Statistical Analysis of Angular/ Linear Directional Damages using Impedance based Structural Health Monitoring

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ABSTRACT: Structural health monitoring (SHM) refers to a damage detection and characterization strategy. Here damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity that adversely affects the performance. Traditionally there are many SHM techniques such as visual inspection, static load response, low frequency dynamic load response etc., which are often time consuming, unreliable and expensive. However newer smart material based SHM techniques such as fibre optical, wave propagation and electro mechanical impedance (EMI) started replacing traditional methods in the past few decades. These smart SHM techniques are less cumbersome, automated and economical. However these smart SHM techniques are in the process of evolution. This paper presents EMI based smart technique which is still not completely evolved, especially its output signatures were not fully understood. This EMI technique employs c, which are surface bonded on the host structure and are excited to produce output structural responses know as admittance signatures. These responses form the basis of interpretation of PZT-structure interaction. The output signatures of many similar damages on one structure may resemble another structure with a single damage. Thus statistical indices such as root means square deviation (RMSD) index is required to comment on final output signatures. This paper presents the quantitative RMSD evaluation of such output signatures obtained from various damages incurred on an aluminium plate in linear and angular directions

1 INTRODUCTION

Structural health monitoring (SHM) is a process to assess, characterize and estimate damages in engineering structure. It can detect the existing damage by identification, location, quantification, and predict the result to prevent economical and human loss (Annamdas 2007, Chakraborty et al, 2015). In the industry, SHM can be used to detect significant structural integrity problems to ensure the safety and reliability of the structure. In the last few decades, the applications of SHM gained more and more attention in engineering structural and construction industry. SHM using electro-mechanical impedance (EMI) method has gained extensive attention in academia in the last couple of decades with the advantage of real time health detection, remote monitoring, high durability etc. (Annamdas and Soh 2010, Annamdas 2012, Annamdas et al 2014).It aims to collect quantified results from the structure for further analysis. Piezoelectric transducers (PZTs) are normally used in EMI method. In this method, electric field is applied across the PZT to facilitate vibrations that results in a health signature.

Any changes in the health signature indicate problem or crack in the structure under investigation. However still lot need to be done before using in actual practise (Annamdas et al 2007, Annamdas and Yang 2012). This study is one development in the processes of taking it into real applications. The main aim of this work is to test how the output signatures changes for damage appearance in angular and angular-linear direction on a 2D plate, that involves signature comparisons and root-means-square deviation (RMSD) analysis.

2 LITERATURE REVIEW

2.1 PZT based Structural health monitoring

SHM aims to diagnose the condition of the structure to assess the health of engineering structures. Damage refers to any changes of a structural system including geometric changes, boundary condition changes etc. It can evaluate different components of the structure at different time to conclude the health situation of the whole structure. It can also help to predict extent of damage and structural remaining life. Modern SHM methods usually use sensors which are mostly made of smart materials that are either automatically or semi automatically transmit data to the computer for further computation, where quantified statistical methods are used (Balageaset al, 2006). After analysis, the structures cane be repaired or retrofitted according to the result. Two strategies are mainly applied in the previous research on PZT based SHM techniques. In the first strategy, PZTs were used in the wave propagation method which is far-field damage detection and the next is in EMI method which is a near-field damage detection method (Hu et al, 2007, Madhav and Soh 2007). EMI method got more attention in the recent past as it can provide real time results without affecting the structure (Annamdas and Annamdas 2009, Annamdas and Yang 2012, Annamdas et al, 2014).

2.2 Piezoelectric transducers

PZT is an active smart material which has a special property to characterize an input by changing its own properties. These inputs are external stimuli by electric field, temperature or force that results in the output signatures that shows changes to fluctuations in structural or PZT stiffness or impedances (Sun et al, 1995). Signatures are modified significantly with the change in mass, stiffness and damping of structure or the applied electric field. PZT is able to pass the vibrations/actuations to the structure as well as collect back the data (information) from the structure at the same time as signatures (Sun et al, 1995, Annamdas and Annamdas 2009).

The signature in basically the electromechanical admittance (Y) which is composed of two parts (Annamdas and Rizzo 2009). One it the real part called as conductance (G) and the other is the imaginary part called as susceptance (B). The relationship is as shown in the equation

$$Y = G + jB \tag{1}$$

The conductance and susceptance can be determined using electromechanical analyser, that supplies electric field to the PZT which is either surface bonded or embedded in the structure. These signatures are the qualitative indicators of the structure’s health.

