A LOW-COST VARIANT OF ELECTRO-MECHANICAL IMPEDANCE (EMI) TECHNIQUE FOR STRUCTURAL HEALTH MONITORING

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INTRODUCTION

The electro-mechanical impedance (EMI) technique has been established as a competitive technique for structural health monitoring (SHM) and non-destructive evaluation (NDE) for a wide variety of modern engineering systems[1-6]. This technique makes use of lead zirconate titanate piezoelectric-ceramic (PZT) patches as impedance transducers[7, 8] by utilizing their direct and converse piezoelectric properties simultaneously. A PZT patch is surface-bonded on the structural component to be monitored and subjected to an alternating voltage excitation through an impedance analyzer/ LCR meter, sweeping through a particular frequency range, generally of the order of tens to hundreds of kHz. At any particular frequency, the patch actuates the structure and the structural response is in-turn sensed and measured in terms of the electromechanical admittance of the patch, consisting of the real and the imaginary components, the conductance and the susceptance respectively. In this manner, frequency plots, termed conductance and susceptance signatures, are generated. Any change in the condition of the structure manifests as a change in these signatures, especially the conductance, which is utilized for SHM and NDE, considering the signatures of the healthy state structure as the baseline. Conventionally, impedance analyzers/ LCR meters, are employed in the EMI technique. However, their unaffordable cost (typically \$20,000 to \$40, 000) tends to restrict its widespread industrial application. This paper presents a new low-cost variant of the electro-mechanical impedance (EMI) technique, suitable for industrial users, making use of a combination of function generator and mixed signal oscilloscope, commonly available in most laboratories. Application of the proposed technique is successfully demonstrated to detect the initiation and progression of damage on a structural component.

THEORETICAL BACKGROUND

For a square PZT patch of length 2*l* surface-bonded to any structure, such as the one shown in Fig. 1, the complex electro-mechanical admittance can be expressed as[7, 8]

$$\overline{Y} = G + Bj = 4\omega \; j\frac{l^2}{h}\left[\overline{\varepsilon_{33}^T} - \frac{2d_{31}^2\overline{Y^E}}{(1-\nu)} + \frac{2d_{31}^2\overline{Y^E}}{(1-\nu)}\left(\frac{Z_{a,eff}}{Z_{s,eff} + Z_{a,eff}}\right)\overline{T}\right] \qquad (1)$$

where d_{31} is the piezoelectric strain coefficient, $\overline{Y^E} = Y^E(1+\eta j)$ the complex Young's modulus of the PZT patch at constant electric field and $\overline{\varepsilon_{33}^T} = \varepsilon_{33}^T(1-\delta j)$ the complex electric permittivity of the PZT material at constant stress, with η and δ respectively denoting the mechanical loss factor and the dielectric loss factor of the PZT patch. Further, ω is the angular frequency, υ the Poisson's ratio and h the thickness of the patch. $Z_{s,eff}$

denotes the effective drive point (EDP) mechanical impedance of the host structure, which takes into account the 2D mechanical interaction between the PZT patch and the structure at the boundary. It is defined as the ratio of the overall harmonic planar force applied on the host-structure along the proposed boundary of the patch (i.e effective force) to the resulting 'effective displacement'. Referring to Fig. 1,

$$Z_{s,eff} = \frac{\oint_S \vec{f}.\hat{n}\,ds}{\dot{u}_{eff}} = \frac{F}{\dot{u}_{eff}} \tag{2}$$

where $\hat{n}$ is a unit vector normal to the boundary and F represents the overall planar force (or effective force) causing area deformation of the structure. $u_{eff} = \delta A/p_o$ is the 'effective displacement', where δA is the change in the surface area of the region considered and p_o its perimeter in the undeformed condition. Differentiation of the effective displacement with respect to time yields the effective velocity, $\dot{u}_{eff}$. Similarly, Z_a denotes the effective mechanical impedance of the PZT patch (in short-circuited condition), which was derived by Bhalla and Soh[7]

