Damage Detection Using Electromechanical Impedance Signatures and statistical outliers

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Abstract: - The present paper presents a numerical method for health monitoring and damage identification of civil infrastructure facilities. The detection and characterization of damages is achieved by extracting the electromechanical impedance characteristics of surface bounded self-sensing piezoelectric ceramic (PZT) patches. The frequency – dependent electromechanical admittance signatures of the PZT transducers are compared with the baseline signature of the undamaged structure to characterize the status level of the health of structures. The damage is quantified at first, conventionally by the well-known root-mean-square deviation (RMSD) index and then by using a statistical confidence method in system identification advanced routines of a mathematical computational software. In this paper a set of numerical simulations using finite element analysis is performed on concrete beams instrumented with PZT transducers. The numerical results demonstrate the advantages of using mathematical modelling methods of system identification as compared to previous damage detection methods, which required good engineering judgement and were insufficient for the complexity of modern structures.

Key-Words: - PZT, Electromechanical Impedance, damage detection, health monitoring

1 Introduction

Civil infrastructures are assemblies of load carrying members that throughout their stipulated design life must satisfy strength and serviceability criteria. However, after a natural disaster, such as an earthquake, structures degrade or experience damage and they will no longer behave as they were originally designed to, which pose safety and reliability hazards. It is well known, that the underlying cause of most structural failures is in the form of incipient damages, which usually remain undetected until they grow to levels enough to cause failure. Early detection of damage can prevent catastrophic failure. However, visual inspection by trained engineers alone cannot make a comprehensive health assessment of great number of structures at short notice, such as immediately after an earthquake. As a result, various damage detection and health monitoring techniques have been proposed and studied in the literature. A good collection of recent techniques in structural damage identification can be found in Chang [1].

Many of the conventional non-destructive evaluation (NDE) methods, such as radiography, acoustic emission, magnetic field, eddy current, thermal field and ultrasonic technique have serious limitations for in situ applications. All of these methods require accessibility to the inspected structural components and usually involve bulky equipment. However, the recent advent of smart materials, such as piezoelectric materials, shape-memory alloys and optical fibres has added a new dimension to structural heath monitoring (SHM). In particular, the electro-mechanical impedance (EMI) technique, which uses smart piezoelectric ceramic (PZT) materials, has emerged as a powerful technique for SHM, [2], [3] [4], [5], [6]. In this technique, a PZT patch is bonded to the structure and a high-frequency (>30 kHz) electro-mechanical admittance signature of the patches serves as diagnostic of the damage status of the structural components. Furthermore, the small, non-destructive PZT can be easily installed into and used to monitor remote, inaccessible location without removal of any finishes or rendering the structure temporarily unusable. The collected data is directly acquired in the frequency domain as opposed to the time domain as in the case for conventional SHM techniques. As a consequence, the impedance method seems to have the leading edge over the existing conventional methods [7], [8].

However, since the impedance-based method primarily relies on experimental data with difficulties in modeling at such high-frequency ranges, the use of system identification procedures is required if changes in the impedance signatures caused by structural damage have to be distinguished from those caused by operational and environmental variability. System identification in combination with statistical analysis procedures enable engineers to simulate a structural system's behavior, as well as locate damage or deterioration of a structure based on changes in structural properties.

This paper will discuss the process of system identification and the resulted impedance-based monitoring in the context of an outlier detection framework. The purpose of the present investigation was to create mathematical models of impedance-based signature data and analyse their validity and accuracy, and also to observe how these models could be an essential aid in analysis structural damage.

2 Electro-Mechanical Impedance (EMI) Technique

The EMI technique uses piezoelectric materials, such as Lead Zirconate Titanate (PZT), which exhibits the characteristic feature to generate surface charge in response to an applied mechanical stress and conversely, undergo mechanical deformation in response to an applied electric field.

Consider a structural component with a PZT patch bonded on it. The related physical model is shown in Fig. 1 for a square PZT patch of length $2\ell_{PZT}$ and thickness h_{PZT}.

