A new criterion for structural damage detection using electromechanical impedance technique

H. Ghoshchian , M.R. Ashory, A. Bakhshizade, M. Akbari.Jami
Modal analysis lab School of Mechanical Engineering, Semnan, Iran

ABSTRACT: Application of the piezoelectric transducers for structural health monitoring based on Electrical Impedance is growing rapidly in aerospace industry and also in civil and mechanical Engineering. In this technique the piezoelectric transducer is installed on the primary of structure and is driven with a high frequency excitation. The impedance is estimated by measuring the output current and voltage of PZT through which the damage in the structure can be detected. In this paper, a new approach is introduced to identify the location of damage in the structure using the statistical methods based on the Frequency Response Function (FRF) in the high frequencies. The method has advantages over the previous techniques to detect the location of crack. The numerical model of a cantilever beam with a crack is used to demonstrate the effectiveness of criterion in predicting the existence and location of damage.

1 INTRODUCTION

Vibration-based methods using modal analysis for damage detection in the structures have received a significant attention in the research communities over the last few decades. The principle behind such methods is that the damage in a structure results in the changes of mass, damping and stiffness properties. Consequently, the modal parameters in terms of the natural frequencies, mode shapes and modal damping also alter. If these changes are detectable, the presence, location and severity of damage can be identified. The research efforts in this field have produced many new techniques for structural damage identification.[1],[2],[3]

The low sensitivity of the vibration-based methods in determination of higher modes is basically related to the practical limitations. In conventional measurement techniques only the first few modes of structure can be obtained. At low frequencies, the mode shapes can only reflect the global changes in the structure [2]. However, as damage is a local defect, it may not be discernible by the methods that use only the lower modes [4]. Doebling et al. [2] pointed out that this limitation can be overcome if the higher frequencies are considered, where the modes reflect the local responses. As more energy is required to produce a measurable response at higher frequencies, it is difficult to excite the structure with the conventional actuators. Even if such an actuation is possible, it would require a large number of sensors to measure the responses. Practically identification of the higher mode shapes is impossible using the conventional methods. As such, so far hardly any modal parameter-based methods exist that use the higher modes of structures.

The Electromechanical impedance (EMI) method is a recent development in the field of smart system-based structural health monitoring, and has the potential to overcome the aforementioned higher frequency measurement problem in the vibration-based methods. The basic feature of this method is in using of the self-sensing smart piezoelectric (PZT) transducer as both the sensor and actuator. A piezo transducer can excite the structure at the high frequencies, typically 10–500 KHz, thus the higher modes of the structure can be activated. These higher modes have the potential to capture the local changes of the structure, where the conventional vibration methods fail. The electrical admittance of piezo-transducer can be expressed as a coupled equation of the mechanical impedance of transducer and the drive-point mechanical impedance of host structure (Liang et al., 1994)[5]. Mechanical impedance of the host structure is dependent on its mass, stiffness and damping properties. Damage in a structure alters the stiffness, damping and mass which change the

mechanical impedance in turn. When a piezo-transducer is bonded to the structure and actuated, the damage-induced change in the mechanical impedance of structure is reflected in the electrical admittance of the piezo-transducer. By extracting the admittance response of piezo-transducer with respect to the frequency of excitation, the changes in the admittance signature becomes indicative of the presence of structural damage. The capabilities of the E/M impedance method and its advantages over the conventional techniques of vibration based methods for identifying the damage have been experimentally acknowledged [6]. A complete perspective of the E/M impedance-based health monitoring is provided by a recent review by Park et al. (2003) [6].
Damage location can be identified by correlating the changes in the natural frequencies at the higher modes with the corresponding mode shapes of undamaged structure as presented by Soh and Naidu et al.(2004)[7].
The E/M impedance method, which is essentially a non-model-based technique, can provide the qualitative and not quantitative information of damage. The way of quantifying damage has mostly been restricted to the non-parametric statistical measures [8].
In this paper, a method for detection of the damage location is proposed using the frequency response function in the high frequencies which is obtained from E/M admittance signatures. Results of the damage location identification are presented for the numerical simulation of damages in a beam using a FEM model.

