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Proof-of-Concept Application of Impedance-Based Health Monitoring on Space Shuttle Ground Structures

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ABSTRACT

Many of the structures responsible for the launch, ground systems and support operations of the space shuttle are still being used well past their nominal expected design life. This has led to an increased interest in monitoring these structures in order to decrease the risk of eventual breakdown or structural failure. One monitoring method, which has shown promising results for such applications, is the impedance-based structural health monitoring technique. This paper presents results from proof-of-concept tests on the launch pad's orbiter access arm bolted connection, solid rocket booster hold down post, mobile launch platform heat shield and crawler transporter bearing. Modifications for future tests are suggested.

1.0 INTRODUCTION

NASA's shuttle program exhibits many technologies on the cutting edge of science. However, much of the program is built upon the aging infrastructure of the Apollo and Saturn V programs, which were begun more than 40 years ago. Most of the infrastructure is located at the Kennedy Space Center in Florida, the NASA center responsible for shuttle launches, ground systems and support operations. There has been increased interest in monitoring the structures responsible for these operations in order to decrease the risk of breakdowns or structural failure. One monitoring method, which has shown promising results for such applications, is the impedance-based structural health monitoring technique. This report documents preliminary proof-of-concept testing performed on the variety of ground system elements used for Space Shuttle launches.

2.0 IMPEDANCE-BASED STRUCTURAL HEALTH MONITORING

The impedance-based health monitoring method is made possible through the use of piezoelectric patches bonded to the structure that act as both sensors and actuators on the system. When a piezoelectric is stressed it produces an electric charge. Conversely when an electric field is applied the piezoelectric produces a mechanical strain. The patch is driven by a sinusoidal voltage sweep. Since the patch is bonded to the structure, the structure is deformed along with it and produces a local dynamic response to the vibration. The area that one patch can excite depends on the structure and material but is generally 0.3 to 2.0 meters. The response of the system is transferred back from the piezoelectric patch as an electrical response. The electrical response is then analyzed where, since the presence of damage causes the response of the system to change, damage is shown as a phase shift or magnitude change in the impedance. Any type of damage that causes a change in local structural properties near a sensor can be detected. This includes cracking, joint loosening, delaminations and a variety of other damage mechanisms. Using ultrasonic frequencies, the short wavelength can detect small structural changes with high degree of signal resolution. Often a damage metric is used to quantify the change in shape of the impedance response. Using an array of sensors one can not only detect, but also locate damage on a structure. However, further characterization of the damage requires a model of the system such as a finite element model or neural network.

2.1 Electro-Mechanical Principle

The health monitoring method utilizes impedance sensors to monitor changes in structural stiffness, damping and mass. The impedance sensors consist of small piezoelectric patches, usually smaller than 25x25x0.1 mm, that are used to directly measure the local dynamic response.

Piezoceramic transducers acting in the 'direct' manner produce an electrical charge when stressed mechanically. Conversely, a mechanical strain is produced when an electrical field is applied. For a linear piezoelectric material, the relation between the electrical and mechanical variables is described by linear relations [1]:

$$\begin{aligned} S_i &= s_{ij}^E T_j + d_{mi} E_m \\ D_m &= d_{mi} T_i + \varepsilon_{mk}^T E_k \end{aligned} \qquad (1)$$

or

$$\begin{bmatrix} S \\ D \end{bmatrix} = \begin{bmatrix} s^E & d_t \\ d & \varepsilon^T \end{bmatrix} \begin{bmatrix} T \\ E \end{bmatrix} \qquad (2)$$

where S is the mechanical strain, T is the mechanical stress, E is the electric field, D is the charge density, s is the mechanical compliance, d is the piezoelectric strain constant, ε is the permittivity, and the subscripts i, j, m and k indicate the direction of stress, strain or electric field. The superscripts E and T indicate that those quantities are measured with electrodes connected together and zero stress, respectively and the subscript t indicates transpose. The first equation describes the converse piezoelectric effect and the second one describes the direct piezoelectric effect.

The process to be used with the impedance-based monitoring method utilizes both the direct and converse versions of the piezoelectric effect simultaneously to obtain an impedance signature for the structure. When a PZT (lead zirconate titanate) patch or an actuator attached to a structure is driven by a fixed alternating electric field, a small deformation is produced in the PZT wafer and the attached structure. Since the frequency of the excitation is very high, the dynamic response of the structure reflects only a very local area to the sensor. The response of that local area to the mechanical vibration is transferred back to the PZT wafer in the form of an electrical response. When a crack or damage causes the mechanical dynamic response to change (a frequency phase shift or magnitude change in the mechanical dynamic response), it is manifested in the electrical response of the PZT wafer.

The electromechanical modeling which quantitatively describes the process is presented in Figure1. The PZT is normally bonded directly to the surface of the structure by a high-strength adhesive to ensure a better electromechanical coupling. The surface-bonded PZT is considered to be a thin bar in axial vibration due to an applied alternating voltage. One end of the bar is considered fixed, whereas the other end is connected to the external structure. 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.

