Advanced Materials Research *Online: 2011-11-29*
ISSN: 1662-8985, Vol. 409, pp 633-638
doi:10.4028/www.scientific.net/AMR.409.633

Characterization of Piezo Fiber-based Sensors Responses in Multifunctional Composites

Mohammad Mehdizadeh[1, a], Sabu John[2, b], Chun H.Wang[3, c], Viktor Verijenko[4,d], Paul Callus[5, e]

[1]School of Aerospace, Mechanical & Manufacturing Engineering, RMIT University, Bundoora Campus, Bundoora, VIC 3083, Australia.

[2]Defense Material and Technology Centre (DMTC) Ltd., Level 2, 24 Wakefield St, Hawthorn, VIC 3122, Australia.

[3]Defense Science and Technology Organization (DSTO) 506 Lorimer St, Fishermans bend, VIC 3207, Australia

[a]mohammad.mehdizadeh@student.rmit.edu.au, [b]sabu.john@rmit.edu.au, [c]chun.wang@rmit.edu.au, [d]viktor.verijenko@dmtc.com.au, [e]Paul.Callus@dsto.defence.gov.au

Keywords: sensor degradation, structural integrity, impedance, capacitance, electrical properties, three-point-bending, strain

Abstract. Structural health monitoring systems (SHMS) are increasingly being considered for implementation in a wide range of industries, including transport, civil infrastructure, and energy production. As the application of SHM systems increase, it will be increasingly important to quantify the durability, reliability, and reparability of the SHM system. This paper investigates the electrical and electro-mechanical characteristics of piezoelectric sensors in an attempt to distinguish sensor failure from structural damage [10]. This study involved the measurements of pertinent electrical properties for MFC (Macro Fibre Composite) sensor under fatigue loading and comparison of the strain measurements to characterize the degradation of the structure as well as the MFC. Changes in the capacitance and inductance of this sensor have been recorded, highlighting deleterious structural changes in the sensor itself without any discernible change in the structure being monitored.

Introduction

The next-generation design of composite structures involve combining multiple functions, The goal of such Multi-functional structures (MFS) is to incorporate various tasks and functions such as structural, electrical and thermal features within a structural housing [1]. Multi-functionality is about reducing the physical distance between subsystems and coupling the functions different subsystems perform [2]. The blending of multiple subsystems into a single material or structure reduces overall system mass and size while simultaneously increasing system performance and functionality. However, the performance and behaviour characteristics of the MFS can be affected by degradation of any of the sub-components. This can be caused by sustained use as well as exposure to severe environmental conditions or damage resulting from external conditions such as loading abrasion, operator abuse or neglect. These factors can have serious consequences on the safety, cost, and operational capability. Therefore, the timely and accurate detection, characterization and monitoring of structural cracking, corrosion, delamination, material degradation and other types of damage are major concerns in the operational environment. [6]

This aim of this paper is to investigate the degradation of fiber-based piezoelectric sensors under fatigue loading by characterizing its electrical properties over time. Furthermore, the characterization of the sensor responses to monitor the status of the structure as well as the sensor itself is addressed both experimentally and analytically in this paper.

Macro-Fiber Composite (MFC)

Developed by the NASA-Langley Research Center, the MFC actuator and sensor is one of the most sophisticated piezo-based sensors yet invented (Fig 2). With superior qualities in performance, behavior repeatability and manufacturability, the MFC has spawned great interest in the commercial and academic community as a tool in multiple engineering applications [6]. While the MFC characteristics render it a singularly useful device, limited characterization and modeling research on the MFC exists. Empirically designed and assembled, the MFC is poorly understood, especially in terms of its underlying operating principles, its dependence on design parameters and its electrical properties [3]. The structure of the MFC is shown in Fig 1.