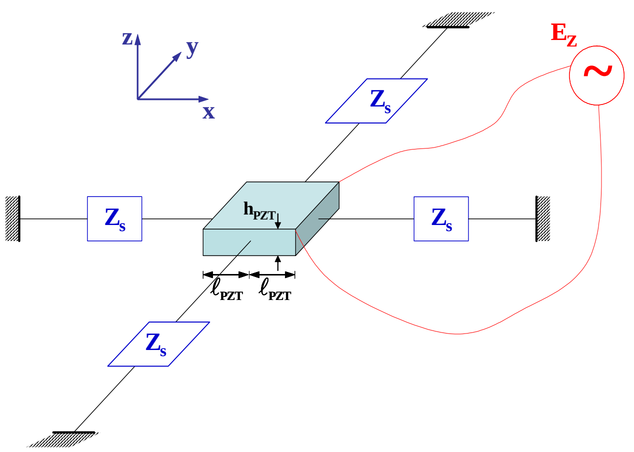

Fig. 1 Model of interaction between PZT and structure

When a harmonic voltage $V=V_0e^{j\omega t}$ is applied in the z-direction, producing an electric field $E=E_0e^{j\omega t}$, an in-plane vibration is induced in both x and y directions. Liang et al [9] first modeled the 1D PZT-structure electro mechanical interaction, while Bhalla & Soh [6] and Soh & Bhalla [10] extended this approach to 2D structures by using the concept of effective impedance.

The constitutive equations of the PZT patch are [10]:

$$S_X = \frac{1}{\overline{E}_{PZT}}\left(T_X - \nu_{PZT}T_Y\right) + d_{31}E \quad (1)$$

$$S_Y = \frac{1}{\overline{E}_{PZT}}\left(T_Y - \nu_{PZT}T_X\right) + d_{32}E \quad (2)$$

$$D = \overline{\varepsilon}_{33}E + d_{31}T_X + d_{32}T_Y \quad (3)$$

where S_X and S_Y are strains, T_X and T_Y are stresses, $\overline{E}_{PZT} = E_{PZT}\left(1+nj\right)$ is the elastic modulus at zero electric field, n is the mechanical loss factor, ν_{PZT} is the Poison's ratio, d_{31} and d_{32} are the piezoelectric constants in the x and y directions, respectively, $\overline{\varepsilon}^T_{33} = \varepsilon^T_{33}\left(1-\delta j\right)$ is the dielectric constant at zero stress, D is the electric displacement and δ the dielectric loss factor. If the PZT material is isotropic on the x-y plane ,which results in $d_{31}= d_{32}$, the electric displacement in equation (3) can be rewritten as:

$$D = \overline{\varepsilon}^T_{33}E + \frac{d_{31}\overline{E}_{PZT}}{1-\nu_{PZT}}\left(u' + v' - 2d_{31}E\right)$$

where $\left(\ \right)' = \vartheta\left(\ \right)/\vartheta x$ and u, v are the displacements responses in x and y direction , respectively which can be derived as the solution of the in-plane vibration problem of the PZT patch [7], [11]:

$$\rho_{PZT}\ddot{u} = \frac{\overline{E}_{PZT}}{1-\nu^2_{PZT}}u'' \quad (4)$$

$$\rho_{PZT}\ddot{v} = \frac{\overline{E}_{PZT}}{1-\nu^2_{PZT}}v'' \quad (5)$$

where $\left(\dot{\ }\right) = \vartheta\left(\ \right)/\vartheta t$ and ρ_{PZT} is the density of the PZT patch.

The electric current passing through the PZT patch can be considered to be given by

$$I = j\omega \int_{-\frac{\ell_{PZT}}{2}}^{\frac{\ell_{PZT}}{2}} \int_{-\frac{\ell_{PZT}}{2}}^{\frac{\ell_{PZT}}{2}} D\,dx\,dy \quad (6)$$

Considering that the electric field is defined by

$$E = \frac{V}{h_{PZT}} \tag{7}$$

and that the input voltage V is an AC voltage of 1 V (rms) magnitude the electric admittance of the PZT patch can be expressed as:

$$Y = \frac{I}{V} = j\,\omega\,\Sigma Q_i \tag{8}$$

where ΣQi is the total charge over the whole surface of the PZT patch and $j = \sqrt{-1}$.

3 Damage Diagnosis by Using Numerical Simulation

The technical literature has demonstrated that closed-form expressions for the equations (4), (5) of electromechanical admittance are only available for simple geometries and structures such as beams [12], circular-plates [13] and rectangular thin plates [14].

In this paper, finite element methodology is used to extract and analyze the electromechanical admittance signals. Then, a frequency response analysis was performed using the FE software package COMSOL [15] and its piezoelectric analysis feature in connection with the enhanced system identification capabilities of the mathematical package MATLAB [16].

Quantitative damage diagnosis with the EMI method is conventionally achieved by using scalar damage metrics, such as the “root mean square deviation” (RMSD) index:

$$RMSD = \sum_{i=1}^{n} \sqrt{\frac{\left[\boldsymbol{Re}(Y_{i,1}) - \boldsymbol{Re}(Y_{i,2})\right]^2}{\left[\boldsymbol{Re}(Y_{i,1})\right]^2}} \tag{9}$$

Where $Y_{i,1}$ is the admittance of the PZT patch computed at pristine undamaged condition and $Y_{i,2}$ is the admittance for the ‘in-question’ condition as compared with the baseline (pristine) computation at each frequency interval *i*. The greater the numerical value of the RSMD metric, the larger the difference between the pristine and the ‘in-question’ admittance computation, indicating the presence of damage in the structure. Zagrai and Giurgiutiu [13] considered different statistics-based damage metrics, such as RMSD, mean absolute percentage deviation, covariance change, and correlation coefficient deviation. However, the main disadvantage of these damage metrics is how to setup appropriate decision limits or statistical confidence on the structural damage condition. The decision-making seems to be rather arbitrary.

