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Title: **Recent Progress in the Application of E/M Impedance Method to Structural Health Monitoring, Damage Detection, and Failure Prevention**

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## ABSTRACT[1]

Recent progress in the application of the electro-mechanical (E/M) impedance method to structural health monitoring, damage detection, and failure prevention is presented. A brief review of the E/M impedance method principles is followed by applications to bolted and spot-welded structural joints, and to polymeric composite overlays to construction engineering structures. The modeling of the interaction between the piezoelectric active sensor and the host structure is described. The development of a meaningful structural damage index that can identify the damage presence, location, and magnitude is treated, and several recent works, including neural networks approach, are cited. Conclusions and suggestions for further work, and relevant bibliography are included.


## 1. INTRODUCTION

### 1.1 BACKGROUND

The electro-mechanical (E/M) impedance method for structural health monitoring, damage detection and failure prevention is a new technology utilizing the emitter-detector properties of active material sensors and the structural drive-point mechanical impedance (Rogers and Giurgiutiu, 1997). In previous work (Giurgiutiu and Rogers, 1997), the authors showed that changes in the high-frequency drive-point mechanical impedance can be sensed in the form of changes in the apparent E/M impedance of the active material sensor. This allows the direct monitoring of impedance changes induced by structural damage. No intermediate equipment between the active sensor and the impedance analyzer is needed. A number of situations have been considered for using the E/M impedance method in conjunction with active material sensors to health monitoring and failure prevention applications. Recent work performed with the E/M impedance technique at the University of South Carolina encompasses damage detection and health monitoring of bolted joints, spot-welded joints, and of the joint between the concrete substrate and a polymeric composite overlay. The bolted joints were selected because damage in the joint can be easily induced and subsequently removed. This reversibility aspect allows for testing the method repeatability, which is essential for method validation. Aluminum thin-gauge plates and multi-site bolt-washer-nut assemblies were used in these experiments. The study of spot-welded joints was performed using fatigue loading of shear lap-tension specimens. In these experiments, gradual propagation of damage, induced by the fatigue loading, was monitored with the stiffness-damage correlation technique. Thus, direct mapping between damage progression and the RMS E/M impedance change was achieved. The propagation of cracks in the adhesive bond between composite overlays and concrete substrates was monitored with an array of sensors affixed onto or embedded into the composite. Correlation between damage progression (crack advancement) and RMS impedance change was established.

Modeling efforts were directed at understanding the subtle interaction between


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the two entities with patently different impedances: the minute active sensor and the large host structure. Although the magnitude of the respective impedances is several orders of magnitude different, careful examination of their real and imaginary parts revealed that the real parts become commensurable around high-frequency resonances. Thus, the high-frequency mechanical behavior of the structure is directly reflected into the electro-mechanical impedance response. Another important aspect discussed in the paper is that of developing a meaning damage index that could adequately identify the presence, location, and magnitude of structural damage. Several efforts are cited, some including neural networks.

The results presented in this paper are further proof of the suitability of the E/M impedance method for structural health monitoring, damage detection and failure prevention. Directions for further work are charted in the conclusions.

## 1.2 PRINCIPLES OF THE HIGH FREQUENCY ELECTRO-MECHANICAL (E/M) IMPEDANCE METHOD

Consider a piezo-electric active sensor in intimate contact with a host structure. When excited at high frequency (typically 100 to 800 kHz), the active sensor sends and receives high-frequency elastic waves through its sensor/actuator functions.

