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Real-time electrical impedance resonance shift of piezoelectric sensor for detection of damage in honeycomb core sandwich structures

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ABSTRACT

A simple and low cost method for structural health monitoring of honeycomb composite shaped in cantilever beam was reported. A lead zirconate titanate (PZT) sensor was attached to the cantilever beam and vibrated resonantly. The real-time imaginary part of electrical impedance of PZT sensor was measured to correlate with the induced mechanical impedance resonance shift of cantilever beam when a proof mass was moved on top of cantilever beam. When a defect was present, it caused a disrupted change of imaginary part of electrical impedance. Such detection is real-time so that no baseline is required to identify the defect accurately.

1. Background

For synthesized material like honeycomb composite, Lead zirconate titanate (PZT) sensor is able to detect the defects such as fiber/matrix cracks and interface disbonds that will deteriorate the integrity of structures [1]. Numerous techniques have been developed to use PZT sensor for detecting such defects. Vibration-based technique has been used to detect the defects based on the changes of modal parameters of a structure in operation [2,3]. However, for honeycomb composite, this technique is insensitive to the defects because composite structures are characterized by high stiffness material which damps out the vibration signal easily.

Another technique based on lamb wave was developed [4–6]. The advantage of using high frequency wave makes it possible to propagate a longer distance with small amount of amplitude loss. Therefore, it is possible to avoid signal loss due to high stiffness of honeycomb composite [7]. However, there are number of drawbacks of using this technique, such as lamb-wave probes are relatively too heavy and expensive; complication of signal processing and interpretation due to concurrent multiple lamb wave modes; baseline from defect-free honeycomb composite is essential to setup the detection system.

In recent years, the electro-Mechanical (E/M) impedance method has gained special attention in the defects detection of composite structures [8–10]. The *E*/*M* impedance method uses low cost, light weight and small piezoelectric transducer, such as PZT sensor, to be embedded on the composite structures. The piezoelectric effect of PZT sensor allows the mechanical impedance of the monitored structure to be experienced by the PZT sensor and convert this mechanical impedance into electrical impedance. This electrical impedance of PZT sensor varies when the mechanical impedance resonance of structure shifts due to the presence of defect like disbond. By measuring the variation of electrical impedance which is correlated to the mechanical impedance resonance shift, the defect can be detected. However, the resonance shift of electrical impedance has to be determined in a selected frequency bandwidth, which is technically difficult to be employed for real-time applications. Furthermore, like many other techniques such as lamb wave, a baseline from defect-free honeycomb composite is required in order to setup the threshold for defect detection.

In this paper, we proposed a simple and low cost method to monitor the real-time electrical impedance resonance shift of PZT sensor which was correlated to the induced mechanical impedance resonance shift of honeycomb composite shaped in cantilever beam. As compared to the conventional E/M method, the new method is capable to measure the real-time electrical impedance ($Z_E(t)$) of PZT sensor. The measurement of time varying electrical impedance resonance shift does not require a baseline to be identified from a defect-free honeycomb composite. As a result, the structural health monitoring process is simplified significantly.

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2. Electrical impedance resonance shift

In our previous work, the resonance frequency of a cantilever beam with proof mass was described as follows [11]:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{3\sum_i E_i(I_i + A_i z_i^2)}{\left(l_b + \frac{l_{pm}}{2}\right)\left(\frac{33}{140}m_b + m_{pm}\right)}} \quad (1)$$

$$I_i = \frac{1}{12}w_i t_i^3 \quad (2)$$

$$z_n = \frac{\sum_i E_i t_i z_i}{\sum_i E_i t_i} \quad (3)$$

where z_n is the location of neutral axis at n layers, E_i is the Young's modulus, t_i is the thickness of the ith layer, z_i is the distance between the center of that layer to the neutral axis, I_i is the area moment of inertia, A_i is the cross sectional area of the ith layer, l_b is the length of the cantilever beam, l_{pm} is the length of proof mass, m_b is the mass of the cantilever beam, m_{pm} is the mass of the proof mass (see Fig. 1). From Eq. (1), we notice that the $(l_b+l_{pm}/2)$ depends on the center gravity (CG) of proof mass from fixed end. In other words, the resonance frequency of cantilever beam can be varied if the proof mass is moved from fixed end ($x=0$) to free end ($x=1$) or vice versa. Fig. 2(a) shows that the resonance frequency of cantilever beam shifts to higher frequency when the proof mass is moved from free end to fixed end.