4 EMI Technique Using Statistical Parametric Modeling Process

The conventional admittance – based SHM technique first begins by obtaining input, output and noise signals. In the so called system identification process the second step is the data cleansing, filtering and averaging. The cleansed signals are then used to produce parametric mathematical models which in turn evaluate the current state of health of the system and predict future states of health.

Parametric models are based on ordinary or partial differential equations that describe the dynamic system. Usually ready made models such as autoregressive (AR) models with exogenous (ARX) inputs are chosen since they are cost-effective and convenient to use. The frequency-domain ARX parametric model provided in the system identification Toolbox of MATLAB [16] attempts to predict the output signal at a particular frequency based on the input PZT driven sinusoidal voltage signal of 1 Volt(rms). The basic equation for an ARX parametric model is a function of frequency (ω) and the shift operator *q*.

$$A(q)\,Y(\omega) = B(q)\,V(\omega) + e(\omega) \tag{10}$$

where *A(q)* is auto regression (AR)
B(q) is extra input
Y(ω) is output
V(ω) is input
e(ω) is disturbance/noise
and

$$A(q) = 1 + a_1 q^{-1} + \dots + a_{na} q^{-na} \tag{11}$$

$$B(q) = b_1 q^{-1} + \dots + b_{nb} q^{-nb-nk+1} \tag{12}$$

The ARX model is characterized by 3 numbers: the auto-regressive order n_a, the exogenous order n_b and the pure time delays n_k. By using MATLAB the parameter a_i and b_i are easily estimated, so they minimize the final prediction error. After this estimation the coefficients *A(q)* and *B(q)* can be obtained. The ARX estimates of values A and B can be plugged into the original equation to obtain the equation governing the output input and noise signals. This parametric equation is then used to simulate the model’s output which is adopted to compare with the 'in-question' admittance condition.

5 Numerical Results

In the present paper, the test structure is a concrete beam 500 mm in length, 100 mm in width and 100 mm in thickness. A PZT patch is considered to be bonded to the upper surface of the monitored beam in a distance of 40 mm away from the left end (Fig. 2). Cracks were then simulated on the upper surface of the beam specimen by considering cross-width notches 5 mm in depth. The first simulated crack was considered at a distance of 50 mm from the patch and the last a 300 mm distance from the PZT patch.

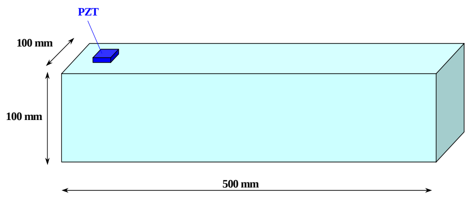

Fig. 2 Beam specimen with a PZT patch

The first crack represents the damage initiation while each new crack represents a new damaged state of the beam specimen. The six induced damage states representing sequential damage growth are shown in Fig. 3. The intention behind simulating the damages in this fashion is to observe the sequential change in the admittance signature when the damage approaches the PZT transducer.

The finite element model was generated in COMSOL 3.2.a using 2633 up to 3471 finite elements and then a frequency response analysis was performed over a frequency range of 20-25 kHz at an interval of 500 kHz. In every damage state, the real part of the admittance (conductance) was acquired and compared to the pristine (undamaged) state. The pristine state was acquired before the first crack was simulated.

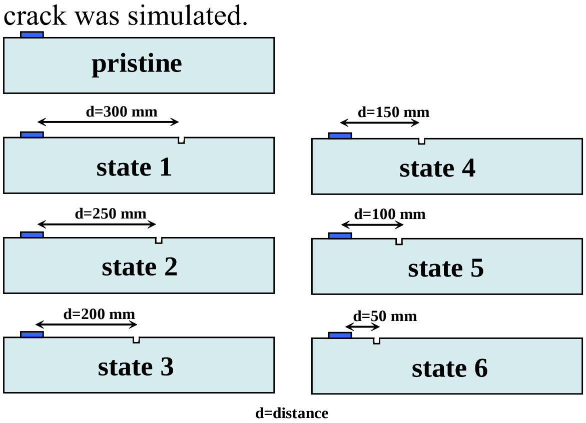

Fig. 3 Simulates sequential damage growth

The RMSD damage metric of equation (9) was plotted for the six different damage state signatures with respect to the undamaged (pristine) signature as shown in Fig. 4. It can be observed that even with the appearance of the first damage states as a crack opening in a distance of 300 mm away from the PZT transducer, the RMSD index has a high value of 0.463. Therefore, the result indicates a high sensitivity if the PZT transducer to detect damages located even at far distances.

