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# Fatigue Crack Detection Test of Weldments Using Piezoceramic Transducers

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**KEYWORDS**: Welded Structure, Structural Health Monitoring, Piezoceramic Transducer, Impedance-based Measurement, Non-destructive Evaluation

**ABSTRACT:** *Welded Structure, Structural Health Monitoring, Piezoceramic Transducer, Impedance based Measurement, Non destructive Evaluation*

*ABSTRACT: Large welded structures, including ships and offshore structures, are normally in operation under cyclic fatigue loadings. These structures include many geometric discontinuities, as well as material discontinuities due to weld joints. The fatigue strength at these hot spots is very important for the structural performance. In the past, various Non Destructive Evaluation (NDE) techniques have been developed to detect fatigue cracks and to estimate their location and size. However, an important limitation of most of the existing NDE methods is that they are off line; the normal operation of the structure has to be interrupted, and the device often has to be disassembled. This study explores the development of a structural health monitoring system, with a special interest in applying the technique to welded structural members in ship and offshore structures. In particular, the impedance based structural health monitoring technique that employs the coupling effect of piezoceramic (PZT) materials and structures is investigated.*

## 1. INTRODUCTION

The integration of actuators and sensors, using smart materials, enabled various applications, including health monitoring and structural vibration control (Kim, 2002, Inman, 1998). In this study, a health monitoring technique is designed and implemented for detecting structural damages, particularly for welded structures, including ships and offshore structures. An impedance based structural health monitoring technique that employs the coupling effect of piezoceramic materials and structures is investigated. The basic principle behind this technique is to apply high frequency structural excitations through the surface bonded piezoelectric transducers, and to measure the impedance of structures by monitoring the current and voltage that is applied to the piezoelectric transducers. Changes in the impedance indicate changes in the structure, which, in turn, may indicate a possible damage occurrence.

A smart health monitoring technique is capable of in situ, on line incipient damage detection in complex structures. Various applications of the impedance based health monitoring technique, with respect to bolted joints, pipes, concrete walls and aerospace structures, have been investigated. The basic concept of this impedance based structural health monitoring technique is to monitor the variations in the mechanical impedance of the structure caused by the presence of damage (Park et al., 2000).

Since structural mechanical impedance measurements are difficult to obtain, this technique utilizes the electro mechanical coupling property of piezoelectric materials. In this coupling property, the electrical impedance of piezoelectric materials is directly related to the mechanical impedance of the structure being bonded, and will be affected by the presence of damage (Liang et al., 1994,; Sun et al., 1995, Doebling et al. 1996,; Giurgiutiu and Rogers, 1997. Park et al., 2003). Through monitoring the measured electrical impedance and comparing it to a baseline measurement, the occurred or imminent structural damage can be qualitatively determined.

## 2. IMPEDANCE-BASED HEALTH MONITORING TECHNIQUE

The impedance based health monitoring method utilizes the direct, as well as the converse, piezoelectric (PZT) effects simultaneously; hence, one PZT patch can be used for both actuation and sensing of the structural response. The concept behind this approach is to monitor the variations in structural mechanical impedance caused by the presence of damage. If a structure is damaged, the structural parameters, such as mass, stiffness, or damping, would be altered. In

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other words, the mechanical impedance would be modified. Since all other PZT properties remain constant, any changes in the electrical impedance signature of piezoelectric materials are attributed to damage or change in the structure. A complete description of this technique is described in the literature (Inman, 1998,; Park et al., 1999, Park et al., 2000).

As an initial investigation for the objective of this study, two pieces of piezoceramic transducers are attached onto a steel bar, as shown in Fig. 1. PZT sensors are attached at a distance of 20mm from the center of the bar. Also shown is a simple circuit to measure the impedance signal, using the piezoceramic patch connected. The PZTs used for this study were PSI-5H4E (Piezo Systems Inc.). The mechanical and electrical properties of PZT transducers are summarized in Table 1. The detailed description of the purpose of the circuit is given in section 3. The resistance used in this study is 100 ohm.

