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Non-Destructive Evaluation of Multi-Layer Actuators

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This paper describes the use of impedance spectroscopy as a means of non-destructively detecting delaminations and damage in piezoelectric multi-layer actuators. The method is based on a test developed to examine multi-layer capacitor devices. Impedance spectra are reported on conventional multi-layer actuators and multi-layers that contain delaminations or have been subjected to damage. The defects within the devices are characterised by ultrasonic evaluation and microscopy. Impedance analysis reveals that the resonance behaviour of the actuator is altered by the presence of defects. By examining impedance data using a complex impedance plot the change in resonance behaviour of a multi-layer actuator due to defects can be observed. The method could be employed as a means of quality control during production or for monitoring the state of the actuator whilst in service, e.g. whether there has been fatigue of the device or it has be subjected to an unacceptably high stress.

Keywords: actuator; impedance; multi-layer; piezoelectric; non-destructive evaluation; resonance; delamination

INTRODUCTION

Multi-layer actuators (MLAs) are used to provide large displacements compared to monolithic materials, at low drive voltage (50-200V) and low power consumption. However, due to the composite structure of these devices and the electrode configuration, MLAs can suffer from fatigue and degradation of performance as a function of time [1-4]. It has been reported that fatigue of MLAs is due to the development of internal stresses around the inactive and active regions of the piezoelectric material at the electrode edges [5,6]. In addition to fatigue, a concern of MLA manufacturers is delamination of the electrode layers during processing which can act as nuclei for crack propagation. Mechanisms of delamination during processing are binder burnout, green state delamination due to inadequate adhesion of the electrode and piezoelectric layer, catalytic reactions of electrode metals with organic additives during burnout and sintering shrinkage mismatch [7]. Therefore, there is a need to detect defects during production *and* to detect the development of fatigue damage during service (self-validation) in a simple and rapid manner.

Non-destructive testing methods to assess the reliability of MLAs have included direct measurement of insulation resistance (IR), induced displacement and acoustic emission which have been used with some success to monitor damage and degradation of MLAs [1,3]. The most promising technique is frequency response analysis, or impedance spectroscopy (IS), which examines the change in resonance characteristic as the degree of damage increases in the device [8-11]. The aim of this paper is to examine the change in resonance behaviour of typical MLAs due to the presence of delaminations and/or cracks introduced into the device. The ability of IS to detect delaminations and damage will be verified by Cscan ultrasonic imaging, which is widely used to detect delaminations in structural composites. Finally, there will be direct observations of defects using optical and scanning electron microscopy of sectioned devices. In addition to examining processing induced defects, damage will also be deliberately introduced into the devices. Various methods used to present impedance data such as 'Bode' diagrams or 'complex plane' (Nyquist plot) will be examined to determine which is most applicable in examining any change in resonance characteristics of an MLA due to damage.

EXPERIMENTAL

Multi-layer actuators were supplied by Morgan Matroc Unilator Division, a commercial supplier of piezoelectric materials and actuators, who deliberately supplied and fabricated a range of multi layer actuators for this research. The MLAs had a cross section of 10mm x 10mm and a thickness of 2mm, consisting of 30 electrodes with an electrode spacing of approximately 85μm through the thickness. The actuators were fabricated from PZT-5H, a soft piezoelectric material.

Impedance spectroscopy was undertaken using a Solatron 1260 Frequency Response Analyser and 1296 Dielectric Interface. A small sinusoidal AC signal of 0.1V was applied to the device in a frequency range above and below the resonant frequency of the device. The resonant frequency was determined from a calculation based on the dimensions of the actuator (assuming width resonance) and an initial frequency sweep. The resonance frequency was typically 185kHz for the samples of the dimension and material used in this study.

Ultrasonic Cscan imaging was carried out in a water bath containing focussed 5MHz transducers and receivers. The ultrasound was passed through the cross section of the actuator, i.e. applied to the 10mm x 10mm surface, as delaminations often occur along the electrodes. An x-y stepper motor and data acquisition software were used to measure signal attenuation and sample position. Defects were deliberately introduced into the actuators using a Vickers indentation testing machine at a range of applied loads.

Destructive sectioning and final device inspection was undertaken using a diamond cutting wheel, polishing to 1μm with diamond paste and subsequent examination using optical microscopy and Scanning Electron Microscopy (SEM) using a JEOL T330.

