carefully accounted for. Further, it is obvious that, in order to minimize the false indication on the structural condition, the sensor diagnostic process needs to be implemented to discriminate the sensor degradation from structural damage in SHM field applications.

4. Summary

A piezoelectric sensor self-diagnostic process that performs in-situ monitoring of the operational status of piezoelectric sensors and actuators was presented. The basis of this process is to track the changes in the capacitive value of piezoelectric materials, which shows up in measured admittance. Both degradation of the mechanical/electrical properties of a PZT and bonding defects between a PZT and a host structure could be identified using the proposed procedure. The effects of the bonding defects on high frequency structural health monitoring techniques are also investigated. The effects are found to be significant, modifying the magnitude and the shape of the propagated Lamb waves, and influencing the measured magnitude and resonances of the electro-mechanical impedance spectrum. These changes could be registered as structural damage unless an efficient sensor-diagnostic process, such as the proposed one in this paper, is implemented in the practice.

Authors are currently investigating the development of an improved modeling technique, which incorporates the comprehensive electro-mechanical effects of the bonding layer on the admittance, for more quantitative estimation of the bonding effect. The development of improved modeling will help to identify the threshold limit of the slope change that can be considered as an acceptable bonding condition. Authors are also investigating the analytical estimation of the influences of bonding defects on the Lamb wave propagations. This study may provide a better understanding of Lamb wave propagations actuated and measured by the PZT active-sensors and help to quantify the effect of bonding defects on Lamb wave signal processing algorithms.

The capacitance of piezoelectric materials is known to be temperature sensitive. Feature identifications and signal processing techniques that are able to normalize the measured admittance data with respect to varying environmental conditions are essential if one is to fully apply the proposed sensor diagnostic process under widely varying temperature conditions. The development of an automated data-processing algorithm to easily interpret the measured admittance signals, coupled with a stand-alone admittance measuring device, is also required to implement the proposed concept to field applications. These issues are currently being investigated by the authors and are the subjects of the next paper.

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