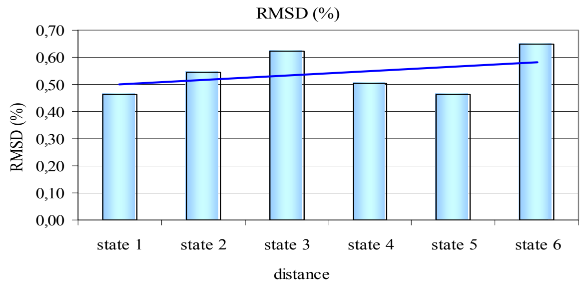

Fig. 4 RMSD metric versus damage distance and its trendline

As the cracks (damage) approach PZT the RMSD index value increases gradually, which is indicated by the linear regression (trend) line in Fig. 4, which is of primary concern in the characterisation of the damages. Besides, the small increments in the RMSD index for all other subsequent cracks after the first can be understood by the fact that the amplitude of the incident elastic waves generated by the PZT decays after encountering the first crack (damage). The energy losses lead to localisation of the propagating elastic wave to near vicinity of the PZT.

In order to proceed with the statistical process analysis the pristine measurement and the System Identification Toolbox of MATLAB are used to obtain the parameters of the proposed ARX model for the undamaged state. From this, A*(q)* and B*(q)* coefficients of (10) are estimated to be:

$$A(q) = 1 + 11.96q^{-1} + 60.06q^{-2} + 171.2q^{-3} + 310.6q^{-4} + 377q^{-5} + 310.6q^{-6} + 171.1q^{-7} + 59.99q^{-8} + 11.93q^{-9} + 0.9958q^{-10} \quad (11)$$

$$B(q) = 0.001069q^{-1} + 0.008252q^{-2} + 0.02814q^{-3} + 0.0554q^{-4} + 0.06887q^{-5} + 0.05 + 0.02808q^{-7} + 0.008209q^{-8} + 0.001054q^{-9} - 2.271e^{-6}q^{-10} \quad (12)$$

Once the coefficients are estimated, the residual errors are extracted as a damage-sensitive feature by subtracting the FEM computed impedance from the predicted output of the ARX model. If the normality assumption is used, there would be a number of outliers the selection of which depends on decision limits based on the specific structure and type of damage investigated. The 99.9 % confidence interval is chosen in our work because it provides acceptable risk. For a sample of 11 frequency-points and 99.9 % confidence interval 0 or 1 outliers beyond the confidence interval for an undamaged state could be expected.

Fig. 5 shows the detrended residual errors for the undamaged with 0 outliers beyond 99.9 % confidence interval for the damage state (identified with the closest PZT crack) with many outliers beyond the upper and lower 99.9 % confidence interval.

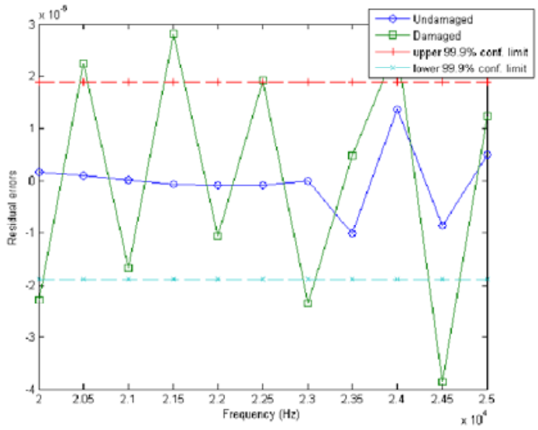

Fig. 5 Residual errors versus frequency and resulted outliers for undamaged and damaged state

It can be also observed that undamaged state results are excellent, showing no positive indication of damage at all frequency points.

The proposed method can be considered as a more quantitative approach for detecting damaged and undamaged states. This decision is made based on the number of outliers within or below the control limit.

6 Conclusions

With the assistance of advanced finite element mathematical computing software, parametric estimation was greatly simplified and the process of system and damage identification was made efficient. Having an accurate parametric model of a system is important in analysing a structure's current state of health and predicting structural behaviour in various conditions.

The health monitoring process proposed here that capitalizes the feature of electro-mechanical impedance signals in combination with the extraction of outliers in the associated prediction error can be efficiently used in determining the damage state of a structure over the traditional SHM approaches.

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