The solution of the wave equation for the PZT bar connected to the structure leads to the following equation for a frequency-dependent electrical admittance [2]:

$$Y(\omega) = i\omega\, a\left(\bar{\varepsilon}_{33}{}^{T}(1-i\delta) - \frac{Z_s(\omega)}{Z_s(\omega)+Z_a(\omega)} d_{3x}{}^{2}\hat{Y}_{xx}{}^{E}\right) \tag{3}$$

In equation (3), Y is the electrical admittance (inverse of impedance), Z_a and Z_s are the PZT material's and the structure's mechanical impedances, respectively, $\hat{Y}_{xx}{}^{E}$ is the complex Young's modulus of the PZT with zero electric field, d_{3x} is the piezoelectric coupling constant in the arbitrary x direction at zero stress, $\varepsilon_{33}{}^{T}$ is the dielectric constant at zero stress, δ is the dielectric loss tangent of the PZT, and a is a geometric constant of the PZT. This equation indicates that the electrical impedance of the PZT bonded onto the structure is directly related to the mechanical impedance of a host structure. The variation in the electrical impedance of a PZT bonded to the structure, over a frequency range, is analogous to the frequency response functions but has much higher resolution and is more easily obtained.

Damage to a structure causes direct changes in the structural stiffness and/or damping and alters the local dynamic characteristics. In other words, the mechanical impedance is modified by structural damage. Since all other PZT properties remain constant, it is Z_s, the external structure's impedance, which uniquely determines the overall admittance.

Therefore, any change in the electrical impedance signature is considered an indication of a change in the structural integrity.

An experimental modal testing using the electrical impedance of PZT patches (as co-located actuators and sensors) is presented by Sun *et al.* [3]. In this paper, the authors discuss that both the point frequency response functions of a single location and the transfer frequency response function between two locations on a structure can be obtained by measured electrical impedance. This work provides a critical insight into the impedance-based structural health monitoring technique, which the electrical impedance of piezo-ceramic materials constitutes a unique signature of the dynamic behavior of the structures.

2.2 Parameters of the Technique

2.2.1 Frequency Range

The sensitivity of the technique in detecting damage is closely related to the frequency band selected. To sense incipient-type damage which does not result in any measurable change in the structure's global stiffness properties, it is necessary for the wavelength of excitation to be smaller than the characteristic length of the damage to be detected [4]. Hence, the frequency range typically used in this technique is in the range of 30 kHz to 250 kHz. The range for a given structure is determined by a trial and error method. There is little analytical work done about the vibration modes of complex structures at these ultrasonic frequencies. It has been found that a frequency range with a high mode density exhibits a higher sensitivity since it generally covers more structural dynamic information [5]. In the impedance-based method, multiple numbers (usually two or three) of a frequency range containing 20-30 numbers of peaks are usually chosen, since a number of peaks imply that there is a greater dynamic interaction over that frequency range. A higher frequency range (higher than 150 kHz) is found to be favorable in localizing the sensing, while a lower frequency range (lower than 70 kHz) covers more sensing areas. This is due to the fact that damping became more dominant at high frequency. It must be noted that there are two different kinds of peaks on measured electrical impedance. One reflects the structural resonant frequencies and the other is the PZT's electrical resonant frequency. The magnitude of PZT's electrical resonant frequencies is much greater than that of structural resonant frequencies, and must be eliminated during the frequency range selection process, since those are insensitive to the presence of structural damage.

2.2.2 Sensing Region

Under the high frequency ranges used in this impedance-based method, the sensing region of the PZT is localized to a region close to the sensor/actuator. Extensive theoretical modeling efforts based on the wave propagation approach have been performed to identify the sensing region of the impedance-based method [6]. Esteban's work also included a parametric study on the sensing region of a PZT sensor/actuator by considering the various factors, such as mass loading effect, discontinuities in cross-section, multi-member junctions, bolted structures, and energy absorbent interlayer. At such high frequency ranges, however, exact measurements and quantification of energy losses became very difficult and very little additional information was obtained. Based on the knowledge acquired through various case studies, it has been estimated that (depending on the material and density of the structure) the sensing area of a single PZT can vary anywhere from 0.4 m (sensing radius) on composite reinforced concrete structures, to 2 m on simple metal beams. Castanien and Liang [7], and Kabeya [8] used transfer impedance or transfer admittance to interrogate the structure in order to extend sensing region of the impedance-based health monitoring technique.

2.2.3 Damage Assessment

While the impedance response plots serve to give a qualitative approach to the analysis, the assessment of damage is made by the use of a scalar damage metric, defined as the sum of the squared differences of the real impedance changes at each frequency step, as shown in equation (4).

$$M = \sum_{i=1}^{n} \left[\operatorname{Re}(Y_{i,1}) - \operatorname{Re}(Y_{i,2}) \right]^2 \tag{4}$$

where M represents the damage metric, $Y_{i,1}$, is the impedance of the PZT when measured at healthy conditions, $Y_{i,2}$ is the impedance of the structure for the comparison with the base line measurement at frequency interval i.

The damage metric simplifies the interpretation of impedance variations and provides a summary of the information obtained from the impedance response curves. Using this damage metric in conjunction with a damage threshold value, this technique can warn inspectors in a green/red light form, whether or not the threshold value has been reached.

2.3 Comparisons with Other Damage Identification Approaches

Traditional non-destructive evaluation techniques include ultrasonic technology, acoustic emission, magnetic field analysis, dye penetrant testing, eddy current techniques, X-ray analysis, impact-echo testing, global structural response analysis, and visual inspections. Each method is prevalent for various applications. For instance, visual inspection is used in the analysis of offshore oil platforms. Acoustic emissions techniques may be used in the remote inspection of nuclear reactor core secondary structures. Each of these various techniques has their positive and negative virtues. For instance, the ultrasonic method is useful in providing details of damage in a structure; these methods however requires the knowledge of damage location a priori and render the structure unavailable throughout the length of the test. Many traditional non-destructive evaluation (NDE) methods require out of service periods, or can be applied only a certain intervals; while the impedance-based method provides continuous, on-line monitoring with the potential for autonomous use.

