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**EFFECTS OF PIEZOELECTRIC (PZT) SENSOR BONDING AND
THE CHARACTERISTICS OF THE HOST STRUCTURE ON
IMPEDANCE BASED STRUCTURAL HEALTH MONITORING**

Prepared by:	Abdul Jalloh
Academic Rank:	Assistant Professor
Institution and Department	Mechanical Engineering Department Alabama A&M University Normal, AL 35762
NASA/MSFC Directorate:	ED 27
MSFC Colleagues:	John Lassiter

Summary

This study was conducted to investigate the effects of certain factors on the impedance signal in structural health monitoring. These factors were: the quality of the bond between the sensor and the host structure, and the characteristics of the host structure, such as geometry, mass, and material properties. This work was carried out to answer a set of questions, related to these factors, that were developed by the project team. The project team was comprised of Dr. Doug Ramers and Dr. Abdul Jalloh of the Summer Faculty Fellowship Program, Mr. Arnaldo Colon-Perez, a student intern from the University of Puerto Rico of Turabo, and Mr. John Lassiter and Mr. Bob Engberg of the Structural and Dynamics Test Group at NASA Marshall Space Flight Center (MSFC).

This study was based on a review of the literature on structural health monitoring to investigate the factors referred to above because there was not enough time to plan and conduct the appropriate tests at MSFC during the tenure of the Summer Faculty Fellowship Program project members.

The surveyed literature documents works on structural health monitoring that were based on laboratory tests that were conducted using bolted trusses and other civil engineering type structures for the most part. These are not the typical types of structures used in designing and building NASA's space vehicles and systems. It was therefore recommended that tests be conducted using NASA type structures, such as pressure vessels, to validate the observations made in this report.

Introduction

The electromechanical impedance method using piezoelectric (PZT) sensors is one of the most recent developments in the field of structural health monitoring. This damage monitoring method is based on the electromechanical coupling between the host structure and the bonded PZT sensor. Damage alters the stiffness, damping and mass of the host structure, which results in changes in the mechanical impedance of the structure. This in turn modifies the effective electrical impedance of the sensor, which is then used to identify incipient damage in the host structure [5, 6]

There are several factors that could affect the performance of the PZT sensor. These include the quality of the bond between the sensor and the host structure, and the characteristics of the host structure, such as geometry, mass, and material properties [13]. It is therefore necessary to understand how these factors affect the quality of the impedance signal that is obtained from the sensor. This work was carried out to answer a set of questions, related to these factors, that were developed by the project team. The project team was comprised of Dr. Doug Ramers and Dr. Abdul Jalloh of the Summer Faculty Fellowship Program, Mr. Arnaldo Colon-Perez, a student intern from the University of Puerto Rico of Turabo, and Mr. John Lassiter and Mr. Bob Engberg of the Structural and Dynamics Test Group at NASA Marshall Space Flight Center (MSFC). The questions are listed in the next section.

This report addresses the following issues that are related to the factors mentioned above:

1. Effects of the quality of sensor bonding on the signal
2. Sensor bonding techniques
3. Sensor geometry
4. Sensitivity of the sensing region
5. Effects of host structure geometry, and material properties on impedance measurements.

This work was based on a review of the literature on Structural Health Monitoring to investigate the factors referred to above because there was not enough time to plan and conduct the appropriate tests at MSFC during the tenure of the Summer Faculty Fellowship Program project members. The surveyed literature documents works on structural health monitoring that were based on laboratory tests that were conducted using bolted trusses and other civil engineering type structures for the most part. These are not the typical types of structures used in designing and building NASA's space vehicles and systems. It is therefore recommended that tests be conducted using NASA type structures, such as pressure vessels, to validate the observations made in this report.

Project Questions

The project questions are listed below. The first four questions were assigned to Dr. Ramers for investigation. His work is documented in his Summer Faculty Fellowship Program Report [12]. The last two questions, questions 5 and 6, were assigned to Dr. Jalloh, and they are addressed in this report.

1. Is there a significant difference in the information provided between the PZT and SCP sensors?
2. Which bands are needed to characterize the PZT and SCP signals?
3. Is there an adequate parsimonious characterization of the piezo signal?
4.
 - a. What are the metrics that can be used for detecting change in the PZT signal indicating change
 - b. What methods and metrics can be used to determine if the PZT is operating correctly?
5. What are the appropriate procedures for attaching PZTs to structures

- a. How does surface area contact affect sensitivity of signal?
 - b. How does quality and type of bond have an effect of the nature of the signals?
 - c. Does gradual degradation (or changes) in the bonding material have an effect on the nature of the signal?
6. In general, how do we size the sensor (length, width, thickness)?