2.3 Root means square deviation (RMSD)

To assess the signature obtained from the testing, quantitative analysis should be further carried out by statistical methods based on comparison between healthy and damaged state signatures for the same frequency, which is as RMSD index.

$$RMSD(\%) = \sqrt{\frac{\sum_{i=1}^{N}(G_i^1 - G_i^0)^2}{\sum_{i=1}^{N}(G_i^0)^2}} \times 100 \qquad (2)$$

Where G_i^0 is PZT's conductance in the healthy state of the structure, and G_i^1 is the corresponding conductance in the later stages during monitoring period.

RMSD index can be computed in various frequency bandwidths to get the superior qualitative and quantitative result. The same equation 2 can be used for susceptance by changing the *G* to *B*. Larger RMSD index indicates increased damage severity in the structure (Yang et al, 2008).

3 EXPERIMENTAL INVESTIGATION AND STATISTICAL ANALYSIS

3.1 Experimental investigation

In the present study an aluminium plate of dimension 20 cm × 19 cm × 1 mm was used for studying the influence of two types of damages along angular-linear and circular directions. A PZT of 26 mm diameter was surface bonded at the centre of the plate. The PZT was connected to Wayne Kerr 6420 impedance analyser by two electric wires.

At each damaged stage, signature is obtained in different frequency ranges between 10Hz to 100 KHz using the analyser. Results were further analysed using RMSD indices.

3.1.1 Angular directional damages

To obtain angular directional damages, thirty-two holes of 3 mm diameter were drilled on the aluminium plate such that it formed a 5.8 cm radius along circular direction considering PZT as the centre. The angular difference between centres of two adjacent holes is 11.25 degree. Figure 1(a) shows the picture of the considered specimen. After drilling, these holes were filled by nuts and bolts of the same size and tightened up. This situation is considered as healthy state or "no damage" state in the experiment. The analyser was turned to generate and receive signals in the frequency range between 10Hz to 100Hz with 0.25Hz intervals. This signature acquisition was repeated thirty-two more times by removing one pair of nut and bolt each time along the counter clockwise order. Thus, thirty-three sets of signatures in total were collected in the considered frequency range.

3.1.2 Angular-linear directional damages

To obtain angular-linear directional damages, several 3mm-diameter holes were drilled along various inclined axis such that every axis consisted of four holes as shown in Figure 1(b).On each axis, four holes were drilled as shown in Figure 1(b). The holes were evenly distributed in one quarter of the plate as shown in figure along 0°, 30° and 60° directions.

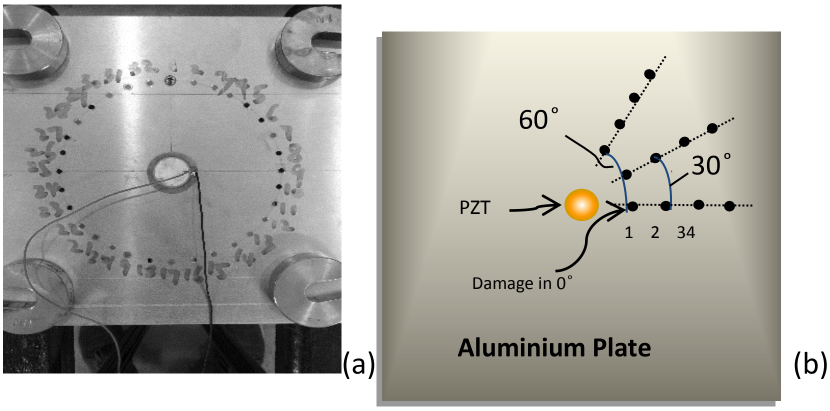

Figure 1. Damage distribution on plate (a) Angular direction (b) Angular-linear directions

Signatures were obtained in the frequency range between 10Hz to 100Hz with 0.25Hz intervals, as done in the previous experiment. The experiment was repeated by removing one pair of nut and bolt from the centre to the edge. Then, another set of four holes were drilled to form a radius line which formed an angle of 30°with the previous line in the counter clockwise direction as shown in Figure 1(b). The experiment were conducted again by repeating the previous procedure to obtain signatures of four damages along 30°. Finally four more holes were drilled and tested along 60° angle.

3.2 Statistical analysis

RMSD index as shown in equation 2 were used to study the difference between angular and angular-linear directions. For the angular directional damages test, each set of result was compared with the result of “no damage” situation. The RMSD for conductance and susceptance values between the damaged state and the “no damage” state was carried out and plotted as Figure 2.