2.4 Comparison to Global Structural Vibration-Based Methods

Like the global structural methods, the impedance-based approach involves the comparison of vibratory patterns ("signatures") taken at various times during the life of the structure. The major difference, however, deals with the frequency range used to detect the changes in structural integrity. Relying on the lower-order global modes, the low-frequency global techniques are not sensitive to damage that has occurred at a very early stage. It has been shown [9] that frequency responses are not very sensitive to changes in the structural integrity. By employing a high frequency range, the impedance-based method provides an alternative procedure that can identify local, minor changes in structural integrity.

2.4.1 Impedance Signature vs. Ultrasonic Testing

In ultrasonic testing of structural components, a piezo-transducer is used to produce an acoustic wave in the component. Based on the time delay of the wave transmission, the change in length (strain), length and/or density of the component is determined. Usually the mechanical nature of the component must be fairly well known before testing so that the frequency of the ultrasonic signal can be chosen to correlate with the mechanical response of the component. Typically, a single frequency wave or only a few different frequencies are used in ultrasonic methods. A broadband signal is not obtained as in the impedance signature method. The ultrasonic method is useful in some structures for obtaining a picture of various embedded components or material anomalies. This method however does not lend itself to autonomous use as does the impedance method and experienced technicians are required to review the ultrasonic data to discern detail.

2.4.2 Impedance Signature vs. Acoustic Emission

The Acoustic Emission (AE) method uses the elastic waves generated by crack initiation, moving dislocations, and debonding for detection and analysis of structures. The AE method is suitable for long-term, in-service monitoring like the impedance method. Both methods are ideal for monitoring critical sections where high structural integrity should be maintained. However, the AE method requires stress or chemical activity to generate the acoustic emission, while the impedance method can easily solve the problems associating with 'how to excite structures' by using the self-sensing actuator concept [10]. The advantage of the self-sensing actuator is more obvious in the sense that, in the AE method, the existence of multiple numbers of travel paths from the source to sensor can make signal identification difficult [11]. In addition, the AE method needs to filter out the electrical interference and ambient noise from the emission signals. Whereas, the limited sensing area of the impedance method helps in isolating changes in the impedance signature due to other far-field changes such as mass loading and normal operational vibrations.

2.4.3 Impedance Signature vs. Impact-Echo testing

For the Impact-Echo (IE) testing, a stress pulse is introduced into the structure from an impact source and resulting stress waves are measured and analyzed by a transducer. The pulse propagates into the structure and is reflected by cracks or debonding of the structures. The IE testing has been used to assess the conditions of various civil structures, including concrete, wood, and masonry materials. However, the IE testing requires an external source to excite a pulse and does not lend itself for autonomous use like the impedance method. The IE testing technique has been shown to be fairly effective for detecting and locating large scale voids and delaminations, but is not sensitive to the presence of small cracks and discontinuities due to the relatively low frequencies involved.

The principal advantages of the impedance approach compared to other techniques are as follows:

- The technique is not based on any model, and thus can be easily applied to complex structures;
- The technique uses small non-intrusive actuators to monitor inaccessible locations;
- The sensor (PZT) exhibits excellent features under normal working conditions, has a large range of linearity, fast response, light weight, high conversion efficiency, and long term stability
- The technique, because of high frequency, is very sensitive to local minor change
- The measured data can be easily interpreted
- The technique can be implemented for on-line health monitoring
- The continuous monitoring provides a better assessment of the current status of the structure, which can eliminate scheduled base inspections.

In summary, the impedance-based technique is able to provide an effective means to qualitatively detect incipient damage in the complex structures. While each of the current damage identification techniques has value and merit, the impedance method [5], [12] is further investigated because of its potential to develop into a completely autonomous monitoring system.

The impedance method has been previously applied and tested on a variety of structures in a laboratory environment. Of particular interest are civil structures, such as a ¼ scale bridge section, pipeline structure and composite reinforced concrete wall tested by Park et al. [12]. In general higher frequency ranges are needed to excite large civil structures. This diminishes the sensing area but allows the sensor to more effectively excite the structure. Bolted lap joints have been tested specifically showing that the impedance response changes with the loosening of a bolt [13]. Aerospace structures such as aircraft panels [14] have been tested. In addition, composite panels in cryogenic temperatures [15] have been tested at NASA's Marshall Space Flight Center.

3.0 APPLICATION OF TECHNIQUE TO GROUND STRUCTURES

On July 24, 2003, several exploratory tests were conducted at KSC in order to investigate the feasibility of using the impedance-technique. Structures tested included the bolted connections of the white room to the launch pad, bolted connections of the support posts for the solid rocket boosters (SRB) on the mobile launch platform (MLP), bolted connections of heat shields on the MLP, and bearings on the space shuttle crawler-transporter.

In all the tests, an HP 4194A impedance analyzer was used in conjunction with a 38 mm by 13 mm (actuating area) macro fiber composite (MFC) patch. Previous experiments have shown that MFC patches are an effective alternative to PZT patches for sensing with the impedance method and have many benefits such as increased durability, integrated leads, and conformability to curved surfaces [16]. Due to the relatively limited availability of MFC's and the desire to perform tests at multiple locations, double-sided tape was used to attach the MFC in all cases except on the crawler transporter.