2 ElECTRO-MECHANICAL PRINCIPLE

Piezoceramic transducers acting in the 'direct' manner produce an electrical charge when they are stressed mechanically. Conversely, a mechanical strain is produced when an electrical field is applied to the PZT. The process of monitoring the impedance-based techniques utilizes both the direct and converse versions of the piezoelectric effect simultaneously to obtain an impedance signature.
The electromechanical modeling which quantitatively describes the process is presented in Figure.1. 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 the 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 [9].

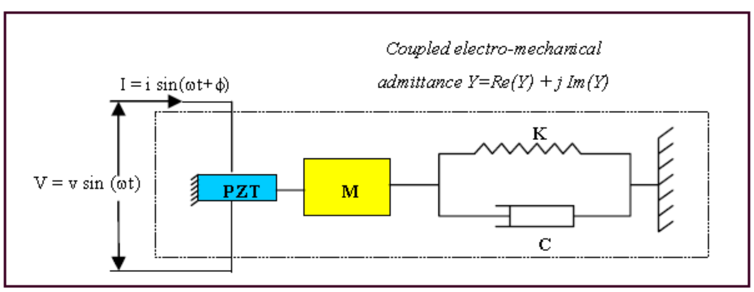

Figure 1 1-D model used to represent a PZT-driven dynamic structural system[10]

The solution of the wave equation for the PZT bar connected to the structure for a frequency-dependent electrical admittance leads to the following equation (Liang *et al*. 1994)[5]:

$$Y(\omega) = i\omega \frac{w_A l_A}{h_A} (\bar{\epsilon}_{33}^{T} - \frac{Z(\omega)}{Z(\omega)+Z_A(\omega)} d_{31}^2 \bar{Y}_{11}^{E}) \quad (1)$$

Where, Y is the electrical admittance (inverse of impedance), Z_A and Z are the PZT material's and the structure's mechanical impedances, respectively, $\bar{Y}_{11}^{E}$ is the complex Young's modulus of the PZT with zero electric field, d_{31}^2 is the piezoelectric coupling constant in an arbitrary direction at zero stress, $\bar{\epsilon}_{33}^{T}$ is the dielectric constant at zero stress. The length, width, and thickness of the PZT actuator are l_A, w_A, and h_A, respectively. 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 PZT electrical impedance over a range of frequencies is analogous to that of the frequency response functions (FRF) of a structure, which contains vital information regarding the health of the structure[5].

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 the other PZT properties remain constant, it is Zs, the external structure's impedance, that uniquely determines the overall admittance. Therefore, any change in the electrical impedance signature is considered as 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*. (1996)[10].

3 MODAL ANALYSIS USING COLLECTED PZT EXCITER–SENSORS

Equation (1) shows that the electro-mechanical admittance of system is affected by the driving point mechanical impedance of host structure. The mechanical impedance can be easily determined from the electro-mechanical admittance which is measured using a commercial Impedance analyzer. The frequency response function may be expressed from the electromechanical admittance as:

$$FRF = \frac{1}{Z} = \frac{1}{Z_A} [\frac{d_{31}^2 \bar{Y}_{11}^{E}}{\bar{\epsilon}_{33}^{T} - \frac{Y h_A}{i\omega l_A w_A}} - 1] \quad (2)$$

This frequency response function in general does not include the mass loading and stiffening effect from a collocated PZT exciter–sensor. Fortunately, the mass loading of a PZT patch on most of the structures may be ignored without causing much error in the FRF prediction. More detailed discussion on the use of electro-mechanical admittance to determine the mechanical frequency response function may be found in the article by Sun *et al* [11].

4 DAMAGE DETECTION

In this paper two criterions are presented for damage detection using the FRFs obtained from electromechanical admittance signature in the high frequencies. The first method, RMSD, has been applied to the FRFs and as a result the locations of the crack are determined. The second technique is the CC method which can also find the crack location. Both methods have been compared using a numerical example.