**Table 1** Electric and mechanical characteristics of PZT

| PIEZOELECTRIC CHARACTERISTICS | | | |
|---|---|---|---|
| Composition | Lead Zirconate Titanate | | |
| Relative Dielectric Constant(@1KHz) | KT3 | 3800 | |
| Piezoelectric Strain Coefficient | d33 | 650×10 12 | m/V |
| | d31 | 320×10 12 | m/V |
| Piezoelectric Voltage Coefficient | g33 | 19.0×10 3 | V·m/N |
| | g31 | 9.5×10 3 | V·m/N |
| Coupling Coefficient | k33 | 0.75 | |
| | k31 | 0.44 | |
| MECHANICAL | | | |
| Density | | 7800 | Kg/m3 |
| Mechanical Q | | 30 | |
| Elastic Modulus | YE3 | 5.0×1010 | N/m2 |
| | YE1 | 6.2×1010 | N/m2 |
| Poisson's Ratio | v | ~.31 | |

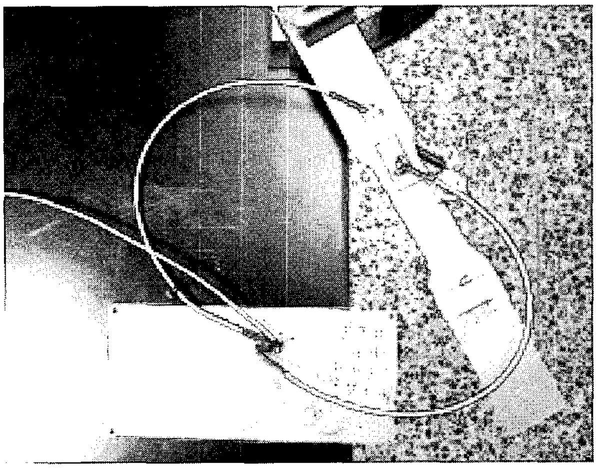

Fig. 1 Circuit attached to a PZT transducer

In order to measure the impedance of the structure under investigation, piezocermic patches with either random or chirp type excitation could be used to excite the structure. A bolt was attached in the vicinity of a PZT transducer. The impedance signal using the sweep sinusoidal excitation at the interval of 100 Hz is obtained, as shown in Fig. 2 and Fig. 3. Both the real part and the imaginary part of the impedance signal are shown in Fig. 2 and Fig. 3, respectively. The thick line indicates the impedance measurement without a bolt attached to the structure, while the thin dotted line indicates the impedance measurement with a bolt. The impedance is measured in the frequency range between 10 kHz and 20 kHz. The difference between the two different conditions is clearly seen. In particular, more significant differences between the two signals is observed in high the frequency range, such as above 15 kHz.

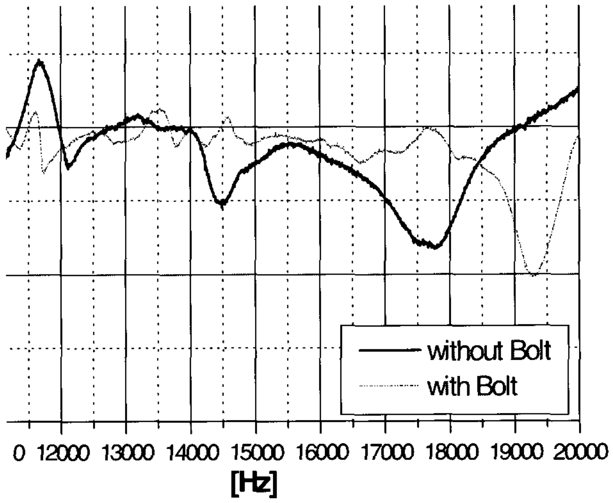

Fig. 2 Real part of the impedance signal with sweep excitation

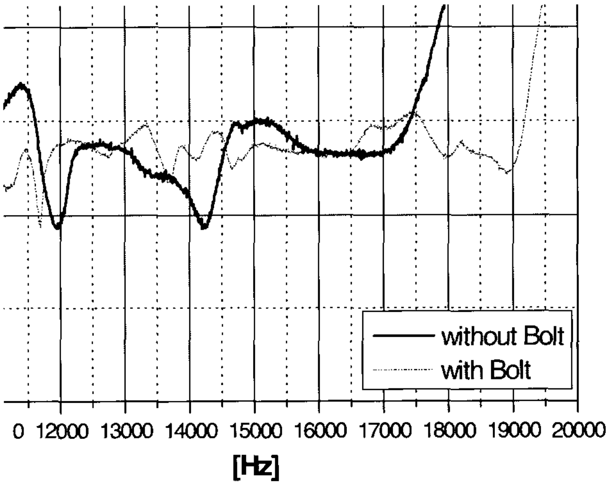

Fig. 3 Imaginary part of the impedance signal with sweep excitation

On the other hand, the same measurements were made using random excitation, instead of sweep sinusoidal excitation. The real and imaginary parts of the impedance measurements are illustrated in Fig. 4 and Fig. 5, respectively. Similar to the case with sweep sinusoidal excitation, the measured impedance exhibited differences between the two cases, i.e. with and without attaching a bolt.