3.1 White Room Tests

A series of tests were performed on the bolted connection that holds the Environmental Control Chamber commonly known as the "white room" located at the end of the Orbiter Access Arm and connected to the fixed service structure of launch pad 39-B as shown in Figure 2. A single row of bolts around the entrance of the room, shown in Figure 3, attaches the box like structure, which is the last room astronauts are in before entering the cockpit, to the fixed service structure. An MFC active sensor was to the white room wall between 2 bolt heads spaced approximately 20 cm apart as seen in Figure 4. Wire leads approximately 2 m long connected the MFC to the HP impedance analyzer. A series of impedance measurements from 10 kHz to 110 kHz were taken over a variety of frequency ranges to determine which frequencies would contain the most information on the structure for the sensor and structure configuration. Frequencies in the range of 20 kHz to 50 kHz were found to contain several resonant peaks indicating that the sensor was able to interrogate the structure in that frequency range. Normally, higher frequencies are more effective at actuating a large stiff structure. However, in this case, the non-optimal sensor bonding limited the sensing range.

With an acceptable frequency range determined, a baseline measurement was made along with a measurement of the structure in an unmodified state. Next, the nut on a bolt adjacent to the sensor was completely loosened, but not removed, and another impedance measurement was recorded. A third measurement was made with the bolt broken loose from the paint. The fourth measurement was with the bolt completely removed. The final measurement was made with the bolt retightened in the joint, although no measurement of the torque applied was made. The measurements are shown in Figure 5. It should be noted that due to the use of double sided tape, rather than cyanoacrylate or epoxy, and the high humidity of the test location, the sensor had to be repressed to the tape on several occasions due to peeling. However, the location of the sensor was never changed. In order to quantify the changes in the shape of the measurements with the implementation of damage, a damage metric was made using the formula given in equation (4). The damage metric was calculated and then scaled by the damage metric at the first damage case. The results are shown in Figure 6. It is clear from the damage metric that an event such as the loosening of a bolt on the white room structure can be detected.

3.2 Solid Rocket Booster Hold Down Post Tests

The next sets of tests were performed on SRB Hold-down Post number 4 of the MLP as seen in Figure 7. Four Hold-down Posts per SRB are responsible for attaching the shuttle to the MLP. Explosive bolts disconnect the SRBs from the MLP at launch. The Hold-down Posts experience tremendous vibrations and blast from the solid rocket motors during lift off. The Hold-down Posts are connected to the MLP via several large bolts. A monitoring system for these joints is desired since the structure has been in use longer than its design life and there is potential for a very large cost of failure, including the possible loss of human life.

The underneath of the support post was highly corroded and uneven, so the MFC sensor was placed at the base of the side of the post as seen in Figure 8. The mounting location was sanded and cleaned with alcohol to provide a good surface for mounting the sensor. The MFC was again mounted using double sided tape so that it could be easily removed for future tests. Unfortunately, the support post was much too massive to obtain a satisfactory impedance response for health monitoring. Figure 9 shows a line with no peaks or other variations for each of the frequency ranges tested. This indicates that little structural information is contained in the response. Higher frequency ranges would not have been effective due to the temporary bonding condition. Future tests could also be improved by placing the sensor on the nut of the bolt being monitored.

3.3 Mobile Launch Platform Heat Shield Test

The third location tested was the heat shield connecting pin bolts, which were also located on the MLP. The heat shields are responsible for protecting many of the systems that control the shuttle and launch pad during launch. The heat shields are fastened with bolted pins to hold them in place. Several of the heat shields recently underwent a redesign, but the old heat shields were tested to identify the damage. These pins are connected to the MLP with bolts, as shown in Figure 10, and have been determined to be critical location that could benefit from a health monitoring system due to accessibility issues.

The same MFC sensor was used as in the previous tests, as well as the same type of double sided tape used to bond the sensor to the structure. Since it was impossible to determine the properties such as size and mass of the structure being tested, it was difficult to predict if the test would be successful at showing structural data. Impedance measurements were initially made at frequency ranges of 10 kHz to 20 kHz as seen in Figure 11. In this frequency range, the impedance decreases significantly as the frequency increases. This trend masks most of the structural peaks since the amplitude of the real impedance at low frequencies, even where there is not a peak, is much higher than the amplitude of peaks. However, some of the variations in the smooth line were repeated in a second measurement, indicating that some structural information was contained in the data. To determine if the variations were peaks due to structural resonances, two impedance measurements with a frequency range of 18 kHz to 20 kHz were made as seen in Figure 12. Since the impedance at the lowest frequency is not as high, the peaks around 18.7 kHz can more clearly be seen. Similar results were obtained in the 20 kHz to 50 kHz range. In order to obtain a response with a more constant impedance (other than structural peaks), either a better bonding condition could be used to make measurements at higher frequency ranges where the slope of the impedance response flattens out, or a different sensor, such as a PZT, could be used allowing the response to flatten out at a much lower frequency.

3.4 Crawler Transporter Bearing Test

The final series of measurements was made on a bearing on one of the two crawler-transporters. The crawler-transporter is responsible for carrying the MLP and attached shuttle to the launch pad. Left over from the Apollo/Saturn V era, the crawler-transporters have been in use approximately 40 years. Massive hydraulic cylinders are used to keep the MLP and shuttle level during its trip to the launch pad. Each crawler has 16 cylinders with 2 bearings per cylinder. Recently, it was found that several of these bearings had cracked. Since no monitoring or inspection system was in place, and the load surfaces are not readily accessible, it was estimated that some of the failed bearings could have been cracked since the Apollo days.