Sensor Bonding

The bonding effects of a PZT sensor significantly affect the estimation of the resonant frequencies of the host structure [15]. Bonding the PZT sensor to the host structure is of utmost importance because the PZT actuation/sensing process depends on the effective electromechanical coupling of the sensor with the host structure being monitored. Bond quality determines the quality of the electromechanical coupling between the sensor and the host structure. As such a study to optimize the quality of the bond between the PZT sensor and the host structure deserves special attention. In the literature, several research teams have documented their work in this area [1, 2, 3, 7, 8, 9, 13, 14, 15].

In their study, which investigated the effects on the bonding layer of the dynamic interaction between a PZT patch and a host structure, Xu and Liu [15] suggested that the bonding effects of PZT sensors should be included to obtain more accurate results.

Ong et al. [8, 9] suggested that adhesives with high modulus should be used in order to obtain maximum repeatability and consistency of the impedance signature.

Bhalla et al. [2] suggested the use of double-sided adhesive tape to bond PZT sensors to host structures.

Giurgiutiu and Zagari [7] demonstrated that the integrity and consistency of the sensor can be assessed by the imaginary component of the impedance measurement. A well-bonded sensor shows a smooth curve while a dis-bonded sensor shows a very strong resonance in the imaginary part. It is therefore possible to determine whether the sensor is perfectly bonded to the host structure or not by tracing the imaginary component. The authors, however, point that qualitative assessment or estimation of the bonding stiffness is a very difficult task.

Berman et al. [1] conducted a set of tests to study the quality of bonding between PZT sensors and graphite reinforcements of a host structure. Different bonding procedures were used in the tests. The test results are summarized in Table 1 below.

Table 1. Procedures investigated for bonding PZT sensors to graphite reinforcement.

	Bonding Procedure	Bond Quality
1	Applied to wet resin, no pressure applied.	Poor. Thick layer of epoxy between sensor and graphite reduces actuation performance.
2	Applied to wet resin, pressure (5 psi) applied.	Mediocre. Layer of epoxy is thinner, but actuation performance still not acceptable.
3	Applied after two hours of curing, no pressure applied.	Poor. Thick layer of epoxy between sensor and graphite reduces actuation performance.
4	Applied after complete curing using cyano-acrylate adhesive, pressure applied.	Acceptable. Layer of cyano-acrylate adhesive much thinner than epoxy, good actuation performance.
5	Applied after complete curing using cyano-acrylate adhesive, fiberglass mesh removed, pressure applied.	Best. Thinnest layer of cyano-acrylate adhesive for optimum actuation performance.

Park et al. [10, 11] observed that brittle piezoceramic sensors can only withstand very small bending. This imposes difficulties in handling and bonding of the sensor into the host structure. Also conformability of piezoceramic sensors to curved surfaces is extremely poor. This makes it necessary to undertake extra treatment of the surfaces before bonding the sensor to the host structure.

Sensor Bonding Techniques

The three main methods used to attach PZT sensors to host structures for structural health monitoring are:

1. **Clamping:** This method is often found to be unreliable since the function of the sensor is to move and it is very difficult to stop the minute vibrations that will sometimes allow the sensor from “walking” out of the clamp.
2. **Soldering:** This method has the advantage of giving a conductive connection. A major drawback is that the movement will cause fatigue in the bond.
3. **Gluing:** This is usually the best approach. Modern epoxy- or acrylate glues, in particular, provide strong, yet flexible bonds. The bond does not experience any

fatigue. Since electrical contact is always required between the sensor and host structure, one possibility is to use conductive glue, usually an epoxy filled with particles. One drawback with these glues is that they are so heavily loaded with conductive particles that the glue line is often weak.

The Structural and Dynamics Testing Group at MSFC have been using the gluing technique to attach sensors to test articles in structural health monitoring tests. The adhesive used is “super glue”, a commercially available product. This seems to be an effective bonding technique, although tests need to be conducted to study the effects on the impedance signal that would result from damage to or deterioration of the bond.

One of the tests conducted by Berman et al. [1] used a vacuum-assisted sensor-mounting technique that provided the tightest possible bond while using the thinnest feasible layer of adhesive. The technique consists of the following steps:

1. A PZT sensor, a square strip of porous release film, a square strip of 0.05 in. thick porous foam, and nylon bagging film were stacked into a four-layer assembly.
2. The mating surfaces of the sensor and composite were cleaned thoroughly with acetone.
3. A one-part cyano-acrylate epoxy was applied to the sensor surface.
4. The assembly was immediately placed on the composite material.
5. A vacuum setup, comprising of a compressor, tubes, and sealant tape wrapped around the sensor assembly, was used to establish a vacuum around the sensor.