The damage metric, defined as the sum of the squared differences of the real impedance changes at each frequency step, is used to simplify the interpretation of the impedance variations and provides a summary of the information obtained from each impedance response curve.

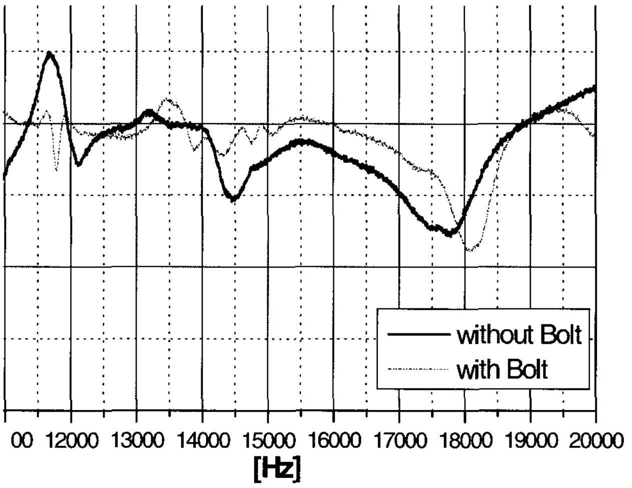

**Fig. 4** Real part of the impedance signal with random excitation

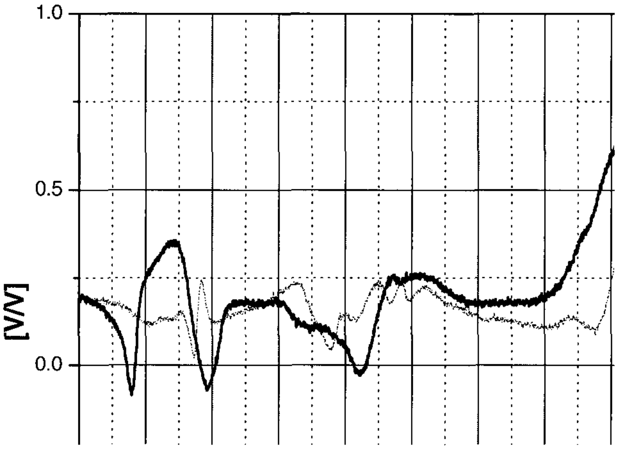

**Fig. 5** Imaginary part of the impedance signal with random excitation

$$M=\sum_{i=1}^{n}\sqrt{\frac{\left[\mathrm{Re}(Z_{i,1})-\mathrm{Re}(Z_{i,2})\right]^2}{\left[\mathrm{Re}(Z_{i,1})\right]^2}} \qquad (1)$$

where, Zi,1 is the baseline, or healthy, impedance of the PZT and Zi,2 is the impedance used for comparison with the baseline measurement at frequency interval i (Peairs et al., 2001). For the root mean squared value, the higher the damage metric value, the larger the difference between the baseline impedance signature and the impedance signature, indicating damage. More complicated damage metric algorithms are available, which take into account temperature and other variables; however, for this initial experiment, temperature was assumed to have remained constant during testing (Park et al., 1999).

Fig. 6 is the metric chart comparing the real and the imaginary parts of the impedance signal, as well as the excitation types, such as sweep sine and random. It is determined that the sweep sine excitation is more indicative of damage occurrences. This demonstrates that the damage metric chart can provide the occurrences of damage, as well as a summary of the impedance variation.