Since this was the last series of tests planned, the MFC sensor was bonded using cyanoacrylate to a sanded and clean spot on the bearing pin as seen in Figure 13. Only a few minutes were allowed for the sensor bond to cure. Impedance was again measured at a variety of frequencies from 10 kHz to 170 kHz to determine suitable ranges for monitoring. All spans measured contained several peaks, although they were still rather small. Also, even at the highest frequency range, the general impedance trend showed significant decrease with frequency. This decay again reduced the prominence of the peaks as seen in Figure 14. However, the improved bonding condition did increase the magnitude of the peaks somewhat and allowed data to be taken at a much higher frequency range as shown in Figure 15.

Damaging the bearing was not feasible, so it is not possible to determine if damage to the bearing would have an effect on the impedance measured at the pin. Reasoning that both the pin and bearing are relatively the same size, it can be expected there would not be an impedance mismatch that would mask the response of one component or the other.

4. 0 CONCLUDING REMARKS

Although none of the exploratory tests showed outstanding results, the data does show great promise for the potential of the impedance method to monitor some of NASA's unique structures. Additionally, these tests were one of the few occasions where the impedance method has been tested on structures *in situ*. Obtaining meaningful results, without ever having previously seen the structures, again indicates that with slight tuning of the monitoring system's features viable systems could be developed.

4.1 Lessons Learned and Notes on Applicability to Ground Structures

The primary lesson learned is that the impedance method can provide a permanent structural health monitoring solution to NASA's ground structures. In addition several positive and negative aspects of the impedance method were discovered or highlighted including:

- The high importance of sensor attachment and robustness.
- The importance of sensor location. Sensors must be placed on part of the structure with low mechanical impedance relative to the other components, or else the effects of damage will not be seen as was the case with the hold down post tests.
- High frequency excitation will provide a better response for large structures, however, the bonding condition much be stiff enough to pass the high frequencies
- Massive structures may require higher than normal excitation voltage or a specialized system.

5.0 RECOMMENDATIONS

Improved results could be obtained by studying optimal sensor placement to ensure that the active sensor excites the critical location of the structure. Increasing the input voltage (by using other hardware) would increase the sensing area and response of the structure. Changing the sensor type to a PZT would increase the actuation force and excite the structure in more directions than a unidirectional MFC. Optimizing the frequency range interrogated by the sensor would ensure that the most structural information possible was available for analysis. Finally, improving sensor to structure bonding conditions would permit a higher frequency range to be monitored, allowing an even more localized sensing area and the ability to excite large structures more effectively. Employing these techniques could lead to a permanent structural health monitoring system that would reduce maintenance costs and improve safety on many of NASA's aging systems.

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FIGURES

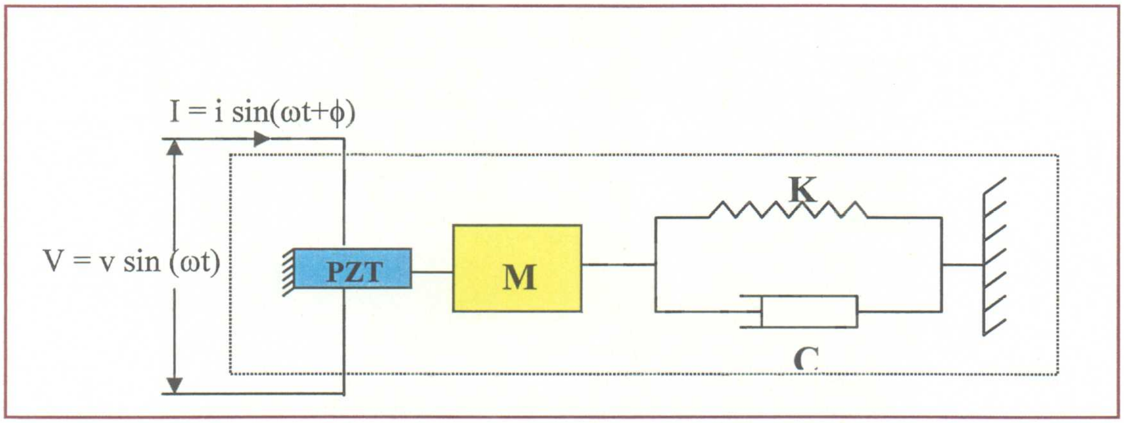

Figure 1. 1-D model used to represent a PZT-driven dynamic structural system.

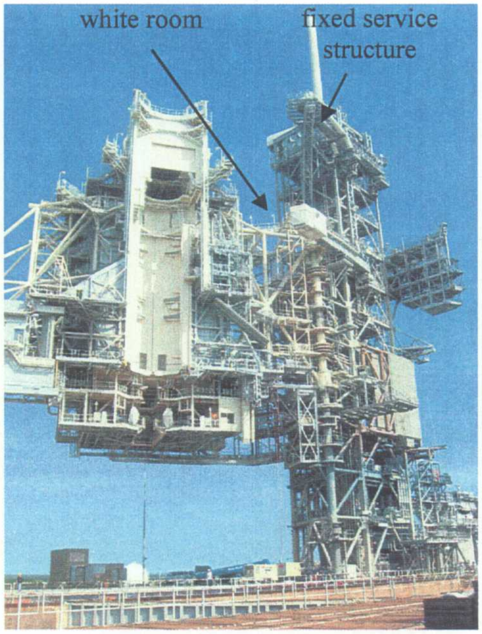

Figure 2. White room attached to fixed service structure.