Thirty-two RMSD indices were calculated in the angular directional for all the damaged states. In the same way, four RMSD indices were calculated for both the conductance and susceptance along each angular-linear damage direction. Thus twelve results in total were obtained for three different sets of angular-linear directional damages.

4 RESULTS AND DISCUSSION

4.1 Angular directional damages

4.1.1 Experiment results

Figure 2 shows the RMSD analysis result of both conductance and susceptance for angular directional damages test. Two graphs roughly show increasing trends. Prior to the thirteenth damage, RMSD of both conductance and susceptance stay on roughly same value, where the RMSD of conductance was equal to 0.82 with standard deviation of 0.14 and the RMSD of susceptance was equal to 0.045 with standard deviation of 0.011. Later, RMSD increased with the additional damages, more dramatically.

The average value of conductance based RMSD between 13 to 32 damages was found to be 2.09 which was twice the value compared to RMSD between 1 to 12 damages. However, several drops appear in the middle of the increasing which resulted in a larger standard deviation of 0.92 which is more than 6 times larger than the previous value. Nonetheless it was an increasing trend.

The average value of the susceptance based RMSD for 13 to 32 damages was found to be 0.12 with a standard deviation of 0.03, three times larger than damages between 1 to 12 damages. The standard deviation of the susceptance after the thirteenth damage was relatively smaller than the conductance and the RMSD increased more constantly.

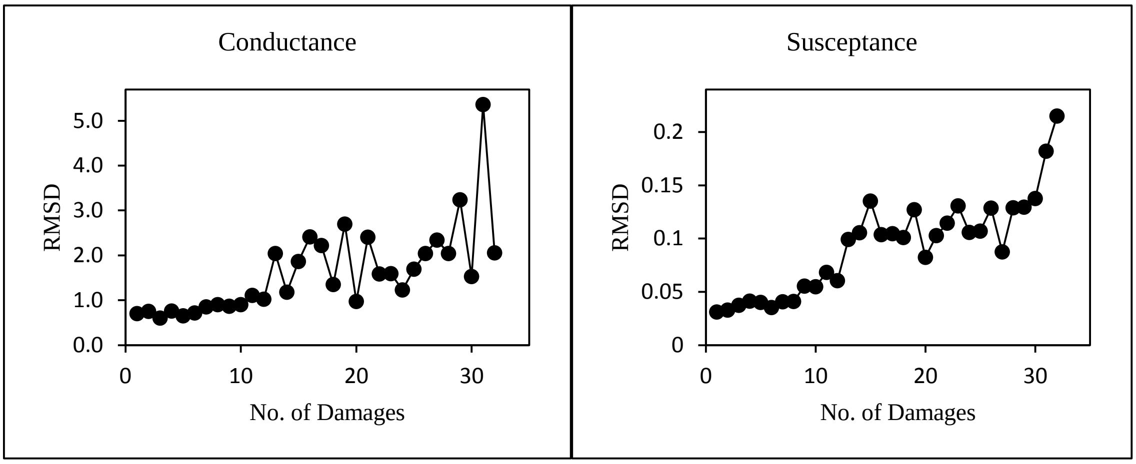

Figure 2. RMSD analysis result for angular directional damages test.

Trend lines of the RMSD index were determined for both conductance and susceptance. For conductance, $y = 0.6513e^{0.0463x}$ can be used to describe the RMSD with $R^2 = 0.6547$, where R^2 is the coefficient of determination which indicates the extent of the signature to meet the statistical model. For susceptance, $y = 0.0341e^{0.0527x}$ can be used to describe RMSD with $R^2 = 0.8275$ which is more close to 1 where the trend line is more fit to the real RMSD value.

4.1.2 Discussion

The growth of the RMSD was exponential for both conductance and susceptance signatures. However, susceptance was found to be better with smaller deviation compared to conductance. Table 1 shows the prediction of RMSD for conductance and susceptance signatures if 5 more damages appear on the structure.

Table 1. Extrapolated RMSD value of conductance and susceptance with appearance of future damages

No. of Damages (Extrapolate)	Conductance	Susceptance
33	3.0015	0.1941
34	3.1437	0.2046
35	3.2927	0.2157
36	3.4488	0.2274
37	3.6122	0.2397
38	3.7834	0.2526

The rate of increase of RMSD obtained from susceptance signatures as indicated in the table is better than the RMSD based on conductance. Thus, in the further usage of SHM technique, the susceptance value of the plate can be used as a better indicator of the structural health condition. The RMSD result will be increasing exponentially as the severity of damage increases.

4.2 Angular-linear directional damages test

4.2.1 Experiment results

Figure 3 shows the RMSD analysis result for angular-linear directional damages, and Table 2 shows the trend line equations of the RMSD results.