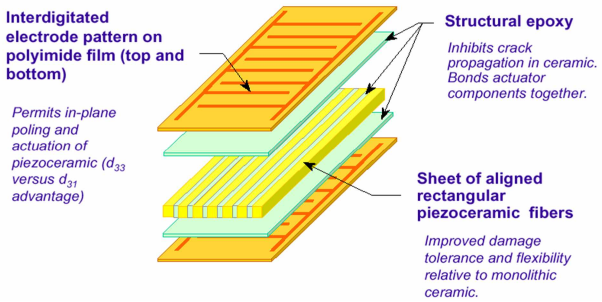


Fig 1: Schematic View of MFC Sensors

Experimental Setup

The MFC sensor is bonded on the surface of a unidirectional cross-ply [(90, 0) $_S$] carbon/epoxy plates with the dimensions of 140×250×1.6 (mm^3) and then cured properly. The sample is then placed in the INSTRON 3KN machine to apply the fatigue loading using three-points bending test. While the sample was under fatigue loading, the L/C/R meter was connected to the sensor to measure Inductance (L), Capacitance (C) and Resistance (R) values and the DT800 Datataker as well as Oscilloscope were connected to the electrodes to capture output voltage of the MFC (Fig 2).

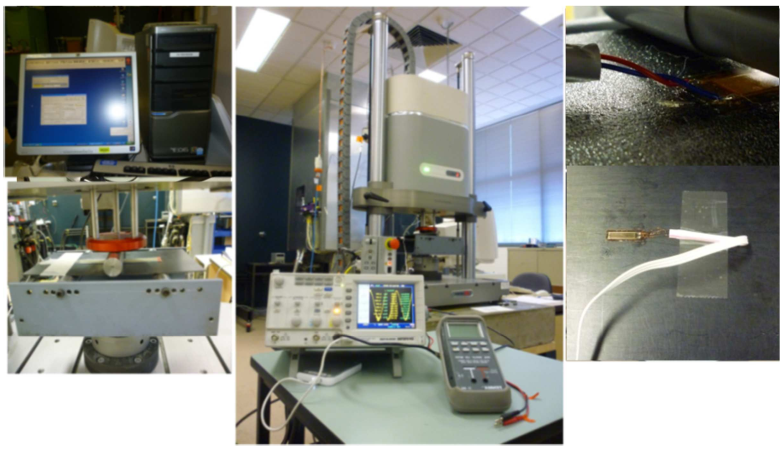


Fig 2: The experimental setup for fatigue test

Also, a strain gauge was attached on the other surface of the carbon/epoxy plate to measure the strain level. The aim was to monitor the changes in the electrical properties and voltage responses of the sensor to detect any degradation in the structure or sensor.
The work presented before by M.Mehdizadeh *et al.* showed that the capacitance and output voltage of the piezo fibre-base sensors can be used to monitor the status of the sensor as well as the structure. Therefore, these parameters along with strain were continuously monitored in order to provide us with the information about the status of the sensor and the structure separately. The following section described the novel technique used to characterize the degradation in the structure as well as the sensor itself as one of the main gaps in certifying SHMS.

MFC Degradation

Strain-based technique From the sensor's diagnostic standpoint, the breakage of sensor/actuator can be easily identified if a sensor does not produce any measurable output, or an actuator does not reasonably respond to applied signals. However, if only a fracture occurs within the sensor itself, the sensor is still able to produce sufficient performance, potentially leading to a false indication on the structural condition. For piezoelectric sensors, the sensor failures are inevitable after undertaking extreme loading/environmental condition, recognizing the fact that the sensors are usually the most delicate part in structural systems. Furthermore, the mechanical and electrical properties of MFC materials could be gradually degraded over their service lives [4]. This degradation of sensor quality, as well as degradation in bonding integrity, will be especially problematic, if one needs to employ large numbers of sensors/actuators over a long period time and to identify when to replace the sensor/actuator network. However, the issues associated with long-term reliability of the MFC sensors under the real-world operational condition, and the methods and metrics that can be used to assess the degradation of the piezoelectric sensor/actuator quality have not been sufficiently addressed in the literature. These issues demonstrate the need for characterization of sensor responses to identify whether the damage is caused within the sensor itself and/or is located within the host structure [4]. The MFC sensor generates electricity due to the deformation or external loading. By assuming the perfect bonding between MFC and the structure, the strain level of the plate should be the same as the strain in MFC sensor unless the MFC itself starts to degrade.