4.1 RMSD method for identification of damage location

The Root Mean Squared Deviation (RMSD) of frequency response function between both the intact and damaged conditions can be defined as:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(FRF_i^1 - FRF_i^0)^2}{\sum_{i=1}^{n}(FRF_i^0)^2}} \tag{3}$$

where RMSD represents the damage location metric, FRF_i^0 is the frequency response function of healthy structure, and FRF_i^1 is the frequency response function of damaged structure at frequency *i*. In the RMSD damage location metric chart, the largest difference amount of RMSD between the nodes indicates the location of damage in the structure.

4.2 CC method for identification of damage location

The correlation coefficient of frequency response function in both the intact and damaged structures also can be obtained as:

$$CC = \frac{1}{\sigma_{FRF^0} \times \sigma_{FRF^1}} \sum_{i=1}^{n} [FRF_i^0 - \overline{FRF}_i^0] \times [FRF_i^1 - \overline{FRF}_i^1] \tag{4}$$

Where σ_{FRF^0} is the standard deviation of healthy Frequency response function, σ_{FRF^1} is the standard deviation of damaged Frequency response function, FRF_i^0 is the mean of healthy frequency response function and FRF_i^1 is the mean of damaged frequency response function. The minimum of CC coefficient value at each node together with the maximum difference of CC coefficient between two nodes can identify the location of damage.

5 NUMERICAL CASE STUDY

A numerical model of a cantilever beam was considered to evaluate the proposed methods to identify the crack and its location in a beam. The geometry of beam and its material properties are given as follows: Young's modulus *E=70 GPa*, density $\rho = 2700\ {kg}/{m^3}$, length *l=700mm*, Cross sectional area *A=w×h=40mm×5mm.* The total number of elements is 40. Two cases of damaged beams were considered. The depth and location of the cracked beams are given in Table1.

Table 1**:** properties of cracked beams

characters	Case I	Case II
l_1 (mm)	245	402.5
cracked Element number	14	23
a (mm)	0.3	0.2

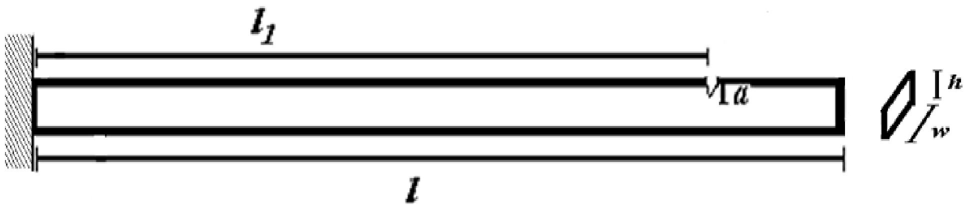

Figure2: Geometry of cantilever beam with a crack

The damaged beam was modeled using the method proposed by Nahvi and Jabbari [13]. In this approach the length of damaged element is smaller than other elements. The Frequency range was selected to be between 25 to 40 KHz. Figures 3and 4 show the frequency response function and the real part of admittance for Case I. The admittance and frequency response function were estimated using equations (1) and (2) respectively.