$$Z_{a,eff} = \frac{2h\overline{Y^E}}{j\omega(1-\nu)\overline{T}} \tag{3}$$

In Eqs. (1) and (3), the term $\overline{T}$ is the complex tangent ratio, ideally equal to $[\tan(\kappa l)/\kappa l]$. However, in the actual situations, it needs correction to accommodate the deviation of the PZT patch from the ideal behaviour. It has shown to be given by[8]

$$\overline{T} = \begin{cases} \dfrac{\tan(C\kappa l)}{C\kappa l} & \text{for single-peak behaviour.} \\[2ex] \dfrac{1}{2}\left(\dfrac{\tan C_1\kappa l}{C_1\kappa l} + \dfrac{\tan C_2\kappa l}{C_2\kappa l}\right) & \text{for twin-peak behaviour.} \end{cases} \tag{4}$$

The constants C_1 and C_2 (or C), and whether the patch conforms to 'single-peak' or 'twin-peak' behaviour, can be determined from the free PZT signatures, before bonding the patch to the host structure[7]. It is clear from Eq. (1) that any change in the EDP impedance of the structure resulting from any damage will alter the resulting admittance signature. This is utilized as the main damage indicator in the EMI technique. Owing to the high frequency of excitations (30-400 kHz range), the damage sensitivity of the EMI technique is far higher than the conventional NDE techniques.

COST-EFFECTIVE HARDWARE SYSTEM FOR EMI TECHNIQUE

Conventionally, the EMI technique employs impedance analyzer or LCR meter, which typically cost in the range of \$20, 000 to \$40, 000. Peairs *et al*[9] proposed a low cost electrical admittance measurement technique based on FFT analyzer, which typically costs \$10, 000, in place of the impedance analyzer. Fig. 2 shows the electrical circuit employed by Peairs and co-workers. It essentially consisted of a small resistance (10-20Ω), connected in series with the PZT patch in-turn bonded to the structure to be monitored. Upon applying an input voltage V_i across the combination through the FFT analyzer, the electric current I through the circuit is given by

$$I = \frac{V_o}{R} \tag{5}$$

where V_o is the output voltage across a sensing resistor R, fed into the measurement channel of the FFT analyzer. Taking into consideration the fact that the electrical impedance of the PZT patch is infinitely large as compared to the resistance R, the coupled electro-mechanical admittance A of the bonded patch can be expressed as

$$A \approx \frac{I}{V_i} = \frac{V_o}{RV_i} \tag{6}$$

This measurement approach was definitely cost-effective than the conventional impedance analyzer based approach. However, the measurement accuracy is not comparable to impedance analyzers, due to the fact that an impedance analyzer makes a truly stepwise measurement at each frequency of the prescribed range at user defined interval, under steady-state harmonic condition. Therefore, the FFT based technique has serious bandwidth restrictions and can be relied upon for up to 100 kHz only. Xu and Giurgiutiu[10] improved the technique by utilizing a pair of function generator and a DAQ card in place of FFT analyzer. They improved the measurement accuracy by utilizing a sweep signal in place of chirp. However, their technique still necessitated FFT of the response spectrum.

In this work, Peairs' technique has been improved and rendered more cost effective. Fig. 3 shows the circuit and the hardware details of the proposed measurement approach. A function generator, Agilent 33220A[11], was employed to generate the voltage signal V_i in place of the FFT analyzer. However, unlike previous approaches[9,10], it was made to produce pure tones of sine waves of gradually increasing frequencies. Agilent 54622D mixed signal oscilloscope was employed to measure the output voltage V_o at each excitation frequency. This also measured the phase lag of V_o with respect to V_i and hence resulted in complex admittance function, much like the measurement of impedance analyzer using Eq. (6). The frequency of the imposed signal was incrementally varied with each measurement conducted under steady-state harmonic conditions, much like the sweep mode available in impedance analyzers/ LCR meters. As a result, this not only ensures higher measurement accuracy, but also eliminates bandwidth restrictions as encountered by Peairs and co-workers[9]. The total cost of the two equipments is about $5000 only. Generally, oscilloscopes and function generators are available in most structural laboratories.