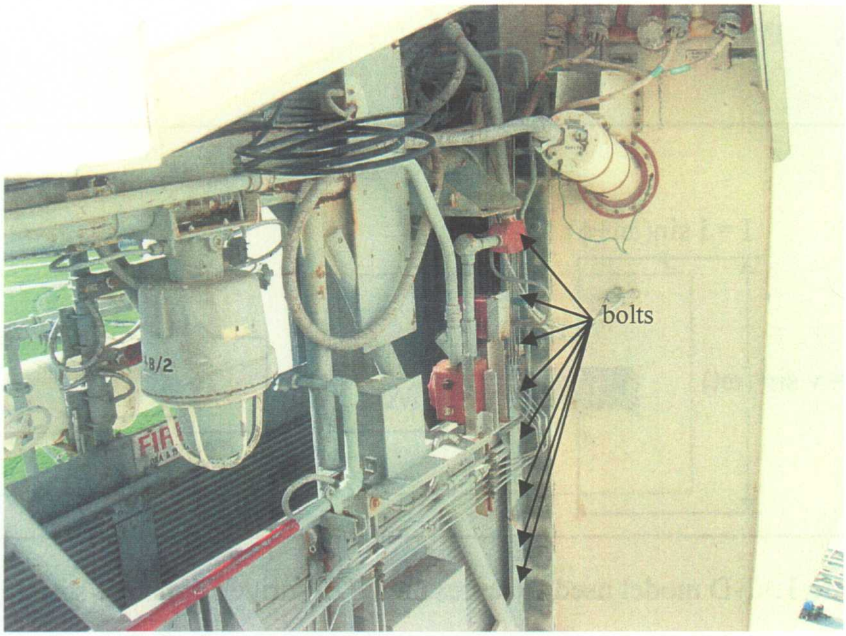

Figure 3. Bolts connecting white room to fixed service structure.

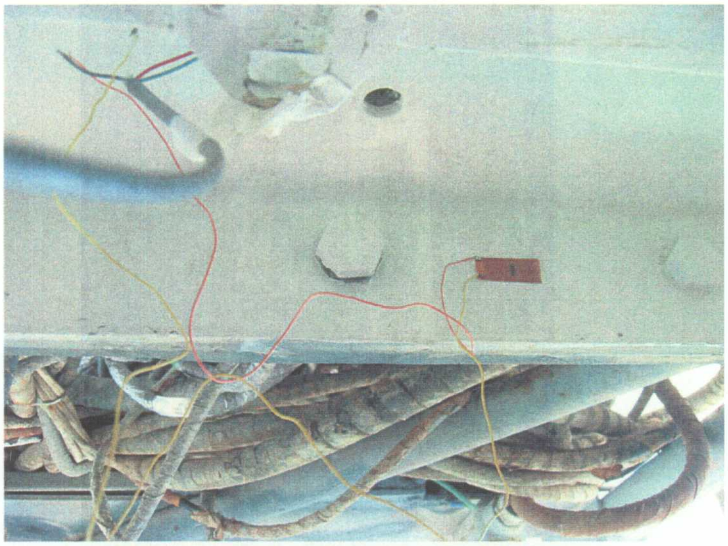

Figure 4. MFC sensor attached between bolt heads with left bolt loosened.

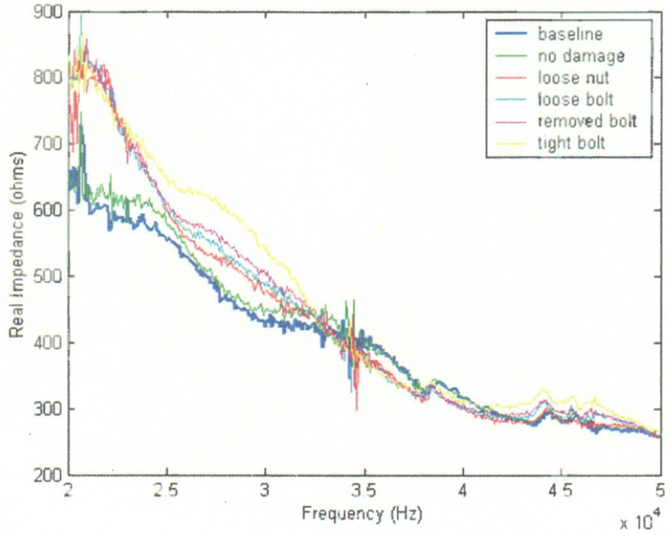

Figure 5. Impedance measurements of white room joint with changing damage level.

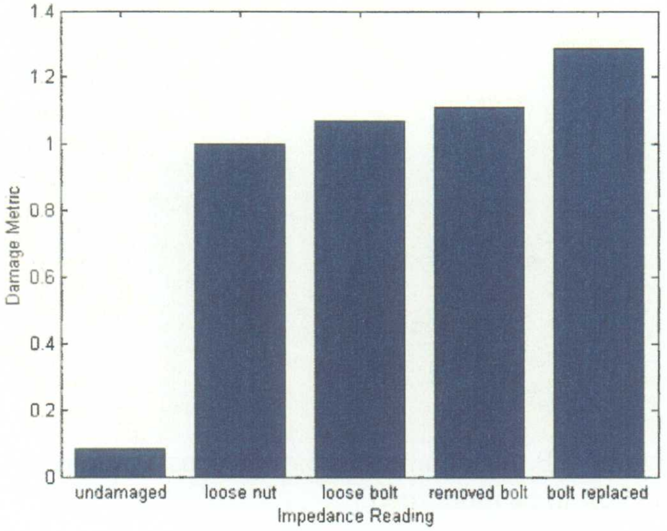

Figure 6. Damage metric for white room joint with changing damage level.

Figure 7. Support post four, which connects to hold-down post four on the SRB.