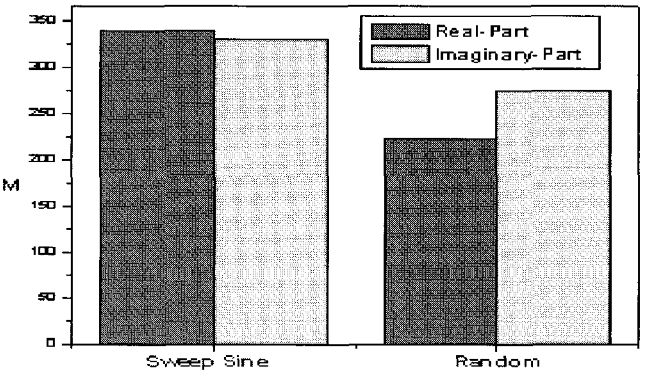

**Fig. 6** Metric chart comparison of the specimen with and without bolt

## 3. IMPEDANCE MEASUREMENT USING FFT ANALYZER

Impedance measurements are typically made using an impedance analyzer, such as the HP 4194A. However, the impedance analyzer is very expensive compared to a typical FFT analyzer, making the method relatively impractical. Therefore, in this study, a FFT analyzer, instead of an impedance analyzer, is used as a new method of generating impedance measurements, utilizing a FFT analyzer with a small current measuring circuit (Peairs et al., 2001).

FFT analyzers, such as those used in modal analysis, are more common and less expensive than impedance analyzers. They also often have the added benefit of being portable. The electrical impedance of the bonded PZT is equal to the voltage applied to the PZT, divided by the current through the PZT. An approximation of the impedance is generated by taking the ratio with the FFT analyzer of the voltage supplied to the circuit, Vi, to the voltage, Vo, across a sensing resistor, Rs, in series with the PZT, as seen in Fig. 7.

This circuit can be recognized as a voltage divider. The output voltage is proportional to the current through the sensing resistor, which, if the sensing resistor is small, is approximately the current through the PZT if the sensing resistor was not included.

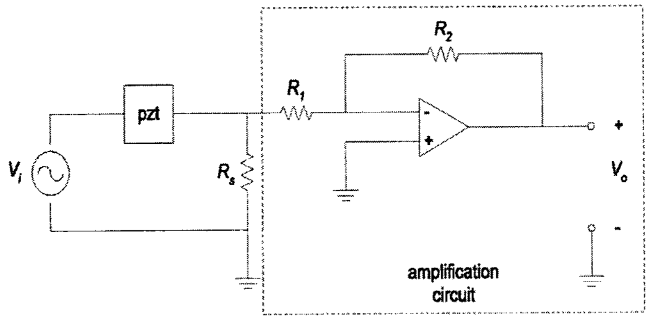

**Fig. 7** Circuit for approximating PZT impedance

The circuit is described by the following equations:

$$I = \frac{V_0}{R} \qquad (2)$$

where I is the current through the sensing resistor. The approximated impedance (Z) is:

$$Z = \frac{V_i}{I} = \frac{V_0}{V_i / R_s} \qquad (3)$$

## 4. FAILURE MECHANISM IN WELDED STRUCTURE

Welded structures have various stress concentration spots, due to geometric discontinuity and weld discontinuity incurred through the welding process. The increased stress values and material discontinuity make the local area vulnerable to fatigue loads and/or other types of loadings (Cho and Horikaw, 1988; Nam and Kim, 1999).

Fatigue is the process of cumulative damage, in a benign or an aggressive environment (e.g. corrosive environment), which is caused by repeated fluctuations in the loads. As shown in Fig. 8, after a certain number of load fluctuations, the accumulated damage causes the initiation and subsequent propagation of a crack, or cracks, in the damaged regions. The process can eventually cause the fracture of components. The number of cycles required to initiate a fatigue crack is the fatigue crack initiation life (Ni). The number of cycles required to propagate a fatigue crack to a critical size is called the fatigue crack propagation life (Np). Although there is no simple or clear definition regarding the boundary between fatigue-crack-initiation and propagation, the total fatigue life (Nt) is the sum of the initiation and propagation lives,