For 0° damages, RMSD indices obtained from conductance and susceptance signatures are almost linear. R^2 value is a parameter to fit a linear trend line with the closest data points, it is 0.9517 and 0.9549 respectively for conductance and susceptance.

For 30° damages, the data fits a cubic equation where the coefficient for the cubic term is positive. Similar trend was absorbed for 60° damages, the RMSD result also shows similar trends for both conductance and susceptance.

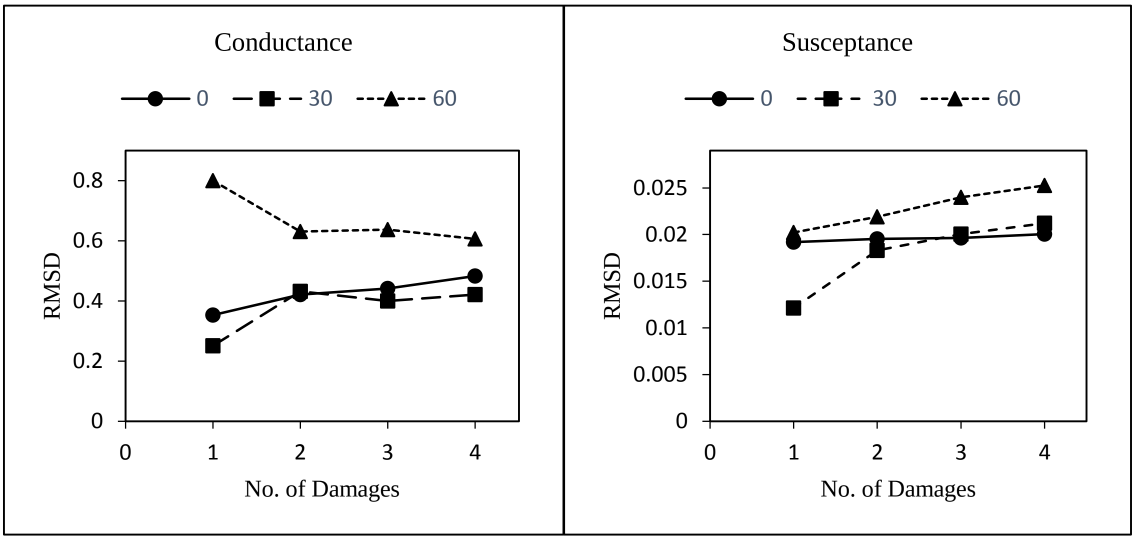

Figure 3. RMSD analysis result for angular-linear directional damages test.

Table 2. Trend line equation of RMSD result for angular-linear directional damages test

	Conductance	Susceptance
0°	$y = 0.0116x^3 - 0.0935x^2 + 0.2677x + 0.1673$	$y = 9\times10^{-5}x^3 - 0.0007x^2 + 0.0017x + 0.0181$
30°	$y = 0.0449x^3 - 0.3763x^2 + 0.9961x - 0.4138$	$y = 0.0006x^3 - 0.006x^2 + 0.0199x - 0.0023$
60°	$y = -0.0353x^3 + 0.2993x^2 - 0.8199x + 1.356$	$y = -0.0002x^3 + 0.0014x^2 - 0.0012x + 0.0202$

4.2.2 Discussion

For the angular-linear directional damages, damages in different angles show different results. However, the trends for conductance and susceptance show consistency. Table 3 shows the extrapolated RMSD value of conductance and susceptance that is prediction based on the equations given in Table 2.

Table 3. Extrapolated RMSD value of conductance and susceptance with appearance of one more damage

	Conductance	Susceptance
0°	0.6168	0.0204
30°	0.7717	0.0222
60°	0.3265	0.0242

5 CONCLUSION

This paper presents EMI based SHM technique which is still not completely evolved. It presented the difference between two types of damages on a laboratory specimen, viz. linear directional damages and Angular-linear directional damages. It was found that RMSD indices for susceptance are relatively better indicator of damages compared to RMSD based on conductance. Furthermore, the results are preliminary and future work should focus on more angular damages. Nonetheless the predictions as obtained in Tables 1 and 3 show that the mathematical equations can be used to get suitable equations i.e. tend lines that can be used to predict RMSD values for future occurrences of damages. This paper is expected to be useful for statistical analysis of signature based SHM.

ACKNOWLEDGMENTS

The author wishes to acknowledge the funding support for this project from Nanyang Technological University under the Undergraduate Research Experience on CAmpus (URECA) programme.

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