The aim here is to relate the vertical displacement of the central point of the plate to the strain. The equation for the deflection of the plate is used along with the geometry of the three points bending test to determine the relationship between the vertical displacement of the center point and the strain as below:

$$\varepsilon = 0.00896\delta \quad (1)$$

In this research, these relations are used to estimate the strain from the vertical displacement of the centre point at the surface of the plate. These strain values are consequently compared with the strain gauge responses as well as the strain measured from MFC output voltage. As long as the MFC is intact, the strain calculated from theoretical relations (ϵ_T) is the same as the strain that calculated from MFC output voltage (ϵ_{MFC})as fibers bend in a same way as the host structure. However, once the degradation in the MFC sensor starts, these values will diverge due to the micro-cracks within the piezoceramic fibers caused by the fatigue. This difference can be used to monitor the degradation of MFC sensor itself.

$$\Delta_{sensor} = \epsilon_T - \epsilon_{MFC} \quad (2) \qquad \begin{array}{l} if\ \Delta \cong 0 \ \rightarrow \text{The MFC is intact} \\ if\ \Delta > 0 \ \rightarrow \text{The MFC is degraded} \end{array}$$

The Δ_{sensor} values are plotted in Fig 3. There is a gradual increase in the trend which can be indicative of the degradation in the sensor due to the fatigue. The degradation of the sensor cause a reduction in the ϵ_{MFC} and accordingly increases Δ_{sensor} . The small fluctuations in the trend are due to the effect of the environmental noises and interference on the output voltage of the sensor. Furthermore, a considerable increase is observed from this graph after 150000 cycles which can be considered as a sign of the sensor damage.

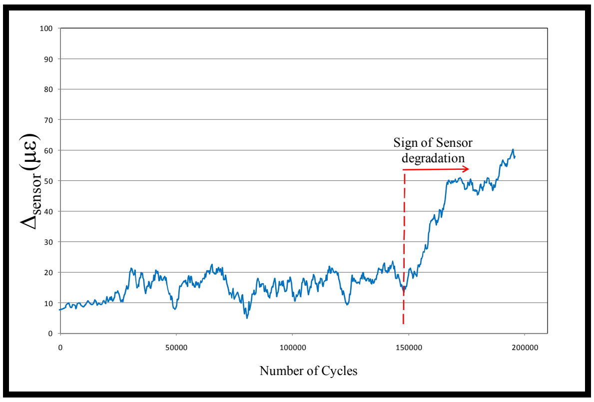


Figure 3: Difference between the calculated strain and MFC strain measurements

Structural Degradation

Strain-based technique One of the techniques presented in this paper for monitoring structural status is based on the strain values gained from measurements as well as the theoretical calculations. In this technique, the strain measurements from strain gage, (ϵ_{sg}) , continuously captured and compared to the strain calculated from theoretical equation (ϵ_T) . As long as the structure is intact, the difference between ϵ_T and ϵ_{sg} ($\Delta_{structure}$) is close to zero. However, once the degradation starts in the structure in the form of crack, delamination etc. $\Delta_{structure}$ starts to increase as the damage in the structure cause a reduction in the strain gage measurements. The following graph (Fig 4) shows $\Delta_{structure}$ versus the number of cycles.

Electromechanical Impedance-based technique The next technique that we used to monitor the structural degradation is impedance-based structural health monitoring (SHM) technique using Fiber-based sensors. In order to investigate the capability of this technique to characterize the degradation in the host structure using the sensor responses, the MFC is attached to a structure as a sensor to simultaneously produce voltage caused by the structural deflection and monitor changes in the electrical-impedance signature. Because the MFC is bonded directly to the structure, the mechanical impedance of the structure is directly correlated with the electrical impedance of the MFC. Thus, by observing the electrical impedance of the MFC, assessments can be made about the integrity of the host structure.

