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LETTERS TO THE EDITOR

MONITORING STRUCTURAL INTEGRITY USING A PIEZOELECTRIC INERTIAL ACTUATOR CUM SENSOR

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1. INTRODUCTION

The use of pseudo-mechanical impedance for monitoring conditions of civil structures or structural components in machinery has been already studied in non-destructive testing community for some time [1]. The measurement of pseudo-mechanical impedance in general requires three devices: a shaker, a force sensor, and an accelerometer. Due to the physical sizes of these transducers, ensuring the measurement of true driving-point mechanical impedance has posed a major difficulty in the use of mechanical impedance as a diagnosis signal [2, 3]. In addition, when it is applied to structures on site, the difficulties of installing and calibrating exciters and sensors also cause major inconvenience.

In 1996, as a part of the effort of using functional materials such as piezoelectric ceramics (PZT), Rogers and Liang studied the electro-mechanical coupling of piezoelectric materials and structures [4, 5]. In their work, PZT patches were bonded on or embedded into a structure and variation of the mechanical impedance of the structure under test is detected by measuring the electrical impedance of the PZT. A one-dimensional model governing the electro-mechanical coupling was developed. Although theoretically useful for structural health monitoring, their method is difficult to apply because of the need of bonding or embedding of piezoelectric material patches. In addition, calibration of the monitoring system is inherently impossible due to the constitution of the measurement system.

Around the same period, reports on inertia actuators employing PZT for making smart structures had appeared in the literature [6, 7]. Yet, impedance was not the focus of these studies. In 1999, the authors of this paper reported some properties of inertia actuators from the viewpoint of electro-mechanical impedance coupling [8, 9], but no discussion on monitoring application was mentioned.

In the present paper, we will demonstrate the use of a piezoelectric inertial actuator affixed to a structure as a collocated sensor cum actuator for monitoring structural integrity. When AC power is applied, the inertial actuator exerts a reaction force to the structure it attaches; concurrently the mechanical impedance of the structure affects the electrical input impedance of the inertial actuator as a result of the electromechanical interaction. In principle, a variation of the mechanical impedance of the structure due to integrity problems can be indirectly detected by measuring the electrical input impedance of the inertial actuator without any other sensors.

Since the present method eliminates the force and acceleration sensors for mechanical impedance measurement, concerns such as cross sensitivity of mechanical impedance head and true driving-point measurement do not exist anymore. Furthermore, as the inertial

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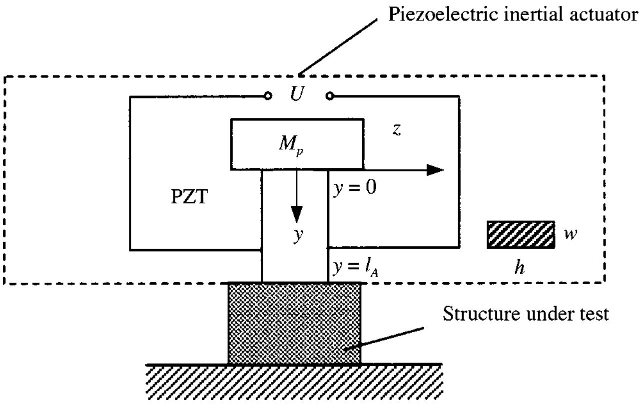

Figure 1. Interaction between a PIA and a structure.

actuator is a stand-alone device that operates without the need of a support, it can be conveniently mounted on or dismounted from any surface structure using magnetic force, for example. In short, measurement of the electrical input impedance of an inertial actuator mounted on a structure may provide a neat and convenient method for monitoring structural integrity on site.

2. WORKING PRINCIPLE

Figure 1 illustrates the interaction of a piezoelectric inertial actuator (PIA) and a structure. A piezoelectric plate, being excited by an AC power, accelerates the reaction mass M_p at one end $y = 0$, which exerts a reaction force to the structure under test at the other end $y = l_A$. The proof-mass, the piezoelectric plate, and other necessary frame structures enclosed in the dashed line constitute a PIA.