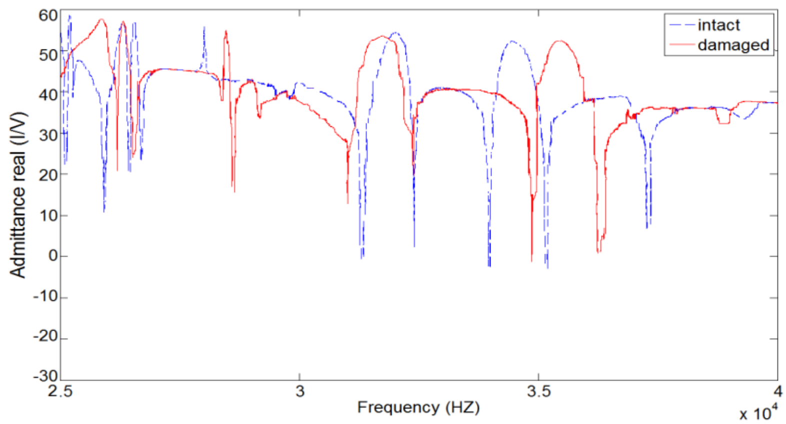

Figure3**:** Real part of admittance in the frequency range of 25 to 40 KHz

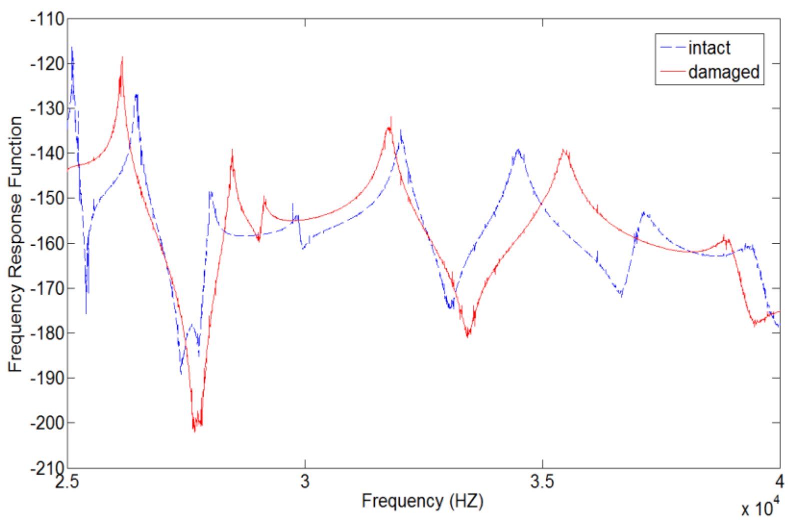

Figure4**:** Frequency Response Function in the frequency range of 25 to 40 KHz

As can be seen the real part of admittance in Figure 3 has peaks at the same frequencies of natural modes in Figure 4, demonstrating that the real part of admittance can indicate the natural frequencies of the structure.

6 RESULTS

The RMSD and CC criterions proposed in this paper for aforementioned damage cases (Table1) have been shown in Figures 5-8.