RESULTS

Figure 1a is a graph of the modulus of impedance, |Z|. of two MLAs as a function of frequency. The parallel resonance frequency, where the impedance is at a maximum, is located at 185kHz, which is similar to values based on the equation $f = 1/2t\sqrt{\rho . s_{11}^{E}}$ for width resonance, where f is frequency, ρ is density (7500 kg m^{-3}), t is actuator width (10mm) and s^{E}_{11} is compliance (16 x 10^{-12} Pa^{-1}). It can be seen that there is a large difference in the impedance as a function of frequency for the two actuators tested. One actuator has a severely damped resonance spectrum and a correspondingly low modulus of impedance at parallel resonance, compared to the other actuator. This is also indicated by the values of the mechanical quality factor Q_m, which are shown in Figure 1a. Based on the assumption that defects will damp the resonance of the actuator, the damped actuator with low maximum modulus of impedance and Q_m will now be labelled 'delaminated' while the actuator with sharp resonance will be labelled 'good'. The resonance behaviour is also observed in the measurement of phase angle (θ) as a function of frequency (Figure 1b).

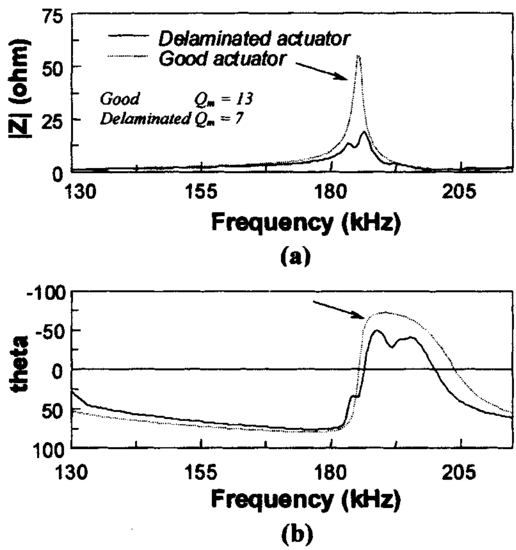


FIGURE 1 Modulus of impedance, |Z| (a) and phase angle, θ (b) as a function of frequency for a 'good' and 'delaminated' MLA. The 'good' actuator is indicated by the arrow.

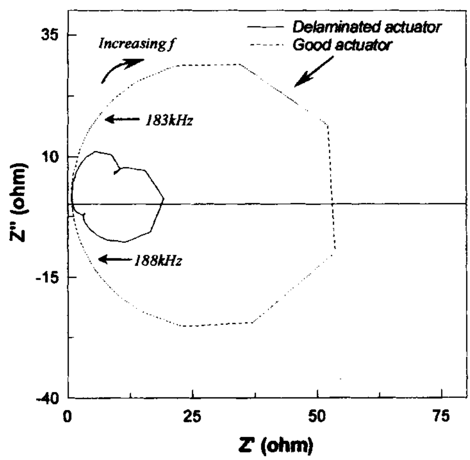


FIGURE 2 Nyquist plot of a 'good' and 'delaminated' actuator. The 'good' actuator is indicated by the arrow.

The difference between the phase angle for the 'good' and 'delaminated' actuator is, however, small in comparison to modulus of impedance-frequency behaviour in Figure 1a.

The differences observed in $|Z|$ and θ can be combined by constructing a complex impedance plot (Nyquist) of Z' versus Z'', where $Z'=|Z|\cos\theta$, the real part of the impedance and $Z''=|Z|\sin\theta$, the imaginary part of the impedance. A Nyquist plot is shown in Figure 2 in which a complete circle is observed as the device passes through resonance frequency. The intercept of the circle with the Z' axis is equivalent to the maximum in impedance of the Bode diagram. Therefore, delaminated and damped multi-layers exhibit smaller diameter complex impedance plots, as can clearly be seen in Figure 2. The advantage of the complex method of presentation is that small changes in resonance characteristics are readily observed and detected compared to the Bode presentation.

To validate that IS was accurately detecting defects in MLAs, the actuators were also examined by ultrasonic Cscan and microscopy. Figure 3 shows Cscan images of the two actuators. The 'good' actuator (as determined by IS) in Figure 3a shows the greatest attenuation of ultrasound and exhibits a clear uniform Cscan image. The 'delaminated' actuator, shown in Figure 3b, has less attenuation and a non-uniform Cscan image, which is indicative of the presence of defects or delamination. The results are therefore in agreement with the IS measurements. It should be noted that a number of samples were analysed by IS and Cscan with good agreement and the results are to be reported elsewhere [12].

The nature of the defects in the actuators was finally determined by sectioning the MLAs and examining microscopically. Figure 4a is an SEM image of the MLA with the damped resonance and the non uniform Cscan. Delaminations can be clearly observed. The 'good' actuator (Figure 4b) with a sharp resonance and uniform, high attenuation has no observable defects. These observations imply that impedance spectroscopy is a possible technique of rapidly electrically detecting the presence of defects in multi-layer actuators.

To provide additional evidence that defects can change the impedance response of a multi-layer actuator, damage was deliberately and systematically introduced into an MLA and the subsequent change in resonance monitored. Figure 5 shows the change in Nyquist plot of a MLA as Vickers indents are introduced into the device. The diameter of the complex impedance plot is reduced, and therefore the degree of damping increases, as damage is systematically introduced into the device.