The admittance of the PIA is coupled with the mechanical impedance of the structure at the excitation point, Z. Assuming that the piezoelectric element has only d_{32} effect, i.e., the induced strain is only in the 2–2 (y) direction when voltage V is applied in the 3–3 (z) direction, the admittance Y at frequency ω can be derived as follows:

$$Y = I/V = \mathrm{i}\omega \frac{w_A l_A}{h_A}\left[\bar{\varepsilon}^{\mathrm{T}}_{33} - d^2_{32}\, \bar{Y}^E_{22}\left(1 - \frac{Z_A(M_p\omega - \mathrm{i}Z)}{M_p\omega(Z + Z_A)}\frac{\tan(kl_A)}{kl_A}\right)\right], \tag{1}$$

where l_A, w_A, h_A is the length, width, and thickness of the piezoelectric plate, respectively, $\varepsilon^{\mathrm{T}}_{33}$ the dielectric constant of the piezoelectric plate in the 3–3 (z) direction under a constant stress, d_{32} the piezoelectric constant, $Y^E_{22} = \bar{Y}^E_{22}\,(1 + \mathrm{i}\eta)$ the complex elastic modulus of the piezoelectric plate in the 2–2 direction under a constant electrical field and η the mechanical loss factor of the piezoelectric plate, $k = \omega\sqrt{\rho/Y^E_{22}}$ the wave number in y direction,

$$Z_A = \frac{1}{\mathrm{i}\omega}\frac{kw_A h_A M_p \omega^2 \cos(kl_A)}{s^E_{22} M_p \omega^2 \sin(kl_A) - kw_A h_A}$$

the short-circuited mechanical impedance of the PIA. The force exerted on the structure can also be derived as

$$F = -\,M_p\omega^2 B\mathrm{e}^{\mathrm{j}\omega t} = -\,\mathrm{i}\omega d_{32}\frac{l_A}{h_A}\frac{ZZ_A}{Z + Z_A}\frac{\tan(kl_A)}{kl_A}V. \tag{2}$$

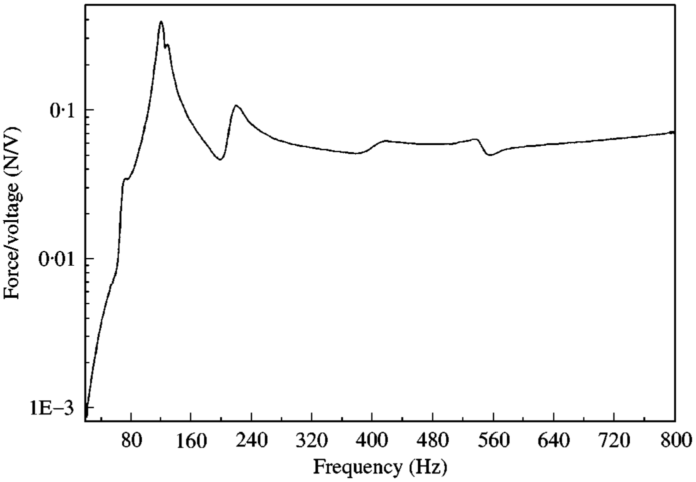

Figure 2. Force output of PIA when clamped on a grounded base.

For the interested frequencies, $kl_A \to 0$ or $\tan(kl_A)/kl_A \to 1$, the above equations can be simplified to

$$Y = I/V = \mathrm{i}\omega \frac{w_A l_A}{h_A}\left[\bar{\varepsilon}^{\mathrm{T}}_{33} - d^2_{32}\bar{Y}^E_{22}\frac{\mathrm{i}ZM_p\omega^2}{M_p\omega K_A + \mathrm{i}Z(M_p\omega^2 - K_A)}\right], \tag{3}$$

$$F = -\,M_p\omega^2 B\mathrm{e}^{\mathrm{j}\omega t} = -\,\mathrm{i}\omega d_{32}\frac{l_A}{h_A}\frac{ZZ_A}{Z + Z_A}V, \tag{4}$$

where $K_A = \bar{Y}^E_{22}\, w_A h_A / l_A$.

From equation (1)–(4), it can be observed that, when affixed to a flexible structure, the input electrical impedance of a PIA is affected by the mechanical impedance of the structure under test.