The relative size and weight of a MFC patch is negligible compared to that of its host structure [7], which in this case is a carbon/epoxy plate. Accordingly, a MFC patch introduces negligible impact on the dynamic characteristics of the host structure. This low impact allows the use of a MFC patch to accurately measure the mechanical impedance of a structure [8]. The electrical impedance (Z)of the MFC sensor is determined by the magnitude and phase of the impedance through the Equation 3. The real part of the impedance equation, resistance R, is not affected by the frequency (f) while the imaginary part, reactance (X), is frequency dependent. The reactance of the MFC can be calculated using Equation 4.

$$Z = R + jX \ , \theta = arctan\left(\frac{X}{R}\right) \tag{3}$$

$$X = X_L - X_C \qquad X_L = 2\pi f L, \ X_C = \frac{1}{2\pi f C} \tag{4}$$

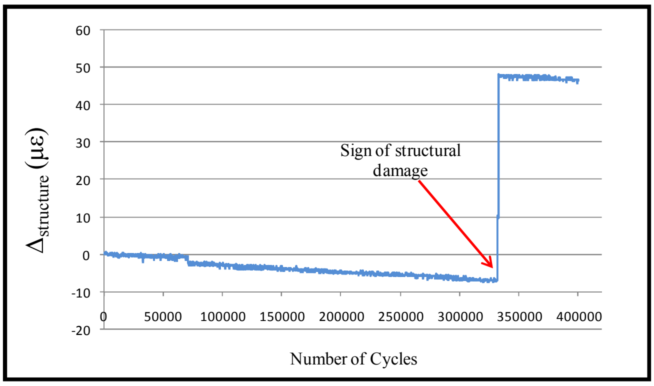
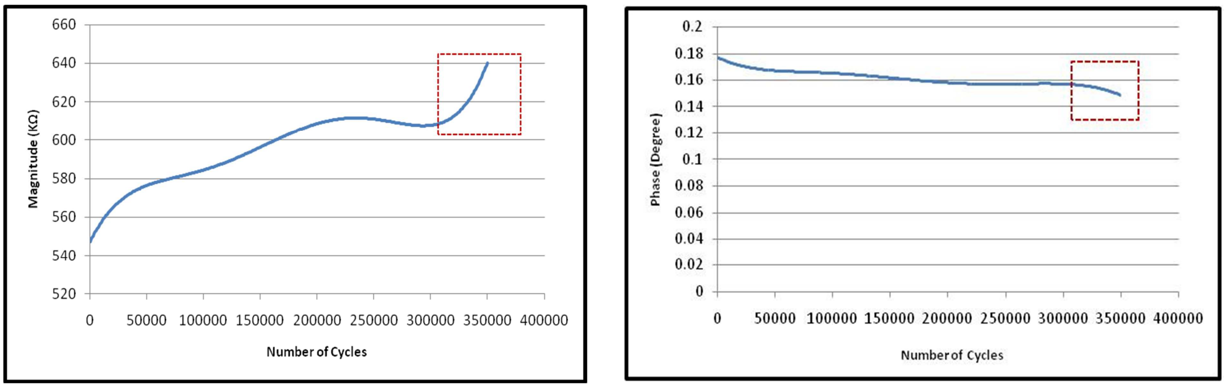


Figure 4: Difference between the calculated strain and strain gage measurements



(a) (b)

Fig 5: Electrical Impedance (a) Magnitude (b) Phase

It should be noted that the capacitance (C) and inductance (L) values are not frequency-dependent in these equations. As it can be seen from Fig 22, there is a gradual increase in the electrical impedance magnitude as the structure undergoes the cyclic loading. Furthermore, the electrical impedance of the MFC is coupled with the mechanical impedance of the structure as it is bonded to the structure. Therefore, the changes in the electrical impedance can be considered as a sign of degradation of the structure. In this graph, there is a sharp change in the trend of the graph at about 300000 cycles which shows a significant change in the structural integrity. Further investigations confirmed this prediction as an opening was observed in the layers of the structure after about 300000 of cycles. The change in the trend of the impedance phase also demonstrate that a phase shift between the current and voltage which caused by the change in the values of the capacitance and the inductance. This shift is also occurred after 300000 of cycles as well. The presented technique is successfully tested and the results show that the mechanical impedance of the structure which itself is calculated form the electrical impedance of the MFC can be used to characterize the structural responses to monitor the integrity of the host structure.