Fig. 4 shows an experimental set up to demonstrate the proposed technique for SHM of a structural steel component. A PZT patch was bonded to the surface of the pipe strut using RS 850-940 epoxy[12]. At any particular frequency, the sinusoidal input signal of 1V rms, generated by the function generator, was spilt into two parts using a T connector. One part was applied across the reference channel of the oscilloscope (to facilitate phase measurement) and the other across the circuit as V_i , as shown in Fig. 4. The resistance R used was 20 ohms. The output voltage V_o across the resistance was fed into the test channel of the oscilloscope for measurement. The process was repeated in the entire frequency range 80-100 kHz at 100 Hz intervals incrementally. The pipe was thereafter damaged by drilling 5mm holes. Damage 1 refers to one hole, damage 2 to two holes and damage 3 three holes. Hence, damage severity gradually increased from damage 1 to damage 3. Conductance signature was obtained for the undamaged and three damage cases. Fig. 5 shows the change in conductance signature resulting from three damages. The prominent effects of damage can be easily observed as the appearance of new peaks in the signature, and lateral and vertical shifts of the peaks. For non-parametric quantification, root mean square deviation (RMSD) was computed as

$$RMSD = \sqrt{\frac{\sum_{j=1}^{N}\left(G_j^1 - G_j^0\right)^2}{\sum_{j=1}^{N}\left(G_j^0\right)^2}} \qquad (5)$$

where G_j^1 is the post-damage conductance at the j^{th} frequency point and G_j^0 the corresponding pre-damage severity value. The RMSD histogram is shown in Fig. 6. It is evident from the chart that with increase the damage, the RMSD is increasing. Hence, the existence of component level damage as well increase of damage severity can be easily inferred, although in relative terms. The EMI signatures can be further calibrated for damage severity either using the method outlined by Bhalla and Soh[7, 8].

CONCLUSION

This paper has demonstrated a new low-cost variant of the EMI technique suitable for widespread industrial application. This technique makes use of a function generator and mixed signal oscilloscope, which are commonly available in structural laboratories, and is much more cost-effective as compared to the conventionally employed impedance analyzers/ LCR meters as well as the FFT analyzers. In comparison to FFT analyzer based approach, the frequency limitation is not there and at the same time, the accuracy is higher due to the measurement being made at each prescribed frequency. Hence, this can pave way for widespread industrial application of the EMI technique.

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LIST OF FIGURES

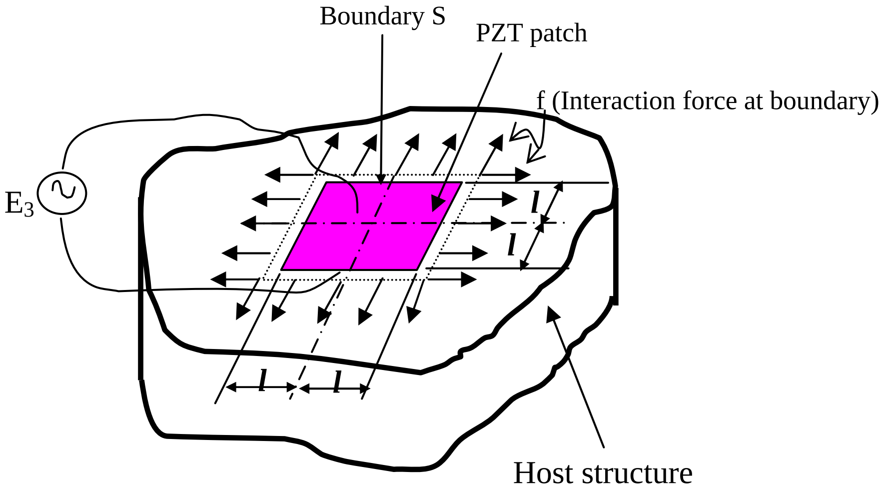


Fig. 1 A PZT patch bonded to a structure.