3. EXPERIMENTAL STUDIES

We first characterized the built PIA. Figure 2 gives the force output of the PIA clamped on a grounded base. Obviously, it is of second order high-pass characteristics with the natural frequency at 122 Hz.

As shown in Figure 3, a clamped–clamped beam was then used as a test structure to demonstrate the validity of the present method. The dimensions of the beam are 700 mm in length, 100 mm in width and 10 mm in thickness. It is made of aluminium and weighs 1·89 kg. The PIA of 200 g weight is affixed at 200 mm to the left end, a mechanical impedance head is inserted between the PIA and the beam under test. Additional masses (15·24 and 32·45 g resp.) are attached at 200 mm to the right end of the beam.

The variations of applied force, acceleration response and accelerance corresponding to different attached mass are compared in Figures 4–6. Accelerance, instead of impedance is used in this validation experiment because of the convenience of comparison. Accelerance is defined as acceleration over force [2], it can be converted to impedance through appropriate processing via analog or digital means.

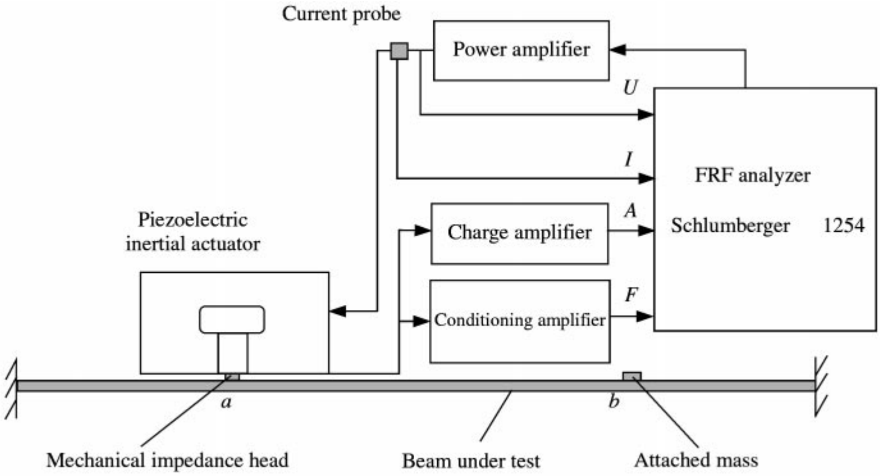

Figure 3. Beam with both ends clamped under test.

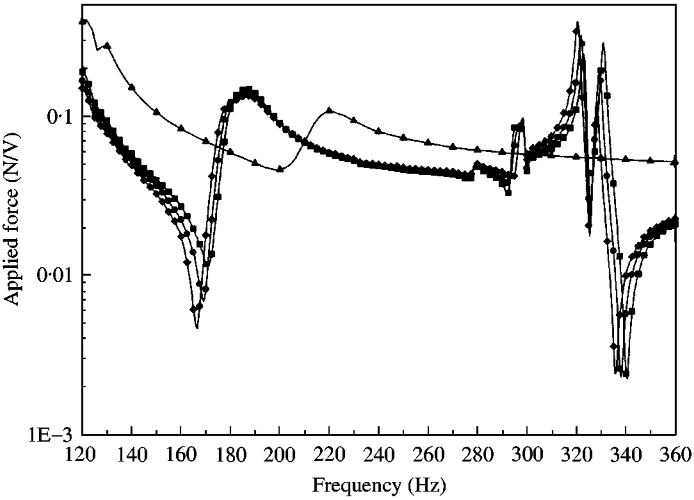

Figure 4. Comparison of force output of the PIA: —▲—, force output of PIA when grounded; —■—, without additional mass attached on; —●—, with 15·24 g additional mass attached on; —◆—, with 32·45 g additional mass attached on.

It can be seen from the experimental results that both the force output of PIA and the acceleration response of the beam vary when the accelerance of the structure changes due to different attached mass. Since accelerance is a characteristic of structures which is independent of the force applied, observing the outstanding variations near the natural frequencies can clearly indicate the changes of structural properties due to the addition of small masses. Similarly, if the structure integrity is changed due to cracks, the accelerance will alter due to the stiffness changes of the structure.