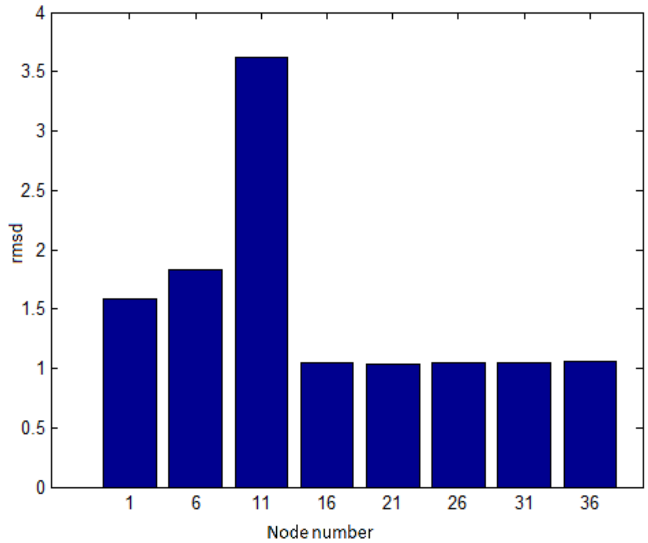

Figure5: RMSD criterion (Case I**)**

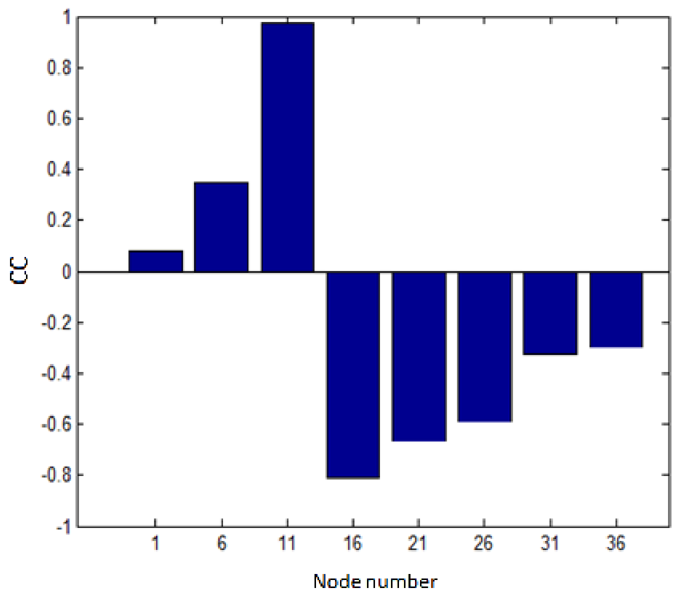

Figure6: CC criterion (Case I)

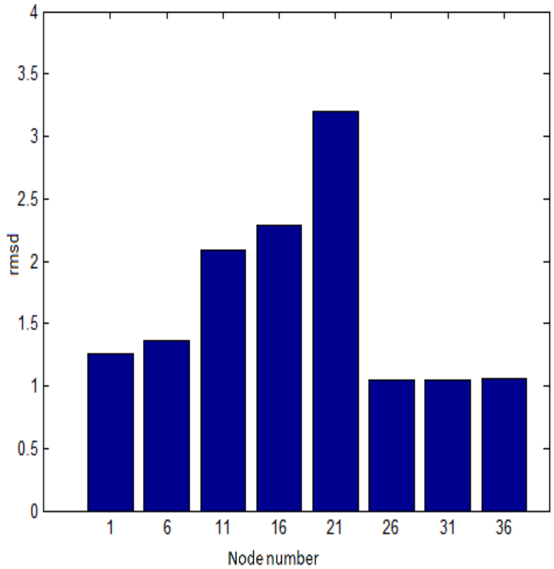

Figure7: RMSD criterion (Case II)

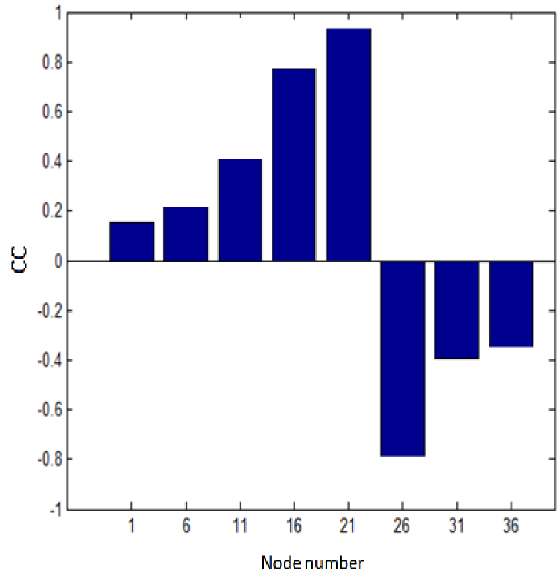

Figure8: CC criterion (Case II)

For case I, the crack is located in element 14 (Table 1), Fig.5 shows that there is a considerable change in RMSD between nodes 11 and 16. Based on the explanations in section 4.1, it can be concluded that the crack is occurred between nodes 11 and 16. Moreover, the minimum CC coefficient value is occurred at node 16 (Figure 6) and the maximum difference in CC coefficients is placed between nodes 11 and 16 which shows that the crack occurs between nodes 11 and 16 in the beam. Both RMSD and CC criterions are plotted for case II and the results show that the crack is located between nodes 21and 26 (Figures 7 and 8).

7 CONCLUTION

The feasibility of using the high-frequency vibrations for structural damage detection has been studied. In this paper, two criterions RMSD and CC are proposed to improve the damage localization of a structure and their performances have been investigated numerically. Results show that the proposed approaches can be used to localize the tiny damages in the structure using frequency response function at high frequencies obtained from the admittance signature.

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