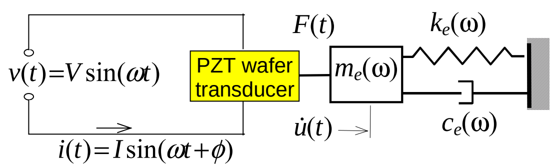
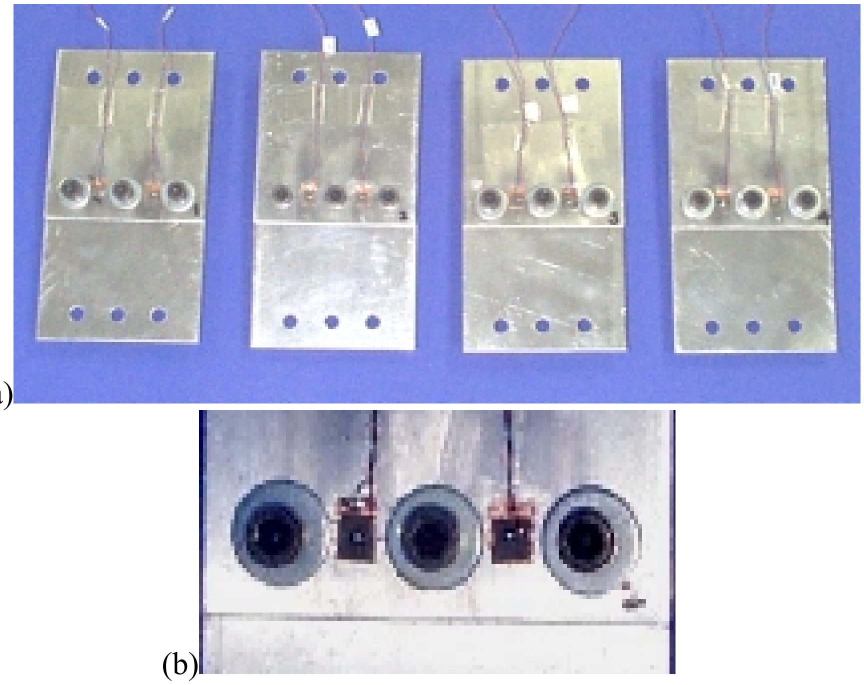



**Figure 1 Electro-mechanical coupling between the PZT transducer and the structure.**

The structural drive-point mechanical impedance, $Z_{str}(\omega) = i\omega m_e(\omega) + c_e(\omega) - ik_e(\omega)/\omega$, (Figure 1) interacts with the internal impedance of the transducer, $Z_{PZT}$, and generates a combined impedance response, $Z(\omega)$, as shown in Equation (1). Thus, the structural drive-point mechanical impedance (itself dependent on the state of structural damage) is reflected into the electrical impedance as seen at the transducer terminals.

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

In Equation (1), $Z(\omega)$ is the equivalent electro-mechanical admittance as seen at the PZT transducer terminals, $C$ is the zero-load capacitance of the PZT transducer, and $\kappa_{31}$ is the electro-mechanical cross coupling coefficient of the PZT transducer ($\kappa_{31} = d_{13}/\sqrt{\bar{s}_{11}\bar{\varepsilon}_{33}}$). The electro-mechanical impedance method is applied by scanning a predetermined frequency range in the hundreds of kHz frequency band and recording the complex impedance spectrum. By comparing the impedance spectra taken at various times during the service life of a structure, meaningful information can be extracted pertinent to structural degradation and the appearance of incipient damage. It must be noted that the frequency range must be high enough for the signal wavelength to be compatible with the defect size. Experiments that have proven the ability of the E/M impedance technique to detect damage in a variety of applications are described next.

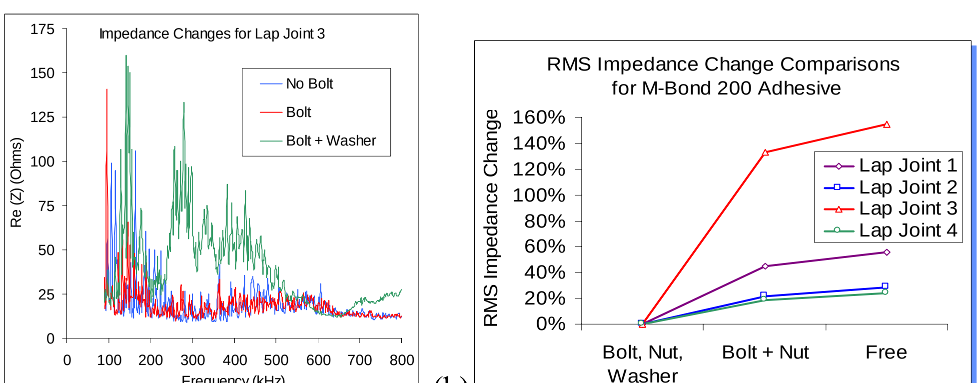


(a) (b)