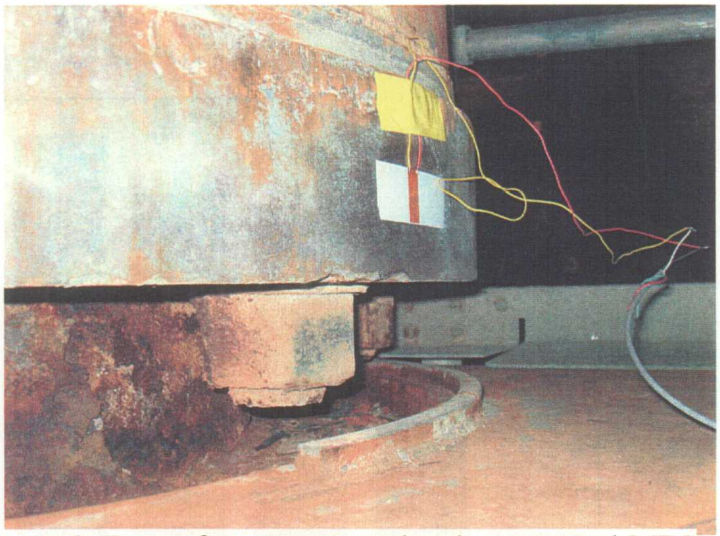

Figure 8. Base of support post showing mounted MFC and bolt to be monitored.

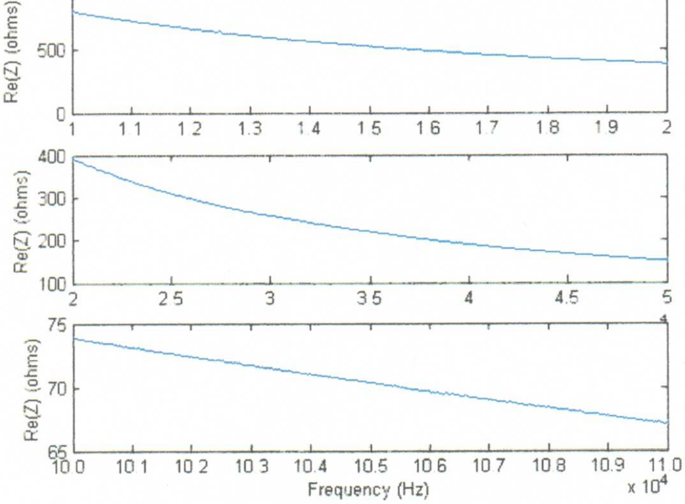

Figure 9. Impedance responses of support post at various frequency ranges.

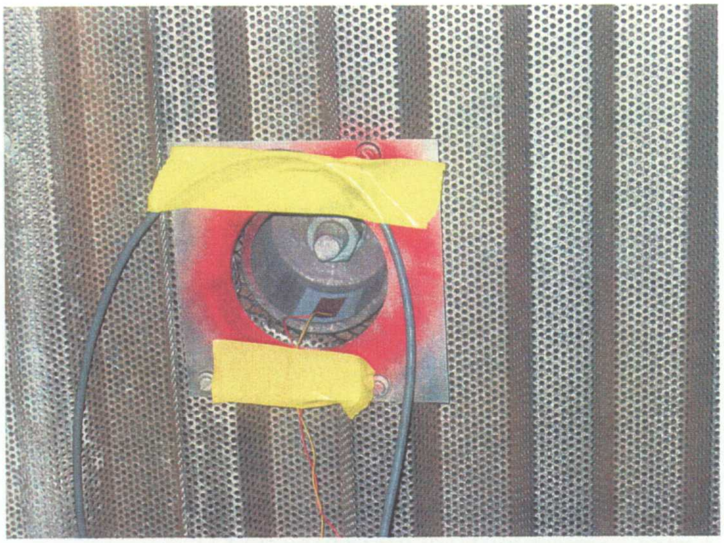

Figure 10. Bolted connection of heat shield pin with MFC sensor installed.

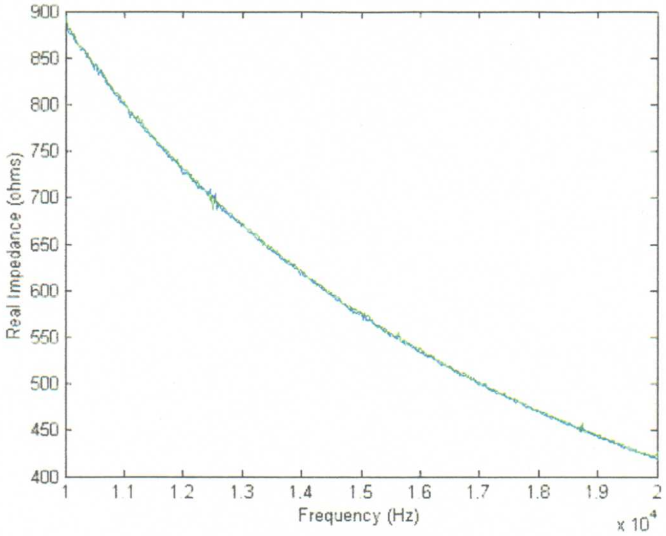

Figure 11. Impedance measurements of heat shield pin jointed connection from 10 kHz to 20 kHz.