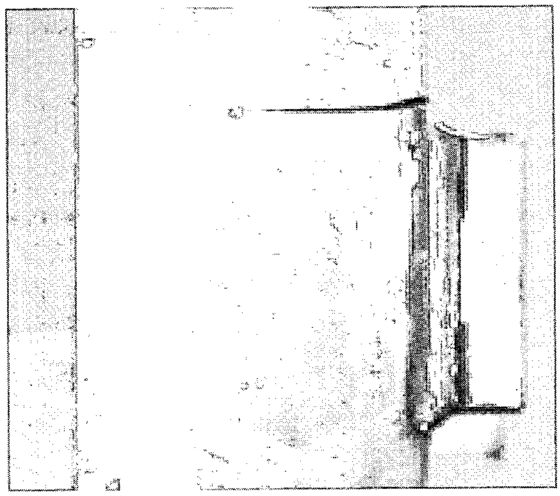

**Fig. 8** A typical fatigue induced crack in weldment

To ensure the safety of structures from fracture, current practices for the safety of ship structures involve the use of an on-board hull surveillance system that can provide real time hull stress, motion, and pressure information to the ship's officers. This information will assist them in making decisions that will enable them to work within design or operational limits, which will reduce structural and cargo damage in heavy weather. However, it is not a total solution to prevent hull structural and cargo damage, and it cannot provide the continuous monitoring of gradual damage occurrence.

There are four important stages in the viewpoint of structural health (or damage) monitoring: 1) detect the existence of damage; 2) detect and locate damage; 3) detect, locate and quantify damage; and 4) estimate remaining service life. In particular, it is important to identify the initiation of a crack at the earliest possible stage, although the significance of the crack size varies by application.

For ship or offshore structures, there are many locations that are difficult to access; therefore, it is not an easy task, if not impossible, to inspect all the damage prone locations. Also, it is not an easy task to distinguish the structural response between those due to wave loading and damages. Therefore, the impedance technique would be an ideal candidate for this type of application, since the frequency range of interest is much higher than the environmental excitation.

## 5. APPLICATION OF THE IMPEDANCE TECHNIQUE TO WELDMENTS

A test specimen with a gusset plate welded on one side surface is manufactured, as shown in Fig. 9. The dimension of the specimen is illustrated in Fig. 10. Four piezoceramic transducers (PSI 5H4E) are placed in the vicinity of the gusset plate in order to monitor the occurrences of damage, such as fatigue cracks. The dimension of each piezoceramic transducer was 20×30×0.2㎜ (width, length, thickness). The test specimen was installed in a servo hydraulic fatigue test machine, with a maximum load capacity of 20 tons. The specimen was tested at stress ratio 1, and the maximum and minimum load was 196MPa, respectively (Kim et al., 2004). Fig. 11 shows a crack initiated at the edge of the test specimen. The piezoceramic transducers are excited using a chirp signal in the frequency range of 10 ~ 20 kHz. A typical transfer signal between sensors 1 and 4 is recorded at 349000 cycles, as shown in Fig. 12. A crack occurred at 510000 cycles, and the corresponding signal is shown in Fig. 13. A significant difference in the signal between two cycles is clearly seen. For example, the peak at 18000Hz in the real part disappeared once the crack occurred in the test specimen. Fig. 14 shows a damaged metric between PZT 1 and 4, obtained using equation (1). It should be noted that no significant change in the measurement was observed before the crack occurrence.