**Figure 2 High-frequency electro-mechanical impedance health-monitoring testing of bolted joints: (a) Four shear lap joint tension specimens. (b) Close-up view of tone of the joints showing bolt-heads, washers, and the two PZT active sensors (Giurgiutiu, Turner, and Rogers, 1999)**

## 2. HIGH-FREQUENCY E/M IMPEDANCE MONITORING OF BOLTED JOINTS

The successful performance of damage detection experiments rests upon the ability to create controlled damage specimens. Generally, the creation of damage is an irreversible process that needs to be performed with utmost care. However, a special situation arises in the case of bolted joints. In bolted joints, damage can be created and also eliminated by modifying the bolted joint parameters, such as the tension in the bolt, or the presence/absents of stiffening washers. Figure 2 presents experiments performed to correlate the E/M impedance readings with the presence of damage in the most common structural joint – the bolted joint. Results of these investigations are shown in Figure 3.



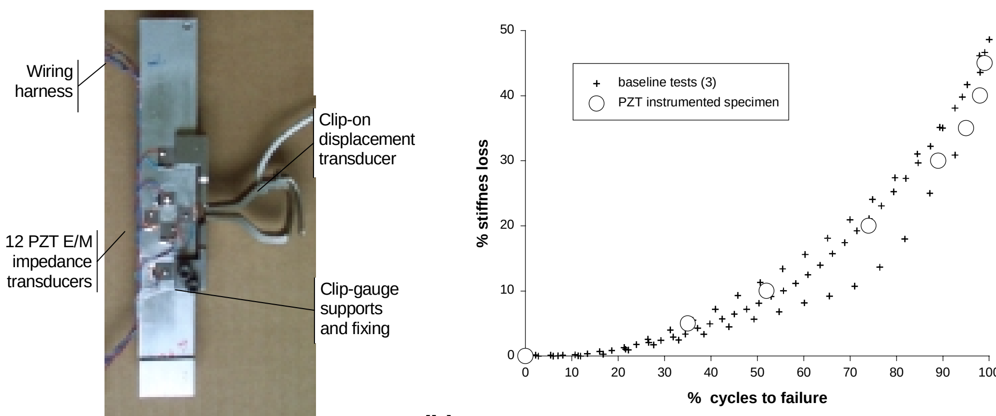

(a) (b)

**Figure 3 Results of the high-frequency electro-mechanical impedance health monitoring testing of bolted joints: (a) electro-mechanical impedance**

**signatures for three structural health situations: *no damage* (bolt + washer); *partial damage* (bolt only); *extensive damage* (no bolt). (b) Correlation between RMS impedance change and specimen structural health (damage progression). (Giurgiutiu, Turner, and Rogers, 1999)**

## 3. HIGH-FREQUENCY E/M IMPEDANCE MONITORING OF SPOT WELDED JOINTS

The spot-welded joint is a joining solution with wide utilization in the automotive industry. Spot welding is a highly productive technology that easily lets itself to mechanization and automation. More recently, spot welding is being also considered by the aerospace industry. Spot welding has the potential to replace the labor-intensive riveting technology currently used in aircraft manufacturing. Figure 4 present the experiment performed to correlate the damage progression in a spot-welded joint. The results of these experiments are presented in Figure 5.