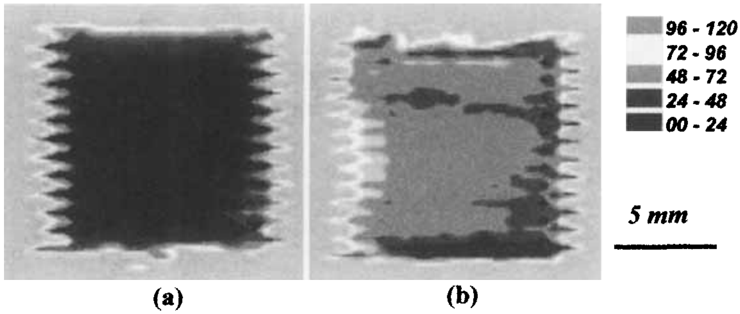


Figure 3. Cscan images of (a) 'good' and (b) 'delaminated' actuators. The legend indicates signal strength. The impedance data of the actuators are shown in Figures 1 and 2.

See Color Plate III at the back of this issue.

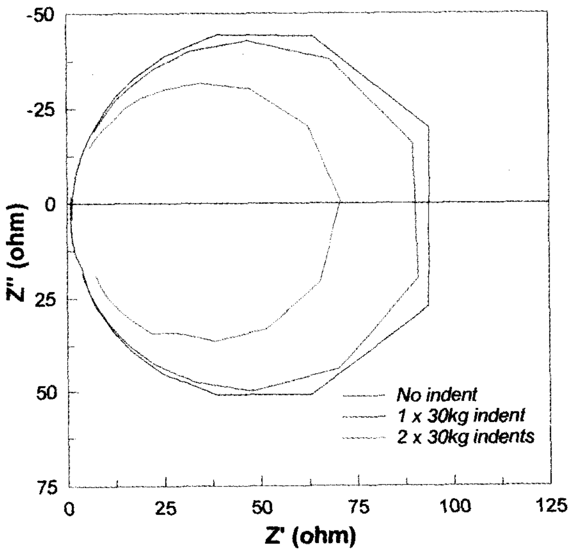
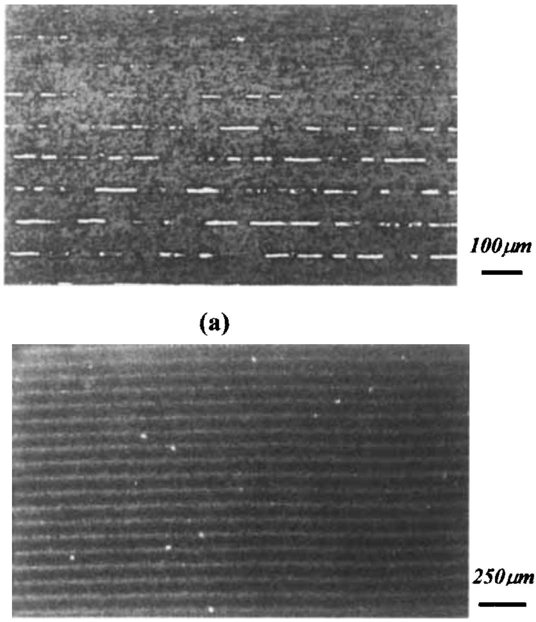


Figure 5. Nyquist plots with indentation defects introduced into an MLA. Diameter and intercept with Z' axis decreases as damage increases. Frequency range 150kHz - 210kHz.

See Color Plate IV at the back of this issue.



(b)

FIGURE 4 SEM images of (a) delaminated and (b) good actuators.

CONCLUSIONS

Impedance spectroscopy has shown to be a valuable technique in non-destructive determination of the presence of defects and delaminations in multi-layer actuators. The test has been used to detect defects induced by processing (such as delaminations) and deliberately induced defects (by indentation). Ultrasonic Cscan imaging, sectioning and microscopic examination have verified the predictions made by impedance spectroscopy.

Impedance spectroscopy detects damage by using the damping nature of the defect and the resultant change in the resonance behaviour of the MLA. The examination of impedance-frequency data in the form of a Nyquist plot has shown to be the most useful in rapidly determining small changes in resonant behaviour.

If the resonance frequency of the MLA is known, the impedance spectrum and the 'health' of the actuator can be determined in measurement times much shorter than imaging methods such as the Cscan. Rapid test times are of importance when the actuators are produced in large quantities. The test could be developed to detect delaminations and other defects during production and/or the monitoring of fatigue during in-service operation. The technique is more suited for in-service monitoring (self-validation) compared to techniques, such as acoustic emission [3], as the electrical connections and circuits are already present to drive the actuators (provided that resonance is not prevented by any clamping of the MLA). Further work will evaluate the sensitivity of the technique and the types of defect detectable by impedance spectroscopy.

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