Impedance Based Detection of Delamination in Composite Structures

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Abstract. Nowadays commercial and military aircrafts are increasingly using composite materials to take advantage of their excellent specific strength and stiffness properties but impacts on composites due to bird-strike, hail-storm cause barely visible impact damage (BVID) that underscores the need for robust structural health monitoring methods. Hence, damage identification in composite materials is a widely researched area that has to deal with problems coming from the anisotropic nature of composites and the fact that much of the damage occurs beneath the top surface of the laminate. This paper focuses on understanding self-sensing piezoelectric wafer active sensors (PWAS) to conduct electromechanical impedance (EMI) in glass fibre reinforced polymer composite to perform structural health monitoring. With the aid of a 3D ANSYS finite element model, an analysis of different techniques for the detection of position and size of a delamination in a composite structure using piezoelectric patches had been performed. The real part of the impedance is used because it is known to be more reactive to damage or changes in the structure’s integrity and less sensitive to ambient temperature changes compared to the imaginary part. Comparison with experimental results is presented to validate the FE results. The experimental setup utilizes as its main apparatus an impedance analyser HP4194 that reads the in-situ EMI of PWAS bonded to the monitored composite structure. A good match between experimental and numerical results has been observed for low and high frequencies. The analysis in this paper provides necessary basis for delamination detection in composite structures using EMI technique.

1. Introduction

Structural health monitoring (SHM) method is very significant in the engineering world and every year new ideas and mechanisms have to be generated and developed. In engineering, exploration of new thing is a must, since from the 21st century many founding and discoveries of magnificent theories and innovative product have been created. Even though with the mind blowing theories and innovations, it is impossible to reach the understanding without further scientifically elaboration and explanation. In few years ago, a smart material has been discovered and it is not being expected that there is material which can react to external stimuli by itself without human intervention. Then, this smart material has been developed to the extent where it can use in the field of structural health monitoring (SHM) and non-destructive evaluation (NDE).

Damage detection on aircraft composite structures has been one of the major concerns of operators during the last two decades [1]. EMI method by using piezoelectric sensors and/or actuators incorporated into composite structures offer a promising option to fulfill such requirements and needs. This method can use finite element analysis combined to experimental results in order to detect
damage. Thus, it is possible to identify, locate and estimate the damage events, comparing dynamic responses between damaged and health structures. The basic idea of the impedance based damage detection method consists on assuming that damage is a combination of different failure modes, which affect the local stiffness of the structure, and this modifies the dynamic characteristics of the structure, i.e., the modal frequencies, mode shapes and modal damping values. Structural Health Monitoring (SHM) can provide, all the time, during the aircraft life, a diagnosis of the material state and the structure situation, as well as a prognostic like the residual strength of the structure. Thus, SHM can reduce the maintenance costs, avoiding useless inspections. Many researchers have been done on the topic of structural health monitoring for composite structure such as Zou et al. [2] reviewed the model-based delamination detection methods for composite structures using vibrations. Firstly, it describes the most commonly, model-based methods for damage detection, used structural modeling techniques for delamination and the effects of delamination on dynamic parameters. Then it focuses on the application of vibration-based model-dependent damage detection methods in composite structures. Finally, the review is devoted to the development of methods with incorporated piezoelectric sensors and actuators for on-line delamination detection for composite structures.

Gresil et al. [3] have conducted, they compared experimental measurements on a beam structure which is the impedance is calculated using electromechanical impedance device such as AD5933 where the FEM model is mechanically coupled to PWAS and the calculated impedance from coupled-field multi-physics-based finite element method (MP-FEM) model where the PWAS is directly excited with electric

Pérez et al. [4] presented the results of an experimental campaign conducted to investigate the feasibility of using vibration-based methods to identify damages sustained by composite laminated due to low-velocity impacts. The experimental program include an evaluation of impact damage resistance and tolerance according to ASTM test methods, characterization of damage by ultrasonic testing and quantification of the effects on the vibration response. The experimental results indicate that impact-induced damages result in detectable changes in the vibration response of coupons.

Moreover, most of the works existing in the literature about composite structures are still limited. In practical, for the composite structures, it is difficult to detect damage. In order to detect damage throughout the whole structure, especially some composite structure, a methodology, which uses impedance based SHM, has been more adequate. Recently, this type of methodology has been used for composite structures. Therefore, this article presents experimental and finite element analyses on glass fiber reinforced polymer (GFRP) composite structures and focus of this paper will be on the analyses the effect of delamination on the EMI system.