**(a)** **(b)**

**Figure 4** **High-frequency electro-mechanical impedance health monitoring testing of spot-welded joints: (a) Photograph of the spot-welded lap-joint specimen instrumented with bonded PZT transducers and a clip-on displacement transducer. (b) Graph of percentage stiffness loss vs. percentage cycles to failure for lap-shear spot weld specimens tested at $P_{max}$ = 2.7 kN and R=0.1 (Giurgiutiu, Reynolds, and Rogers, 1998).**

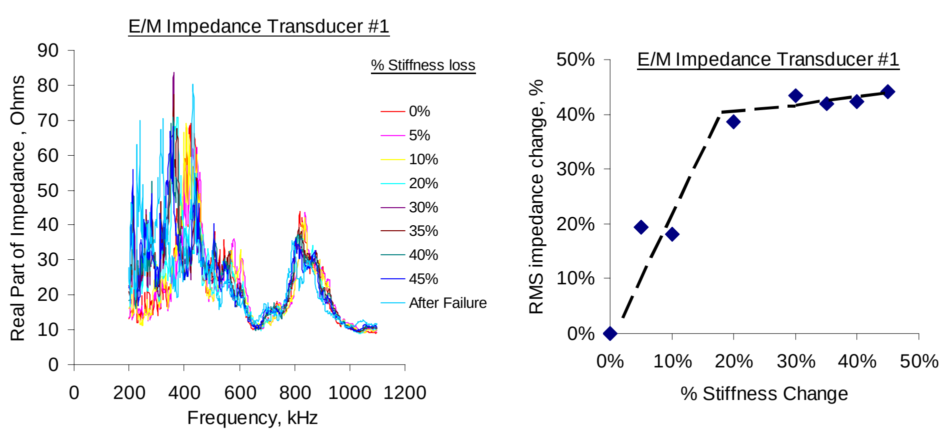



**Figure 5** **Results of spot-welded joints health monitoring: (a) E/M impedance signatures for increasing amounts of specimen stiffness loss (available for viewing in color at http://www.engr.sc.edu/research/lamss/spot1a.htm); (b) Correlation between RMS impedance change and specimen stiffness**

**loss (damage progression) (Giurgiutiu, Reynolds, and Rogers, 1998).**

## 4. HIGH-FREQUENCY E/M IMPEDANCE MONITORING OF COMPOSITE OVERLAYS ON CONCRETE STRUCTURES

Composite overlays are thin sheets of fiber reinforced polymeric material (1/8-in to 1/4-in) adhesively bonded to conventional construction engineering materials. The composite may be applied as: (a) wet lay-up; or (b) precured panels; or (c) partially cured prepregs. For wet lay-up and prepreg systems, the adhesive is the polymeric resin itself. For precured rigid panels, separate adhesive material needs to be used. Structural upgrades with composite overlays offer considerable advantages in terms of weight, volume, labor cost, specific strength, etc. However, one critical issue is the still unknown in-service durability of these new material systems. Their ability to safely perform after prolonged exposure to service loads and environmental factors must be ascertained before wide acceptance in the construction engineering community is attained. Several investigators have reported the use of E/M impedance method to monitor cracks and disbonds in composite overlay systems on civil structures (Quattrone, Berman, and Kamphaus, 1998; Raju, Park, and Cudney, 1998).

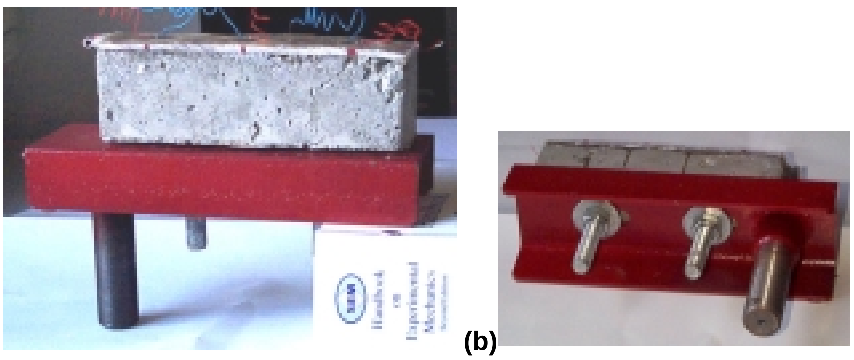
(a)  (b)