For the same test, the electrical input impedance of the PIA corresponding to the cases without and with additional masses are measured and shown in Figure 7.

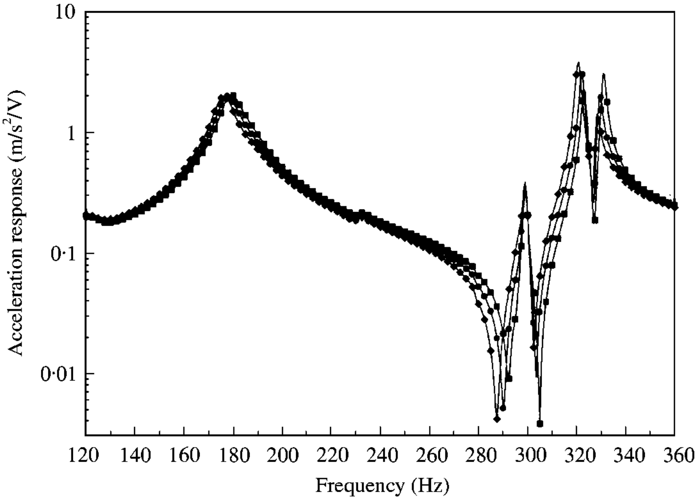

Figure 5. Comparison of acceleration response of the beam: —■—, without additional mass attached on; —●—, with 15·24 g additional mass attached on; —◆—, with 32·45 g additional mass attached on.

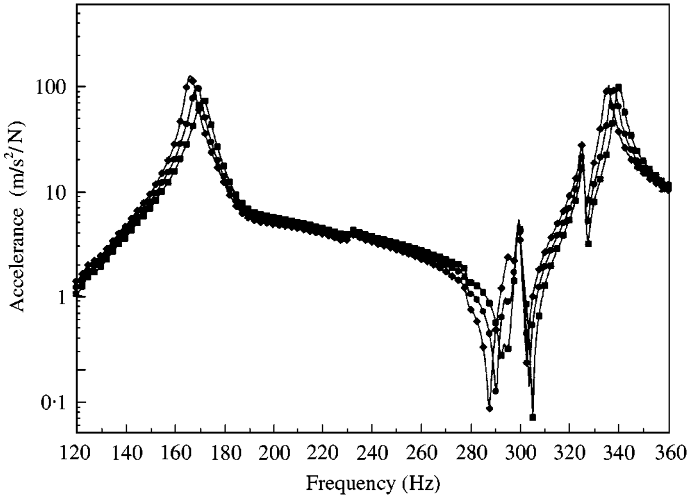

Figure 6. Comparison of accelerance of the beam: —■—, without additional mass attached on; —●—, with 15·24 g additional mass attached on; —◆—, with 32·45 g additional mass attached on.

It can be seen from the experimental results that the electrical input impedance of the PIA directly reflects the accelerance of the structure. This confirms the theoretical relationship derived earlier in this paper. The variations of the input electrical impedance are distinguishing and clear when the conditions of the beam vary, which can be due to changes of mass or stiffness. Considering the fact that the weights of the added mass are very small compared with the weight of the beam, the sensitivity of the input electrical impedance of the PIA are quite good and suitable for monitoring, especially at resonance frequencies.

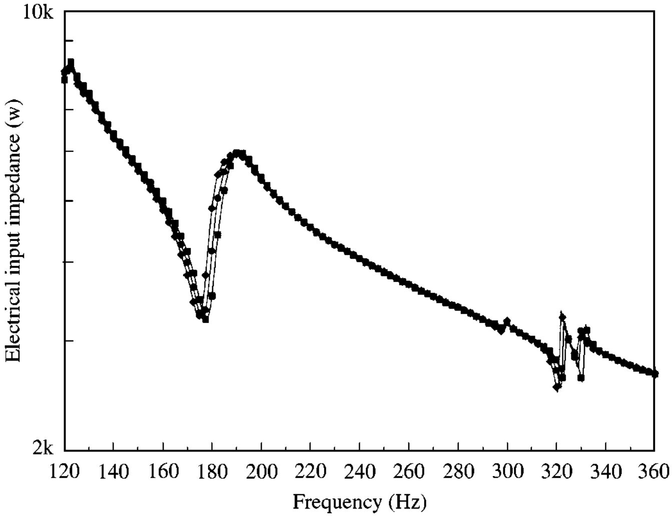

Figure 7. Variations of electrical input impedance of PIA corresponding to the three conditions: —■—, without additional mass attached on; —●—, with 15·24 g additional mass attached on; —◆—, with 32·45 g additional mass attached on.