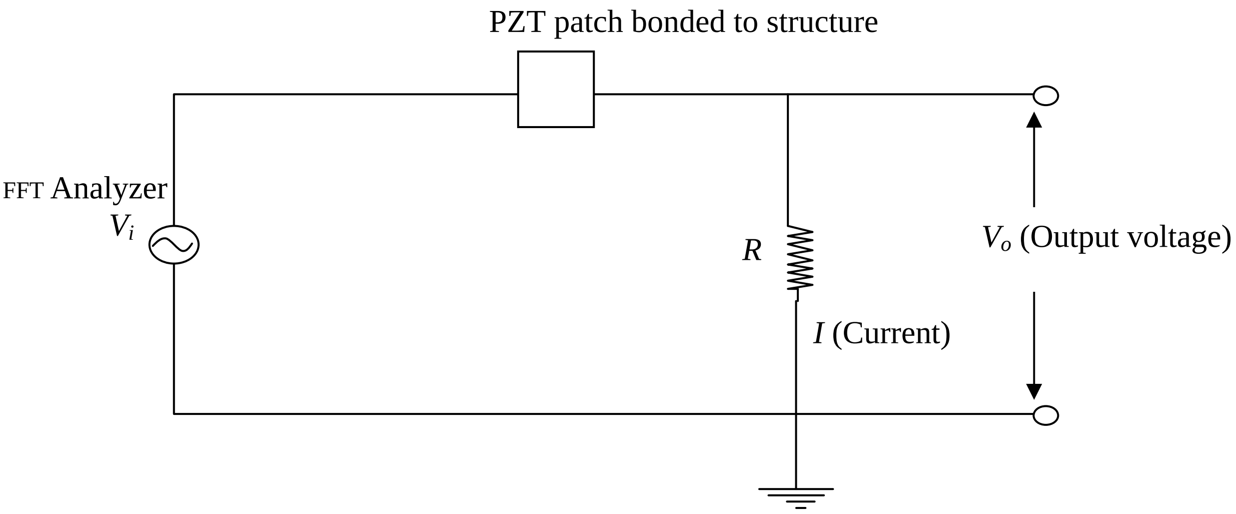


Fig. 2 Circuit for measuring PZT admittance employed by Peairs et al (2004)

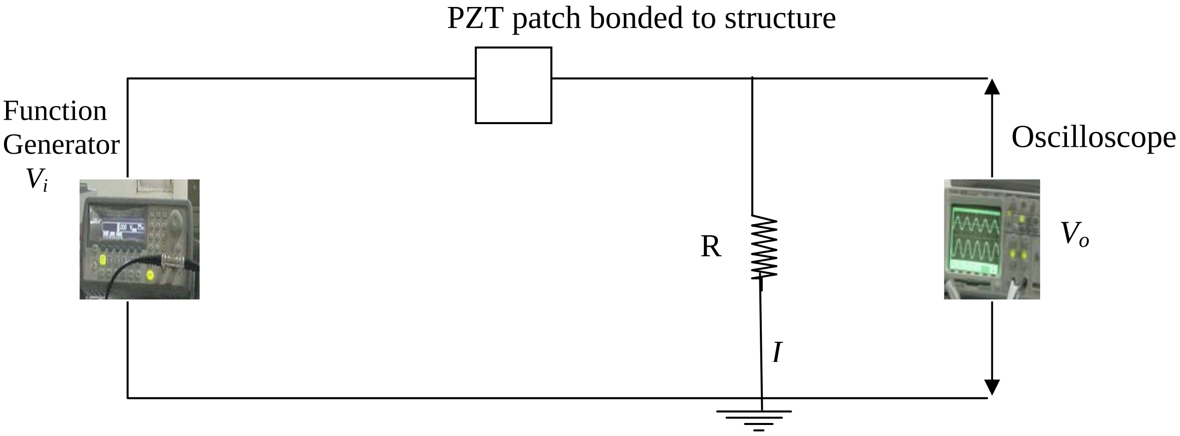


Fig. 3 Low-cost variant of the technique of Peairs et al (2004)