**Figure 6 University of South Carolina test specimen for E/M impedance technique disbond detection: (a) support fixture, concrete brick and composite overlay; (b) retention bolts (Giurgiutiu, Whitley, and Rogers, 1999).**

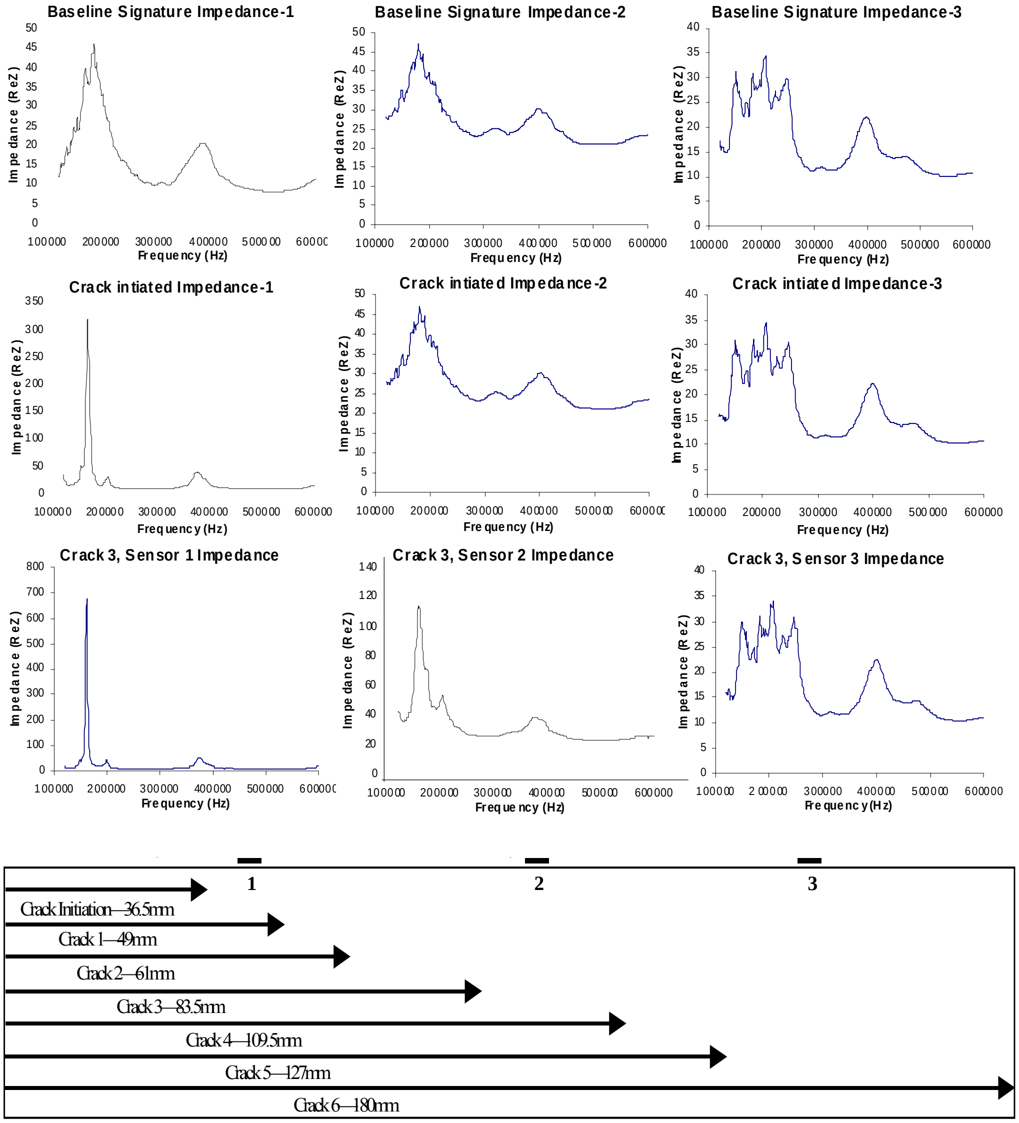
Composite overlay

PZT active sensors

Reaction bolts

Concrete substrate

Support fixture




(a)