4. CONCLUDING REMARKS

It is well understood [3, 5] that the mechanical impedance of a structure reflects the properties of the structure and is independent of the loading from its environment. Variations of the mechanical impedance directly indicates changes of structural properties, such as stiffness changes due to cracking, mass changes due to wearing, or changes of boundary conditions due to malfunctions of a coupling machine element. As revealed above, the electrical input impedance of a PIA attached to a structure is a sensitive function of the mechanical impedance of the structure at the attaching point. Therefore, any change of structural conditions due to problems of structural integrity, changes of supporting conditions, etc., can be detected by comparing the records of input electrical impedance of a PIA attached to a structure.

There are a few major advantages when the present technique is employed for monitoring health conditions of structures on site. Firstly, the method does not require conventional load and motion sensors for monitoring. The method is technically sensor-less as the measurement of electrical impedance requires voltage and current detection but requires no transducer. Secondly, the present method can be implemented via a self-contained, integrated device, namely an inertia actuator with a piezoelectric patch or an electro-magneto coil as the driving component. The device can be conveniently attached to a structure on site indoor or outdoor through glue bonding or magnetic attraction and thus avoids the major inconvenience of mounting and dismounting actuators and sensors required in conventional modal testing methods when used for health monitoring. Thirdly, although only qualitatively reflecting the relative changes of mechanical impedance of a structure, the present method does pick up the pseudo-mechanical impedance at a single point and avoids the coupling effects between the force and motion sensors mounted together on the structure. This problem can be significant as discussed by Ewins [2].

Since each resonance appearing in a mechanical impedance spectrum is associated with a particular modal shape, it is possible to diagnose structural problems by investigating in detail the changes of the electrical impedance of the PIA. Work along this line is in progress [8].

REFERENCES

1. P. Cawley 1987 *NDT International* **20**, 209–215. The sensitivity of the mechanical impedance method of non-destructive testing.
2. D. J. Ewins 1984 *Modal Testing: Theory and Practice*. England: Research Studies Press.
3. M. L. David and L. B. David 1997 *Proceedings of the 15th International Modal Analysis Conference, Orlando, FL*, 1210–1215. Improved driving point measurements with a coincident mechanical impedance head.
4. C. Liang, F. P. Sun and C. A. Rogers 1996 *Smart Materials and Structures* **5**, 171–186. Electro-mechanical impedance modeling of active material systems.
5. S. W. Zhou, C. Liang and C. A. Rogers 1996 *Journal of Vibration and Acoustics—Transactions of the American Society of Mechanical Engineers* **118**, 323–331. Impedance-based system modeling approach for induced strain actuator-driven structures.
6. J. Dosch, G. A. Lesieutre, G. H. Koopmann and C. L. Davis 1995 *Proceedings of the Smart Structures and Material Conference, San Diego, CA*, Vol. SPIE-2447, 14–25. Inertial piezoceramic actuators for smart structures.
7. Guran 1998 *Structronic Systems: Smart Structures, Devices and Systems*, Vol. 4. Series on Stability, Vibration, and Control of Systems. Singapore, River Edge, NJ: World Scientific.
8. S. F. Ling and Y. Xie 2000 *Proceedings of the 18th International Modal Analysis Conference, San Antonio, TX, U.S.A.*, 1901–1905. Mechanical impedance detection utilizing sensing capability of piezoceramic inertial actuator.
9. Y. Xie and S. F. Ling 1999 *Proceedings of the Asia-Pacific Vibration Conference, Singapore*, 129–133. Study on tuning mechanical impedance of inertial actuator with passive shunt circuits.