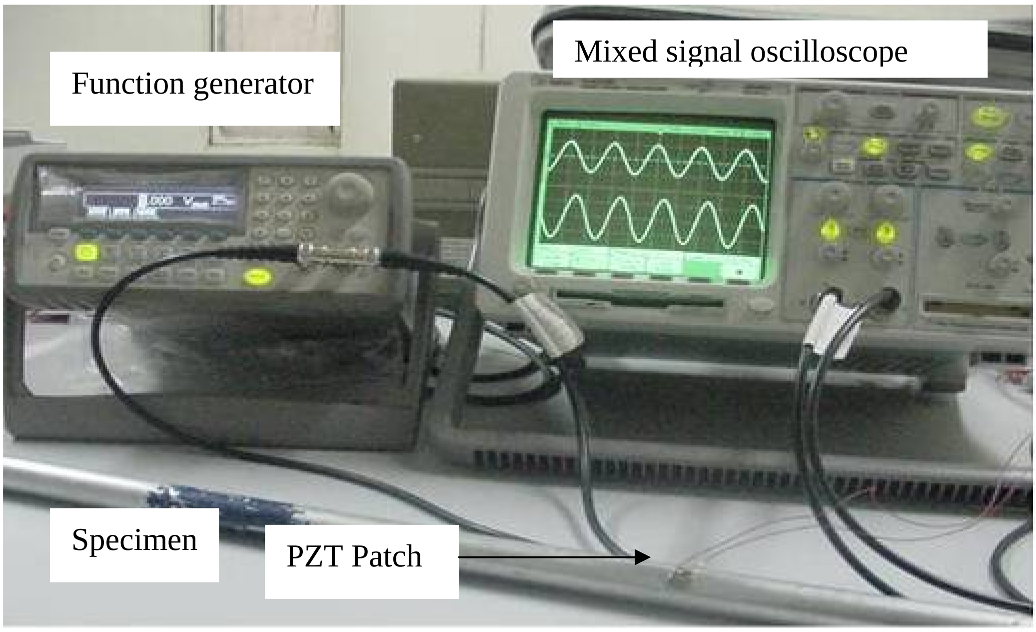
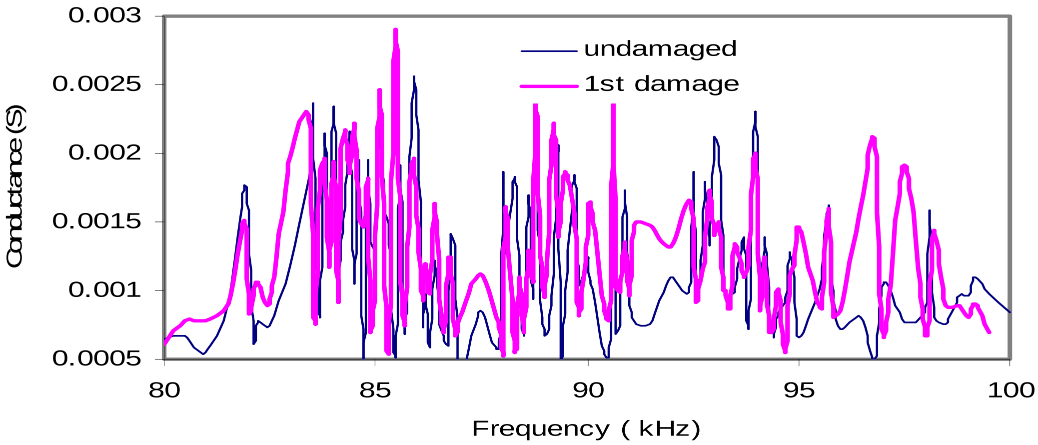
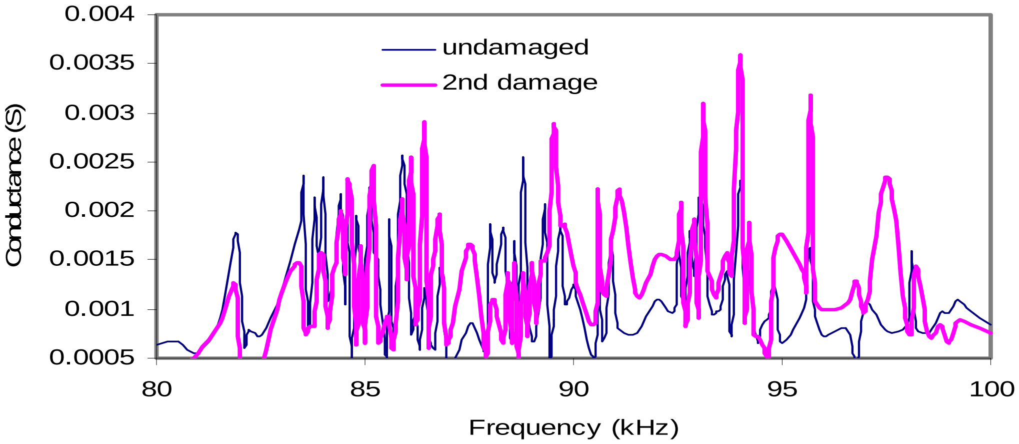