(b)

**Figure 7 High-frequency electro-mechanical impedance health monitoring testing of composite overlay repairs of civil infrastructure correlates crack position with E/M impedance spectrum. As the crack advances from crack 1 through crack 6, the sensor E/M spectra changes accordingly (Giurgiutiu, Whitley, and Rogers, 1999).**

Figure 6 shows the type of specimens used at the University of South Carolina to correlate the E/M impedance readings with crack propagation in the bond between a composite overlay and a concrete substrate. Figure 7 illustrates the correlation between crack propagation and E/M impedance reading as measured during these experiments. The specimen underwent controlled amounts of cracking in a DCB-type test performed in an MTS universal testing machines. A number of cracks of increasing length were generated (Figure 7b). The high-frequency E/M impedance spectrum (Figure 7a), as measure by the active transducers placed on the composite overlay, remained undisturbed until the crack front came into the active sensor proximity. At that moment, the changes in the E/M impedance spectrum clearly detected the presence of the crack. As the crack progressed, the E/M impedance spectrum of the sensors left behind the crack front remained, again, unchanged, while the sensors ahead of the crack tip became sensitive to the approaching front.

## 5. MODELING OF E/M IMPEDANCE INTERACTION BETWEEN ACTIVE SENSOR AND HOST STRUCTURE

Giurgiutiu and Rogers (1999) studied the interaction between an active sensor and the host structure. The scope of the study was to illustrate how Equation (1), which uses structural and PZT stiffness values of several orders of magnitude difference, can still reflect changes in structural dynamics. The active sensor was considered affixed to the structure's surface and in intimate contact with it (Figure 8). The pin-end model was used to resolve the interaction forces between the active sensor and the host structure. When the sensor is activated, the sensor sees from the structure end reactions of magnitude $F_{PZT}$. In its turn, the structure sees from the sensor equivalent pairs of actuation forces ($F_a$) and moments ($M_a$) which induce axial and flexural vibrations in the structure. The interaction of the two entities, active sensor and host structure, can be described in terms of their frequency–dependent complex dynamic stiffness, $k_{PZT}(\omega)$ and $k_{str}(\omega)$, respectively.

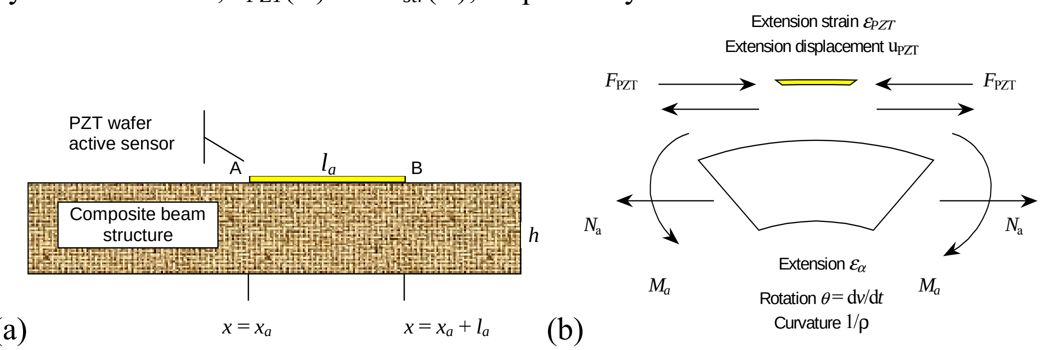



**Figure 8 Model of the interaction between a PZT active sensor and a substrate beam structure: (a) geometry; (b) forces and moments.**