2. Impedance based SHM

The electro-mechanical impedance method for structural health monitoring, damage detection, and NDE was explained in detail by Giurgiutiu et al. [5]. An overview of its principles is given next. Consider a piezoelectric transducer wafer intimately bonded to the surface of a structural member. When excited by an alternating electric voltage, the piezoelectric transducer applies a local strain parallel to the surface. Thus, elastic waves are transmitted into the structure. The structure responds by presenting to the transducer the drive-point mechanical impedance

\[ Z_{str}(\omega) = i\omega m_e(\omega) + c_e(\omega) - ik_e(\omega) / \omega \]  \hspace{1cm} (1)

Through the mechanical coupling between the PZT transducer and the host structure, and through the electro-mechanical transduction inside the PZT transducer, the drive-point structural impedance directly reflects into the effective electrical impedance as seen at the transducer terminals (Figure 1).
The apparent electro-mechanical impedance of the piezo transducer as coupled to the host structure is given by

\[ Z(\omega) = \left[ i\omega C \left( 1 - k_{31}^2 \frac{k_{str}(\omega)}{k_{PZT} + k_{str}(\omega)} \right) \right]^{-1} \]  

(2)

Here, \( Z(\omega) \) is the electro-mechanical impedance as seen at the PZT transducer terminals, \( C \) is the zero-load capacitance of then PZT transducer, \( k_{31} \) is the electro-mechanical cross coupling coefficient of the PZT transducer (\( k_{31} = d_{31} \sqrt{\varepsilon_{33}} \)), \( k_{str}(\omega) \) is the dynamic stiffness of the structure, and \( k_{PZT} \) is the stiffness of the PZT-wafer active sensor [7].

### 3. Experimental Analyses

The experimental analyses were carried on composite structure. The structures are made of glass fiber reinforced polymer (GFRP) with PZT transducers bonded to its surface. The beam considered is 60 mm x 10 mm x 1 mm whereas the piezoelectric patch has dimensions of 7mm diameter and 0.2mm thickness. There is also adhesive layer between the beam and piezoelectric patch with 30μm thickness. An impedance analyzer HP4294 was used to read the in-situ E/M impedance of piezoelectric wafer active sensors (PWAS) attached to the monitored structure. The experimental set up is shown in Figure 2.

**Figure 1.** Electro-mechanical coupling between the PZT transducer and the structure.

**Figure 2.** Experimental set up
4. Finite element analyses

All the specimens are numerically modeled with 3D mesh shown in Figure 3. The GFRP is modeled using 20 node SOLID186 layered structural solid in order to obtain a 3D five laminated layers beam with $0^\circ$ orientation along x-axis and the adhesive layer is modeled with 20 node 3D SOLID95 element. Next for piezoelectric wafer active sensor transducer, it will be modeled with SOLID226 element which is for 3D 20 node coupled field analysis. The size of the mesh for all the elements is 0.5 mm for the frequency range between 0 to 5 MHz and 7 MHz to 15 MHz.

Figure 3. FE model of composite structure beam

In a finite element model of piezoelectric wafer active sensor, SOLID226 has degree of freedom (DOF) up to four DOFs per node. Electric voltage degree of freedom (DOF) will be used in order to obtain charge accumulation data for the model. PIC255 material properties will be used in the piezoelectric wafer active sensor. The material properties are given in Table 1.

Table 1. PIC255 Properties

| Piezoelectric Stiffness Matrices |
|----------------------------------|
| \[
\begin{bmatrix}
123.0 & 76.7 & 70.25 & 0 & 0 & 0 \\
76.7 & 123.0 & 70.25 & 0 & 0 & 0 \\
70.25 & 70.25 & 97.11 & 0 & 0 & 0 \\
0 & 0 & 0 & 23.15 & 0 & 0 \\
0 & 0 & 0 & 0 & 22.26 & 0 \\
0 & 0 & 0 & 0 & 0 & 22.6 \\
\end{bmatrix}
\] |
| \( \text{GPa} \) |

where \([c_e]\) and \([\varepsilon_e]\) are piezoelectric stiffness matrix and relative permittivity. For the adhesive layer, 0.00003 m thick isotropic properties are considered. The Young’s modulus, Poisson ratio and density of the adhesive layer are \(E = 5 \text{ GPa}, =0.4\) and \(\rho = 1700\), respectively (Gresil et al., 2012). A homogeneous orthotropic material with assumed density of 1960 is assigned to the GFRP composite beam. The orthotropic properties of the glass fiber reinforced polymer beam are listed in Table 2.
Table 2. Unidirectional Glass / Epoxy Properties.