The vacuum field forces the sensor tightly against the composite surface and yields a good bond within two hours.

Sensitivity of the Sensing Region

The sensing range of an impedance sensor in general, is closely related to the frequency ranges used, the material properties and geometry of the host structure, and the properties of the sensor [10, 11]. This report will address issues related to the properties and geometry of the host structure.

It has been demonstrated experimentally that the sensing area is localized to a region close to the PZT sensor [1, 4]. This characteristic enhances the sensing ability of PZT sensors to detect damage without being affected by far field boundary conditions, external loading, or normal operational vibrations of the system. Depending on host structure material properties, it has been estimated that the sensing area of a single PZT sensor can vary anywhere from 0.4 m (sensing radius) on composite reinforced concrete structures, to 2 m on simple metal beams.

Several factors affect the sensing region of the host structure in structural health monitoring. Some important factors and their effects are given in Table 2 below [4]. It should be noted that the conclusions in Table 2 were deduced for the most part from tests conducted on bolted truss structures.

The factors in Table 2 should be taken into account when attaching PZT sensors to host structures. The rating scheme shown in the right-hand column of Table 2 indicates the factor's importance: 0 corresponds to a factor of no importance, while 5 would be the most important factor.

Table 2. Factors to consider when attaching PZT sensors to host structures.

Factors	Important Effects	Rating
Material stiffness and density	Impedance shifts to the right and up for stiffer materials	1
Energy absorbent materials	Decrease in amplitude for softer intermaterials. Significantly larger for highly damped materials	2
Material damping	More damped materials give shallower peaks	3
Discontinuity in cross-section	Important attenuation at large cross-section discontinuities	3
Bolted joints	Size of bolt more important than its material. Shearing force at the interface is the most important factor. Major source of energy loss	5

In his study, Esteban [4] made the following conclusions based on the information in Table 2:

1. The impedance shifts to the right and has an increased amplitude for stiffer materials, while most damped materials would tend to give more shallow signals. These factors must be taken into considerations if sensors are to be attached close to areas of different materials.
2. For intermaterials that are softer than the host material, the area of material discontinuity acts as an energy absorbent. This characteristic brings the amplitude of the response down. Conversely, if the intermaterial is harder than the host material, the opposite effect is observed.

3. The sensing range of the PZT sensor will be affected by the internal damping of the material of the host structure. As such, the number of sensors needed to monitor the system should vary accordingly.
4. Cross-sectional discontinuities in the host structure are a source of signal attenuation. This characteristic was observed even for relatively small cross-sectional discontinuities. The number of sensors in this region should also vary accordingly.
5. The size of the bolt in bolted joints plays a great role in the attenuation of the propagating wave, while the bolt material was less critical.

Sensor Geometry

Certain PZT sensor geometries are more favorable than others in conducting structural health monitoring. Laboratory tests [1] have shown that:

1. Increasing the thickness of the sensor (bonded to the host structure) decreases the capacitive contribution of the sensor, thereby decreasing the heights of the peaks in the impedance signature.
2. Increasing the contact area of the sensor causes an increase in the sensor's capacitive contribution, thereby increasing the height of the peaks in the impedance signature. This implies a greater dynamic interaction between the sensor and the host structure
3. Sensor plates as small as 0.50 in. square and 0.01 in. thick are sufficient for structural health monitoring.

It should be pointed out that no information was found in the surveyed literature that directly relates the size of a PZT sensor to the geometry and/or properties of the host structure. However, effective structural health monitoring can be accomplished even with very small PZT sensors.

Conclusions and Recommendations

Although this work was not based on tests conducted at MSFC as was originally envisioned, the review of the literature on structural health monitoring has yielded some very useful information that addresses the project questions that were assigned to the author. Based on this review, it was concluded that:

1. The quality of the bond between the PZT sensor and the host structure has a significant effect on the quality of the signal. Also, several bonding procedures, the resulting quality of the bond and the effect on the signal in each case were reviewed

2. The thickness of the sensor, the size of the contact area of the sensor and the size of the sensor were all found to have effects on the impedance signal.
3. The sensing area was found to be localized to a region close to the PZT sensor. Depending on the material properties and geometry of the host structure, the sensing region can extend anywhere from 0.4 m (sensing radius) on composite reinforced concrete structures to 2 m on metal beams.
4. Several factors that must be considered when attaching PZT sensors to host structures. Some of these factors include material stiffness and density, energy absorbing capacity of materials, material damping, discontinuity in cross-sections, and bolted joints. The effects of these factors on the impedance signal and the relative importance of each factor were reviewed.