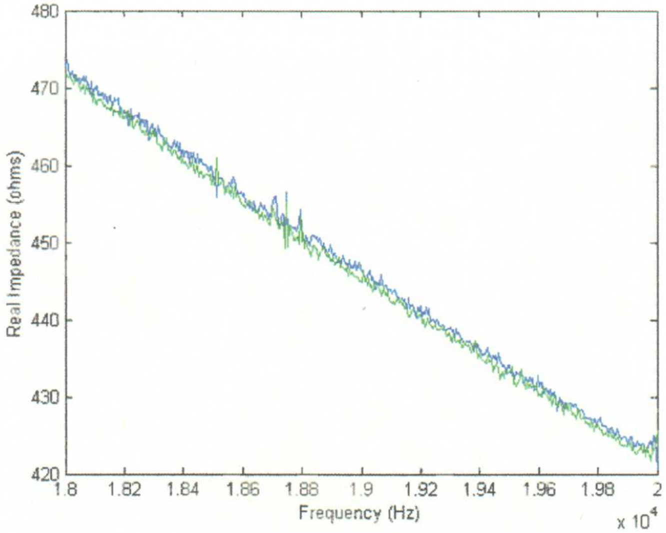

Figure 12. Impedance measurements of heat shield pin jointed connection from 18 kHz to 20 kHz.

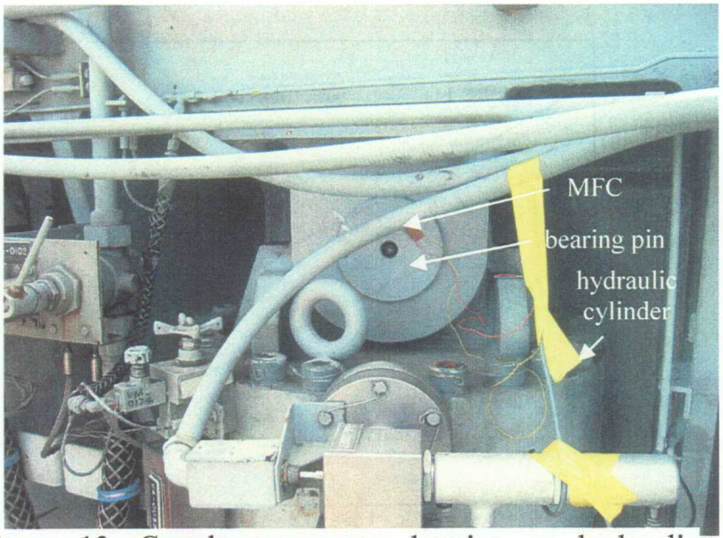

Figure 13. Crawler-transporter bearing on hydraulic cylinder with MFC sensor installed.

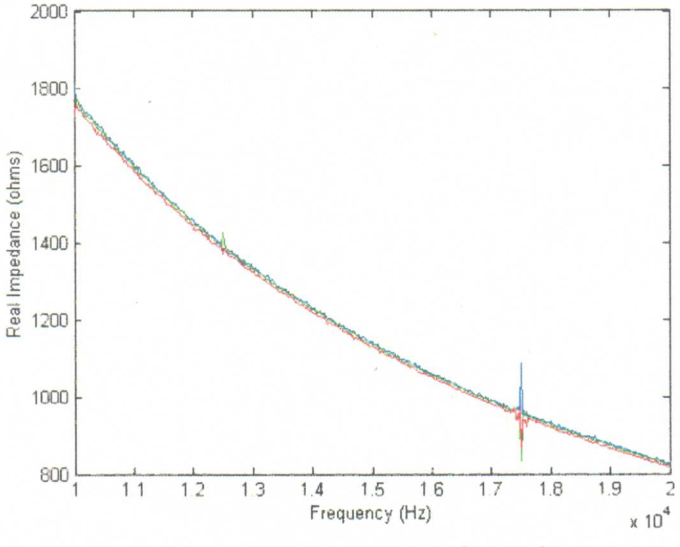

Figure 14. Impedance measurements of crawler-transporter bearing pin from 10 kHz to 20 kHz.

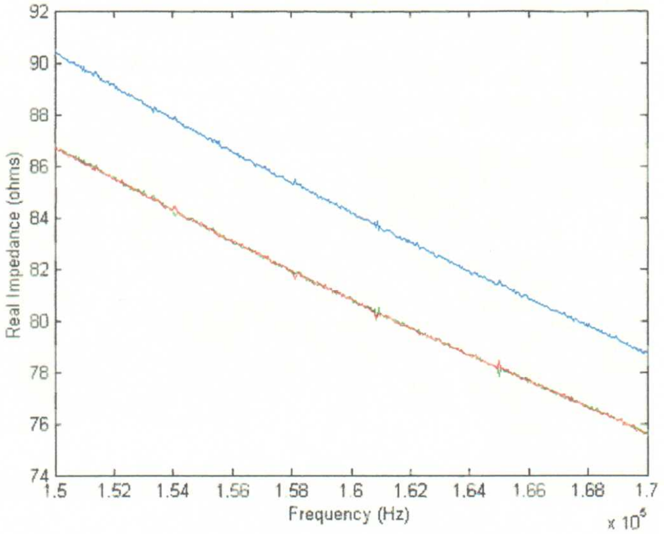

Figure 15. Impedance measurements of crawler-transporter bearing pin from 150 kHz to 170 kHz.

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None

14. ABSTRACT

Many of the structures responsible for the launch, ground systems and support operations of the space shuttle are still being used well past their nominal expected design life. This has led to an increased interest in monitoring these structures in order to decrease the risk of eventual breakdown or structural failure. One monitoring method, which has shown promising results for such applications, is the impedance-based structural health monitoring technique. This paper presents results from proof-of-concept tests on the launch pad's orbiter access arm bolted connection, solid rocket booster hold down post, mobile launch platform heat shield and crawler transporter bearing. Modifications for future tests are suggested.

15. SUBJECT TERMS
Condition monitoring; smart materials; impedence based methods; damage detection; structures

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