The resonance shift of cantilever beam will be smooth and continuous unless the cross sectional area which determines the area of moment inertia, is constant. When a defect, for an example, disbond is formed along the cantilever beam, both cross sectional area (A) and area of moment inertia (I) change at the affected location. This will cause a disrupted change in resonance shift of cantilever beam. To demonstrate how this characteristic of cantilever beam can be reflected by monitoring the continuous resonance shift of cantilever beam, a simple example was presented in Fig. 2(b). Assuming that a disbond is found at location of CG=0.6. This disbond caused a total 10% change in I and A. When the proof mass is moved on the cantilever beam as per described, a disrupted change of resonance shift is recorded. As shown in Fig. 2(b), this example confirms that the 10% change of I and A causes 4.8% disrupted change of resonance shift. Although the value of disrupt change could be small and therefore difficult to detect, this small change can be "amplified" if it is monitored by measuring the real-time mechanical impedance resonance shift of cantilever beam because every 1 Hz of mechanical impedance resonance shift causes tenth or hundredth ohms change in its magnitude. This amplification effect can greatly improve the accuracy for detecting such disrupted change.

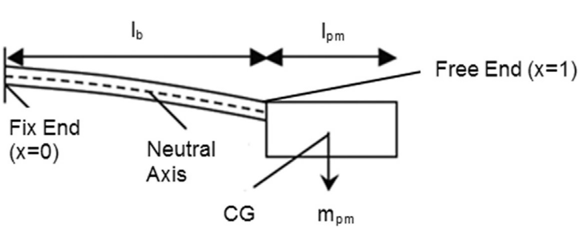

Fig. 1. Schematic diagram of a cantilever beam with proof mass [11].

Based on the E/M impedance method, the induced resonance shift of cantilever beam can be monitored by measuring its mechanical impedance resonance and hence the electrical impedance resonance of PZT sensor as per described earlier. In order to monitor the instant change of electrical impedance resonance shift, it has to be measured on real-time basis. However, the conventional approach such as discrete Fourier transform is unable to obtain the real-time electrical impedance resonance shift. To overcome this problem, a novel method has been developed [12–14]. This method is able to process the electrical impedance at single frequency and present its magnitude in time domain by using the Hilbert transform. It has been used successfully for the real-time monitoring of resistance spot and arc welding process as well as bio-whisker sensor for geometry detection of high aspect ratio microholes. Although the working principle of the method has been discussed in detail in our previous work, we would like to highlight that the characteristic of real-time impedance is suitable for this application because the input frequency of PZT sensor can be fixed at the resonance frequency of PZT sensor. When the mechanical impedance resonance shift of cantilever beam is induced by moving the proof mass, the corresponding electrical impedance resonance shift of PZT sensor is measured concurrently at that fixed frequency. In order to demonstrate the capability of new method, a pilot study was carried out to detect the disbond of a honeycomb composite structure shaped in cantilever beam.

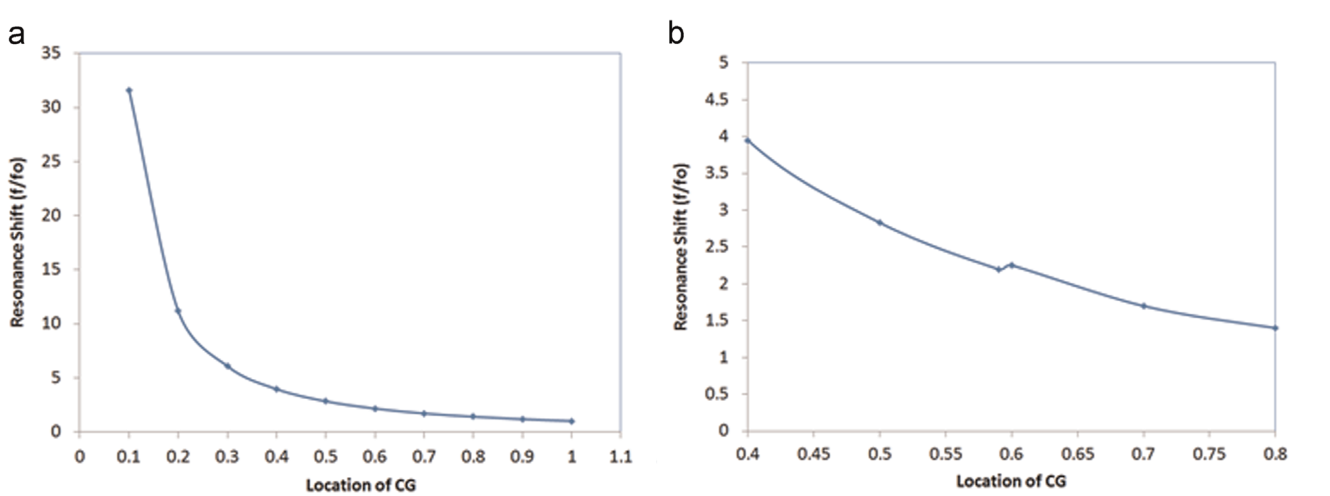

Fig. 2. (a) Resonance frequency shift of cantilever beam with respect to the location of proof mass. (b) Disrupted change of resonance frequency shift with presence of disbond at center gravity, CG=0.6.