Using modal expansion over a selected high-frequency bandwidth ($N_1 \le n \le N_2$), closed-form expressions for structural stiffness were derived:

$$k_{str}(\omega) = \left( \left(\frac{h}{2}\right)^2 \frac{1}{\rho A} \sum_{n=N_1}^{N_2} \frac{C_n}{m_n\left(\omega_n^2 + 2i\omega\omega_n - \omega^2\right)} \left[X_n'(x_a) - X_n'(x_a + l_a)\right] \right)^{-1}, \qquad (2)$$

where

$$C_n = \sqrt{\frac{2}{l}} \frac{1}{\beta_n} 2\sin\beta_n \frac{2x_a + l_a}{2} \cdot \sin\beta_n \frac{l_a}{2} \qquad (3)$$

and

$$X_n'(x_a) - X_n'(x_a + l_a) = \sqrt{\frac{2}{l}} \beta_n \left[\cos\beta_n x_a - \cos\beta_n\left(x_a + l_a\right)\right] \qquad (4)$$

The mechanical stiffness of the PZT active sensor with respect to an axial force applied in the $x_1$ direction is simply $k_{PZT} = A_a / s_{11} l_a$, where $A_a = t_a \cdot b_a$ is the PZT cross-sectional area.

Thus, the E/M impedance and admittance could be reconstructed from Equation (1). The simulated E/M impedance and admittance real parts faithfully display the pointwise dynamic response signature of the structure (Figure 9). Thus the high-frequency mechanical behavior of the structure is directly reflected in the high-frequency spectrum of the active sensor electrical impedance/admittance.

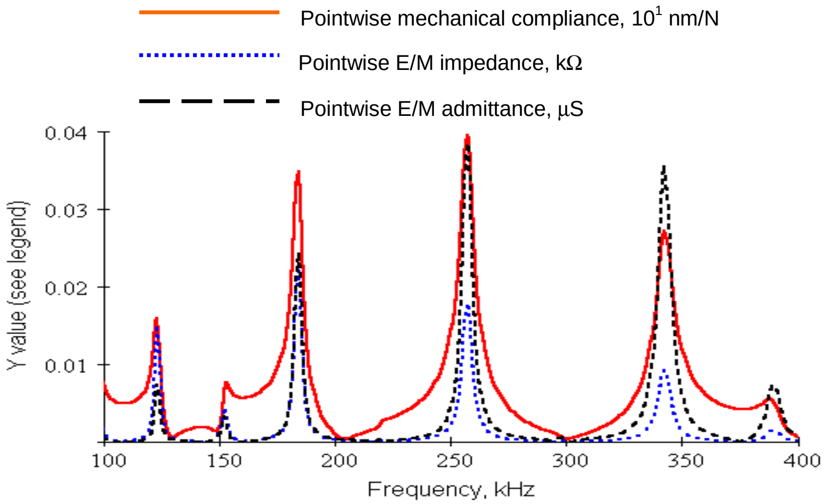



**Figure 9** **Pointwise mechanical compliance, E/M impedance, and E/M admittance of a composite beam**

Figure 10 shows how the E/M impedance signature changes when damage takes place in the beam. In this example, damage was simulated by varying the thickness of the beam. This thickness change corresponds to a delamination, which virtually splits the beam into two regions, such that the PZT wafer active sensor remains attached to a locally thinner beam. In our simulation, a 55% effective post-delamination thickness was considered. The clear difference between the two signatures, pristine and damaged, is apparent. The plots in Figure 12 indicate that the effect of damage is to shift to the left the resonance frequency peaks, and to increase their value. These modifications in the E/M impedance signature are essential in identifying the presence of structural damage.