This work was based on a review of the literature on Structural Health Monitoring to investigate the factors that relate to the project questions to above. The conclusions in the surveyed literature were made, in the most part, from tests conducted on bolted trusses and other civil engineering type structures. These are not the typical type of structures that are employed in designing and building NASA type space vehicles and systems. It is therefore recommended that tests which replicate those in the surveyed literature be conducted using NASA type structures. The purpose of these tests will be to investigate the effect on the impedance signal in structural health monitoring from the factors related to the project questions.

Additionally, is recommended that tests be conducted to study the characteristics of PZT sensor bonding in cryogenic temperature environments and also on the effect of cryogenic temperatures on the impedance signal.

References

1. Berman, J, Quattrone, R., Averbuch, A., Lalande, F., Cudney, H., Raju, V., and Cohen, G. L., (1999). "Piezoelectric Patch Sensors for Structural Integrity Monitoring of Composite-Upgraded Masonry and Concrete Structures", *Construction Engineering Research Laboratory Technical Report 99/72, US Army Corps of Engineers*.
2. Bhalla, S., Naidu, A. S. K., Ong, C. W., and Soh, C. K., 2002. " Practical Issues in the Implementation of Electromechanical Impedance Techniques in NDE." *Proceedings of SPIE International Symposium on Smart Materials, Nano-, and Micro-Smart Systems, December 16-18, Melbourne, Australia (paper no 4935-77)*.
3. de Faria, A. R., 2003. "The Impact of Finite-Stiffness bonding on the Sensing Effectiveness of Piezoelectric patches." *Technical Note, Smart Materials and Structures 12, N5 – N8*

4. Esteban, J., 1996. "Modeling of the Sensing Region of a piezoelectric actuator/sensor." *Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, Va.*
5. Giurgiutiu V., and Rogers C. A., 1997. "Electromechanical (E/M) Impedance Method for Structural Health Monitoring and Non-destructive evaluation." *Proc. 1st Int. Workshop on Structural Health Monitoring (California: Stanford University, 433-444)*
6. Giurgiutiu V., and Rogers C. A., 1998. "Recent Advancements in the Electro-Mechanical (E/M) Impedance Method for Structural Health Monitoring and NDE." *Smart Structures and Materials Conf. (San Diego, California, Proc. SPIE 3329 536-547)*
7. Giurgiutiu V., and Zagrai, A. N., 2002. "Embedded Self-Sensing Piezoelectric Active Sensors for Online Structural Identification," *ASME Journal of Vibration and Acoustics, Vol. 124, 116-125.*
8. Ong, C. W., Lu, Y., and Soh, C. K., 2002a. "The Influence of Adhesive Bond on Electromechanical Admittance Response of a PZT Patch Coupled Smart Structure." *Proceedings of the 2nd International Conference on Structural Stability and Dynamics, December 16-18, Singapore.*
9. Ong, C. W., Yang, Y., Wong, Y. T., Bhalla, S., Lu, Y., and Soh, C. K., 2002b. "The effects of adhesive on the Electromechanical response of a Piezoceramic transducer Coupled Smart Structure." *Proceedings of ISSS-SPIE 2002 International Conference on Smart Materials and Systems, December 12-14, Bangalore, India (ISSS2002/SA-592).*
10. Park, G., Inman, D. J., Farrar, C. R., 2003. "Recent Studies in Piezoelectric Impedance-Based Structural Health Monitoring," *4th International Workshop on Structural Health Monitoring, September 15-17, Stanford, California, 1423-1430.*
11. Park G., Sohn, H, Farrar, C. R., Inman, D. J., 2003. "Overview of Piezoelectric Impedance-Based Health Monitoring and Path Forward." *The Shock and Vibration Digest, Vol. 35, No. 6, 451-463.*
12. Ramers, D. L., 2004. "Analysis of Piezoelectric structural Sensors with Emergent Computing Techniques," *NASA Faculty Fellowship Program Report.*
13. Tseng, K. K-H., and Naidu, A. S. K., 2002. "Non-Parametric Damage Detection and characterization using Smart Piezoelectric Material." *Smart Materials and Structures II, 317-329*
14. Wang, B., Jiang, Y., Li, Y., Wang, X., and Xiong, K., 2003. "Experimental Research on the Response Characteristic of Piezoelectric Transducers Debonding from Composite Beam." *Proceedings of the 4th International Workshop on Structural Health Monitoring, Stanford, CA, 1416 – 1422.*

15. Xu, Y. G., and Liu, G. R., 2002. "A Modified Electromechanical Impedance Model of Piezoelectric Actuator-Sensors for Debonding Detection of Composite Repair Patches." *Journal of Intelligent Material Systems and Structures*, Vol. 13, No. 6, 389-405.