Summary

From the work presented in this paper, the characterization of the structural degradation as well as the sensor degradation is address and the presented techniques are successfully tested. This damage in the sensor can give rise to 'false positive' readings in sensors used and caused the reduction in the capacitance values. The first sign of degradation in MFC sensor observed after 150,000 cycles.

In this study, the characterization of the sensor responses to assess the status of the host structure as well as the senor itself is addressed. The difference between the theoretically calculated strain and the strain gage measurements which is plotted in Fig 21 is used to monitor structural degradation. The difference between these two values should be close to zero as long as the structure is intact and any increase in this difference can be considered as a sign of structural degradation. Furthermore, the changes in the magnitude as well as the phase of the electrical impedance of the sensor were used to monitor the state of the structure due to the electromechanical coupling between sensor and the structure. The graph shown in Fig 22 predicted damage after about 350000 cycles which was confirmed by the strain measurements in Fig 20. The visual inspection was also confirmed the existence of the damage as an opening was observed in the structure. A strain-based technique was used to monitor sensor degradation. The comparison between MFC strain measurements and the calculated strains from theoretical equations can used to monitor the status of the sensor itself. As long as the difference between these two values is close to zero, the sensor is intact. The degradation in the sensor causes a reduction the strain measurements and therefore increases its difference with theoretical value which can be considered as the sign of sensor degradation (Fig 20). The capacitance of the sensor is also employed to monitor the degradation of the sensor (Fig 18).

Future Work

- The degradation of the sensor under various loading conditions will be investigated
- The FEM Modelling will be used to validate experimental results.
- The reparability of the surface-mounted/embedded system as one of the major industrial problems will be determined
- The use of actuation properties of the MFC to characterize the responses will be investigated

Acknowledgement

Funding for this work by the DMTC (Defense Material and Technology Centre) Ltd. Australia is gratefully acknowledged.

References

[1] Matic, P. , "Overview of Multi-functional Materials," Proc.SPIE, Active Materials: Behavior and Mechanics, V. 5053, pp. 61-69, (2003).

[2] Inman, D and Ruggiero, D., "Composite Materials with Embedded Sensing," Center for Intelligent Material Systems and Structures Department of Mechanical Engineering Virginia Tech, USA, (2007)

[3] Lloyd, J, "Electrical Properties of Macro-Fiber Composite Actuators and Sensors," Master Thesis, Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, (2004).

[4] Park, G., Ruggiero, E., Inman, D. J., "Dynamic testing of inflatable structures using smart materials," Smart Materials & Structures., v 11 n 1. p 147-155.,(2002)

[5] Wilkie, W.K., Bryant, G.R., High, J.W. et al., " Macro-Fiber Composite Actuator (LaRC-MFC): Technical Overview," NASA Langley Research Center, (2000)

[6] Kessler, S., "Certifying a Structural Health Monitoring System: Characterizing Durability, Reliability and Longevity," Proc. of the 1st International Forum on Integrated Systems Health Engineering and Management in Aerospace, Napa, CA,(2005).

[7] Overly, T. G. S., Park G.,"Development of an extremely compact impedance-based wireless sensing device," Smart Materials and Structures 2008 IOP Publishing Ltd., (2008)

[8] Seunghee, P., Crisso B.L., "MFC-based structural health monitoring using a miniaturized impedance measuring chip for corrosion detection," Research in Nondestructive Evaluation 18(2): 139-50.,(2007)

[9] Roach, D., "Smart Aircraft Structures: a Future Necessity," High-Performance Composites Magazine, (2007).

[10] Chambers, J, "Durability Testing of an Aircraft Structural Health Monitoring System," Massachusetts Institute of Technology, MS Thesis, Cambridge, MA, (2006).