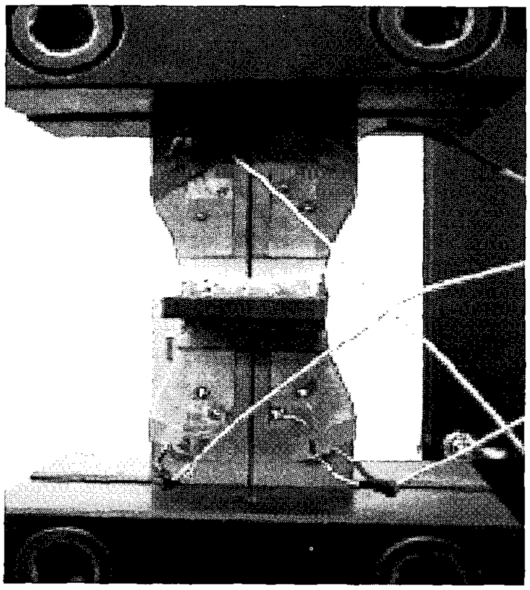

*Fig. 9 Weld test specimen installed in fatigue test machine*

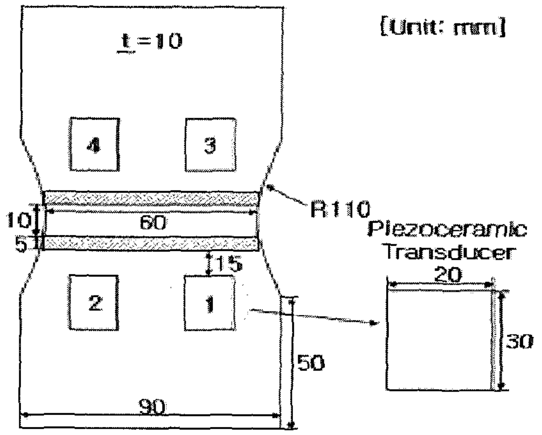

Fig. 10 Dimensions of specimen and PZT

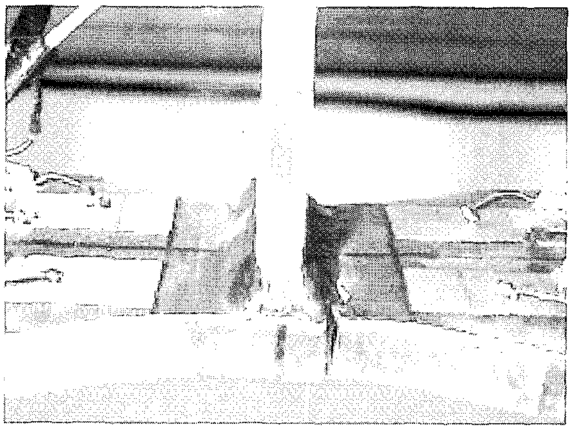

Fig. 11 Fatigue crack propagating in weldment

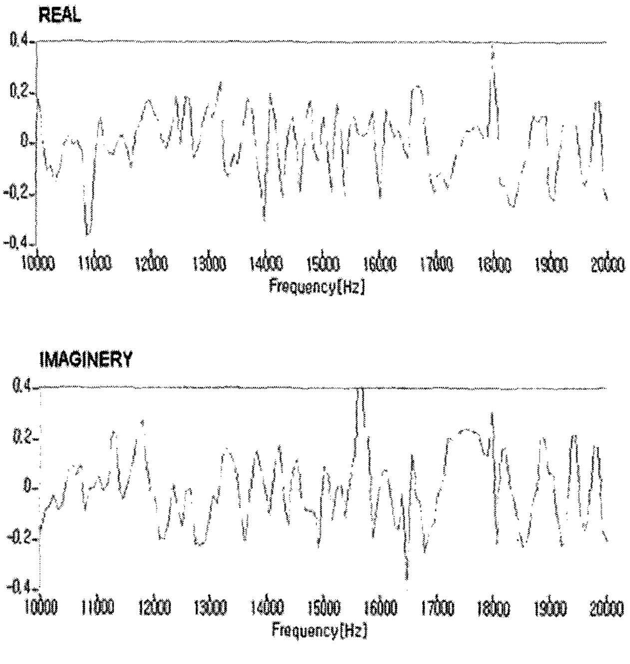

Fig. 12 Measurement between PZT 1 and 4 at 349000 cycle

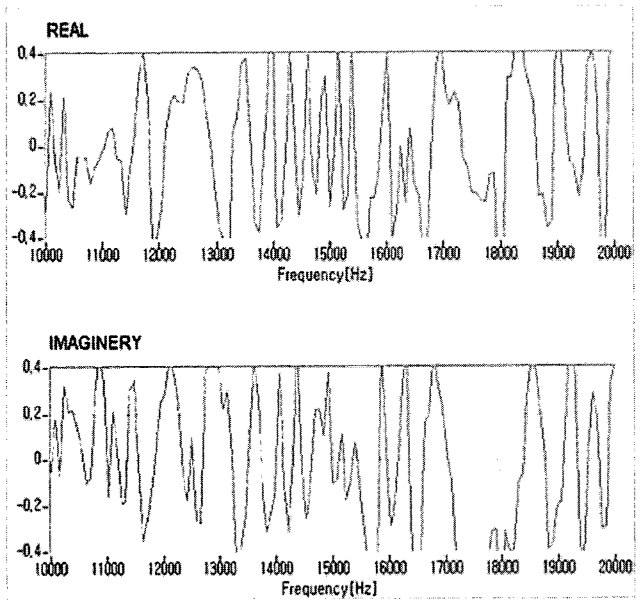

**Fig. 13** Measurement between PZT 1 and 4 at 510000 cycle

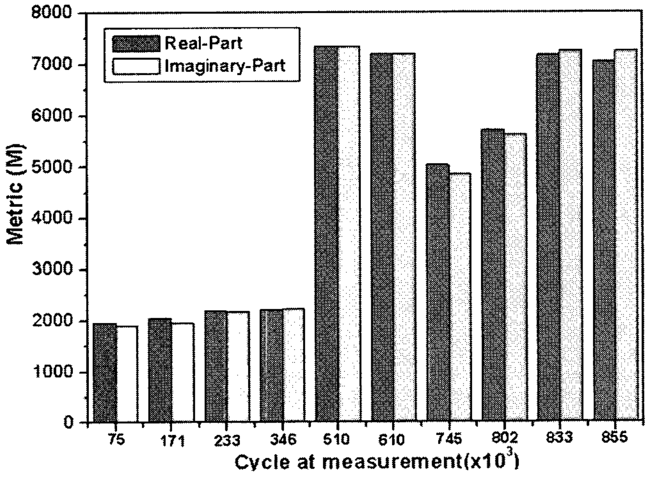

**Fig. 14** Damage metric between PZT 1 and 4

## 6. CONCLUDING REMARKS

In this study, a technique that allows a single piece of PZT material to detect structural damage has been investigated. In particular, an impedance based health monitoring technique is employed, which uses piezoceramic transducers as self sensing devices. A damage identification scheme, which tracks the changes of mechanical impedance, due to the presence of damage, has been applied to assess the health condition of structures. The results indicate that this integrated technique can provide an effective means for detecting damage on the structure while in service. Further study will be carried out to monitor fatigue damages, particularly for welded structures.

## ACKNOWLEDGEMENTS

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## REFERENCES

Cho S.M. and Horikawa K. (1988), "A Prediction of Intial Fatigue Crack Propagation Life in a Notched component Taking Elasto-Plastic Behavior," Vol 2, No 4, pp 61-70.

Doebling, S.W., Farrar, C.R., Prime, M.B., and Shevitz, D.W. (1996), Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in Their Vibration Characteristics, A Literature Review, Los Alamos National Laboratory Report LA-13070-MS.

Giurgiutiu, V. and Rogers, C.A. (1997), "Electro-mechanical (E/M) Impedance Method for Structural Health Monitoring and Non-destructive Evaluation", International Workshop on Structural Health Monitoring. Stanford University, CA, pp 433-444.