| Young’s Modulus (GPa) | Poisson Ratio | Shear Modulus (GPa) |
|-----------------------|--------------|---------------------|
| $E_{11}$              | $E_{12}$     | $E_{13}$            |
| 21.0                  | 2.779        | 2.779               |
| $\mu_{12}$            | $\mu_{13}$   | $G_{12}$            |
| 0.33                  | 0.4          | 4.481               |
| $\mu_{23}$            | $G_{23}$     | $G_{13}$            |
| 0.33                  | 4.9          | 4.481               |

The composite beam will be assigned with mass damping coefficient and stiffness damping coefficient of and, respectively.

5. Result and discussion

Several studies have provided the result of impedance response on piezoelectric patch on the composite structure. However, only two works, [3] and [5] are chosen because they have the most information regarding the material properties and simulation result on impedance response. Experimental results for pristine and damaged will be compared and also the impedance signal obtained from the experiment and simulation will be compared and discussed. The first simulation result of composite beam and circular piezoelectric patch are shown in Figure 4.

![Figure 4](image-url)

**Figure 4.** Comparison of experimental and FE simulation (a) for a frequency range 0–5 MHz; (b) for a frequency range 5–15 MHz.

The comparison between the simulation and experimental results show a good agreement It has revealed two different regions of behavior: (a) below 5 MHz, the result from a FE model with
structural damping were taken as has a good matching with the experimental result from and (b) above 5 MHz, the experimental result matches better with a model with structural damping $\beta = 10^{-9}$.

5.1 Delamination effects:
The composite structures have a tendency to delaminate which reduces the strength and stiffness and thus limits the life of a structure. This behavior of composites has caused concern amongst the designers to find the ways to delay or prevent delamination in order to increase the life and the load bearing capability of the structure. We studied the effect of a delamination introduced between the layers 4 and 5 as illustrated in Figure 5.

![Comparison of experimental for Healthy and Delamination of laminate GFRP](image)

It can be seen that, when delamination is introduced in the composite, there will be shifts in response peaks and modification of peaks amplitude. From Figure 5(a), the four major resonance peaks that shift leftwards have higher amplitude. Splitting of the laminated beam between the third ply and the fourth ply caused the PWAS to respond in shorter distance compared to the respond of PWAS on healthy GFRP beam where longer respond is needed to detect non–gap plies of the composite beam. The gap that exists between the plies caused the PWAS to detect the thinner beam first resulting in lower amplitude and shorter distance.
to higher amplitude of resonance peaks. For frequencies higher than 2.5 MHz, the impedance response between delaminated and healthy beam is significant as there is major resonance peak that exist in that range of frequencies except that the impedance response of the delaminated beam has a lower value of electrical impedance compared to the electrical impedance value of the healthy beam. This shows that significant changes of impedance response can observed clearly in Figure 5(b). These shifting of peaks and changes of the resonance amplitude occurred vividly because the nodes on the delaminated region are not directly connected with each other or disengaged with each other during meshing.

6. Conclusion:

Different methods are used to identify damage in composite structures. Impedance analyzer and piezoelectric transducers are used for data acquisition. The analyses were carried out to obtain modal parameters of both an undamaged and a damaged structure. Experimental and numerical analyses were presented. For the numerical analyses, finite element for piezoelectric active composite was implemented in Ansys 14.5. The analyses were performed to obtain modal parameters of both healthy and damaged structures, simulated in the structure by delamination introduced between the layers 4 and 5. The experimental and numerical results showed that this system can be used for continuous monitoring of structures. It gives information on the overall condition of the structures. The experimental analyses combined to the damage diagnose if the structure is damaged or not. Finally, it is possible to conclude that there is a great future perspective for the application of impedance-based SHM by using piezoelectric sensors for composite structures. However, there are still a lot of work that needs to be done numerically as well as experimentally to determine and investigate the effect of different variables introduced to the system.

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