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ScienceDirect

Procedia Engineering 188 (2017) 340 – 347

Procedia Engineering

www.elsevier.com/locate/procedia

6th Asia Pacific Workshop on Structural Health Monitoring, 6th APWSHM

Durability of structural health monitoring systems under impact loading

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Abstract

This paper reports an experimental study on the degradation of Piezoelectric Wafer Active Sensors (PWAS) under impact loading. Carbon/epoxy laminates with surface bonded / embedded sensors were subjected to different levels of impact energy, and the performance of PWAS was monitored using impedance analysis. The effect of direct and indirect impact loading on the degradation of piezoelectric sensors was also examined. Using the force history data, a reduction in the flexural stiffness of the embedded specimens was identified. Examining the capacitance, output voltage and electromechanical impedance of PWAS, it was found that the degradation of the sensors under impact loading depends on the level of impact energy, location of the impactor as well as the number of impacts. Identification of the structural damage and sensor's degradation was verified using SEM micrographs.

Peer-review under responsibility of the organizing committee of the 6th APWSHM

Keywords: durability of SHM systems; impact loading; surface bonded; embedded; impedance

1. Introduction

Structural Health Monitoring (SHM) systems are developed to decrease the maintenance cost and increase the life of aircraft by fundamentally changing the way structural inspections are performed. However, this important objective can only be achieved through a consistent and predictable performance of SHM systems under different service conditions. The capability of a piezoelectric-based SHM system in detecting structural flaws strongly depends on the signals, which can be affected by flight conditions, raising questions about long-term durability and reliability of SHM systems. Exposure to certain environments as well as mechanical loading may alter their performance, so during data

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Peer-review under responsibility of the organizing committee of the 6th APWSHM
doi:10.1016/j.proeng.2017.04.493

analysis stage, factors such as degradation may need to be taken into account to prevent misdiagnosis of damage, inaccurate results and false alarms. Apart from environmental effects, piezoelectric transducers are likely to be subjected to mechanical loads, including static- and fatigue-loading as well as impact events. Such loadings could result in numerous types of damage including micro cracking, debonding in the adhesive layer and degradation of piezoelectric properties.

The durability of piezoelectric transducers under fatigue loading has been extensively investigated. Doane and Giurgiutiu [1] studied the effect of fatigue loading on Piezoelectric Wafer Active Sensors (PWAS) bonded to 1-mm thick aluminum substrates. Five specimens were tested under different mean tensile load, varying from 577- 1,157 N. All PWAS survived the testing with the aluminum always failing first. After an initial settling in period (from 50k-100k cycles) the Electromechanical (EM) impedance remained constant up until failure. In another study [2] with a similar system, it was found that 510K cycles at 800 με had no effect on the output voltage. For the case of 510k cycles at 1,700 με, a 15 % reduction in the output voltage occurred in the first 100k cycles then remained constant. Furthermore, cycling PWAS at 2,600 με resulted in an 18 % reduction after 390k cycle with a large standard deviation. Paget [3] investigated the effect of fatigue loading on embedded PWAS in carbon/epoxy composite laminates. For the fatigue tests conducted up to 400k cycles at ±0.15 % of the failure strain, only a slight reduction in the Lamb wave response of the PWAS was observed. For higher strain levels (±0.20 % and ±0.30 %) a significant reduction was identified between 50k -100k cycles. This was attributed to matrix cracking and debonding between adhesive and PWAS, which was more noticeable for the 0.30 % case. Finally, Muscat [4] looked at bonded PWAS under 4-point fatigue bending. These were bonded to a carbon/epoxy laminate, with a layup of $[45/-45/90/0]_S$. Each specimen had two PWAS so that the pitch-catch method could be used. For the 4-point bending, the surface with the PWAS was placed under tension and tested at three strain levels, 4,000 με, 6,000 με and 7,000 με. All PWAS failed before 100k cycles, with cracks developing where the wires had been soldered to the sensors.

In the open literature, a limited number of publications can be found in which the effect of impact loading on the functionality of a PWAS was investigated. As identified by Kessler [5] and Chambers [6], before an SHM system could be certified, impact testing on PWAS would be necessary for distinguishing between the damaged sensor and structural damage. Most investigations, reported in the open literature, have been focused on the identification of damage in the structures caused by impact loading using PWAS [7-9], and no substantial investigations have been undertaken to assess the durability of the sensors under such loading. The aim of this investigation was to study the effects of impact loading on the durability of PWAS bonded to or embedded in a carbon/epoxy composite laminate. Only low energy impact levels that can be caused by events such as hail, tyre debris or small birds were considered.

2. Materials & experimental procedure

2.1. *Materials*

For this investigation, APC-850 (Navy II) sensors were purchased from APC International Ltd. All PWAS were circular disc-shaped with a diameter of 6.35 mm (1/4 inch) and had a thickness of 0.254 mm. For the embedded specimens, the solid electrode type sensors were chosen, which has its silver electrodes on each side of the sensor. Temco 28 AWG magnet wires, with a diameter of 0.36 mm and insulation temperature of 200 ºC [10], were soldered to the PWAS. To prevent carbon fibers from short-circuiting the PWAS, Kapton tape with a thickness of 30 μm was utilized as an insulator. For the surface bonded specimens, wraparound electrode type sensors were used. This electrode type has an insulation strip which enables the bottom electrode to wrap around the edge of the sensor and sits on the top surface of the PWAS. The thicknesses of the wires were not a major concern for the bonded sensors, so 22 AWG Teflon insulated wires (diam. 0.64 mm) were used. Aerospace grade AS4- 3501-6 carbon/epoxy prepreg tape was used for all testing, which consists of AS4 3k carbon fibers in a Hexcel 3501-6 epoxy matrix. The layup configuration chosen for this study was $[0/\pm45/90]_S$. The composite panel was cured at 180 ºC and 100 psi for 2 hours. Each panel was then cut using a diamond saw, producing specimens with dimensions of 35 × 28 × 2.14 mm.