Inman, D.J (1998), "Smart Structures Solutions to Vibration Problems", Proceedings, of International Conference on Noise and Vibration Engineering, Leuven, Belgium, pp 1-12.

Kim, M.H. (2002), "Simultaneous Health Monitoring and Vibration Control of Adaptive Structures using Smart Sensors", Shock and Vibration, Vol 9, No 6, pp 329-339.

Kim, M.H., Kang, S.W., Na, S.S., Park, G. and Inman, D.J. (2004), "An Impedance-based Health Monitoring System with Application to Welded Structures", 15th International Conference on Adaptive Structures and Technologies, Bar Harbor, Maine, U.S.A.

Liang, C., Sun, F.P. and Rogers, C.A (1994), "An Impedance Method for Dynamic Analysis of Active Material System", Journal of Vibration and Acoustics, Vol 116, pp 121-128.

Nam K.W. and Kim S.J. (1999), "Life Prediction by Retardation Behavior of Fatigue Crack and its Nondestructive Evaluation," Vol 13, No 3-1, pp 36-48.

Park, G., Kabeya, K., Cudney, H. and Inman, D.J. (1999), "Impedance-Based Structural Health Monitoring for Temperature Varying Applications", JSME International Journal, Vol 42, pp 249-258.

Park, G., Cudney, H. and Inman, D.J. (2000), "Impedance-Based Health Monitoring of Civil Structural Components", ASCE, Journal of Infrastructure Systems, Vol 6, No 4, pp 153-160.

Park, G., Sohn, H., Farrar, C.R. and Inman, D.J. (2003), "Overviewof Piezoelectric Impedance-Based Health Monitoring and Path Forward", Submitted to The Shock and Vibration Digest.

Peairs, D.M., Park, G. and Inman, D.J. (2001), "Self-monitoring and Self-healing Bolted Joint", Proceedings of 3rd International Workshop on Structural Health Monitoring, Stanford, CA, pp 430-439.

Sun, F., Chaudhry, F.,Z., Liang, C. and Rogers, C.A. (1995), "Truss Structure Integrity Identification Using PZT Sensor-Actuator", Journal of Intelligent Material Systems and Structures Vol 6, pp 134-139.

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