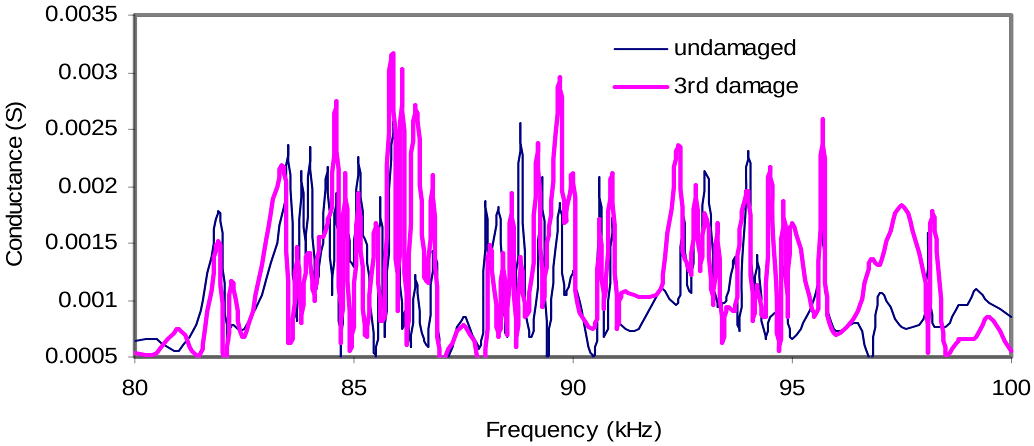
Fig. 4 Experimental set up for proposed technique.



(a)



(b)



(c)

Fig. 5 Changes in conductance signature with damage progression.
(a) Damage 1 (b) Damage 2 (c) Damage 3

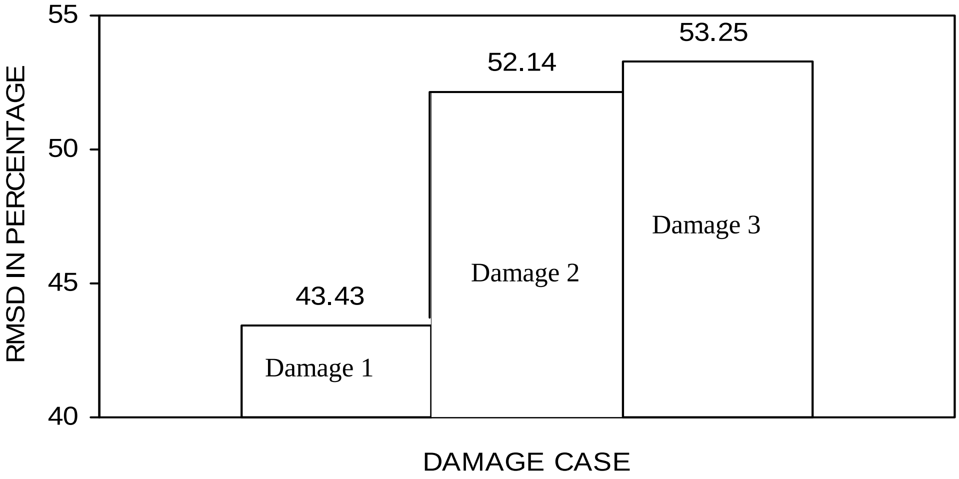


Fig. 6 Variation of RMSD with increasing damage severity.