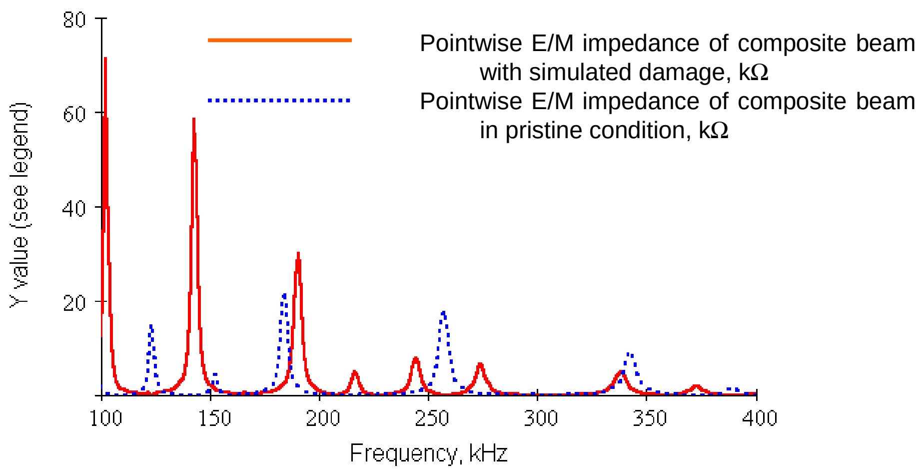



**Figure 10** **Pointwise mechanical compliance, E/M impedance, and E/M admittance of a composite beam with simulated damage (45% effective thickness decrease due to delamination).**

## 6. DAMAGE INDEX IDENTIFICATION OPTIONS

Damage index identification remains an open question in the practical application of E/M impedance technique. The damage index is a scalar quantity that serves as a metric of the damage taking place in the structure. Ideally, the damage index should be able to evaluate the E/M impedance spectrum and indicate damage presence, location, and severity. Historically, damage indexed based on the root mean square (RMS) change (Euclidean norm) of the E/M impedance real part has been used. The expression of the RMS damage index is:

$$DI = \sqrt{\frac{\sum_{N} \left[ \mathrm{Re}(Z_i) - \mathrm{Re}(Z_i^0) \right]^2}{\sum_{N} \left[ \mathrm{Re}(Z_i^0) \right]^2}}\,, \qquad (5)$$

where $N$ is the number of sample points in the spectrum, and the superscript 0 signifies the initial (base-line) state of the structure. However, this simple damage index has been shown sensitive to other effects but damage (e.g., temperature variation), and such effects may have to be compensated out before meaningful damage detection can be attempted. Hence, novel damage index algorithms are being developed.

Quin *et al.* (1999) developed an E/M impedance damage index (DI) scheme based on the differences of the piecewise integration of the frequency response curve between the damaged and undamaged cases. In addition, improved characterization of the structure is achieved by the separation of transverse and longitudinal outputs through directionally attached piezoelectrics (DAP).

Lopes *et al.* (1999a, b) used neural network techniques to process high-frequency E/M impedance spectra. In analytical simulation studies, a three level normalization scheme was applied to the E/M impedance spectrum base on the resonance frequencies. First, the sensitivity of certain resonance frequencies to the location of the damage was identified. Second, the excursion of the frequency change with damage amplitude at each location was calculated. Thirdly, the normalized percentage frequency change for each damage severity was calculated. One-layer and two-layer neural networks were constructed and successfully trained on analytical models with simulated damage. When applied to actual E/M experiments (4-bay bolted structure and 3-bay screw-connected space frame), the neural network approach was modified to another set of normalized values: (i) the area between damaged and undamaged impedance curves; (ii) the root mean square (RMS) of each curve; and (iii) the correlation coefficient between damaged and undamaged curves. These values were calculated for both real and imaginary parts of the impedance spectrum. Good identification of damage location and damage amplitude was reported.

## 7. CONCLUSIONS AND FURTHER WORK

This paper has presented recent progress in the application of the electro-mechanical (E/M) impedance method to structural health monitoring, damage detection, and failure prevention. A brief review of the E/M impedance method principles was followed by applications to bolted and spot riveted structural joints, and to polymeric composite overlays to construction engineering structures. The modeling of the interaction between the piezoelectric active sensor and the host structure was described. The development of a meaningful structural damage index that can identify the damage presence, location, and magnitude was considered, and several recent works, including some using neural networks, were cited.

Further work in this field should concentrate on improving the modeling such that the E/M response to several types of damage in different structural systems could be adequately predicted. The influence of sensor size and power on the detection localization, area of influence, and minimum damage size should be considered. And transition of the technology to practical use through the construction of miniaturized, autonomous health monitoring equipment with tele-transmission and data logging capabilities should be attempted.

## 8. ACKNOWLEDGEMENTS

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