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Implementation of heterodyning effect for monitoring the health of adhesively bonded and fastened composite joints

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ABSTRACT

Composite materials are a preferred choice when high strength/weight ratio and resistance to corrosion are needed. For assembly, composite parts are joined by using adhesives and/or fasteners. Due to the increased use of composites, there is a need for reliable and affordable structural health monitoring (SHM) methods for the detection of weakened bonds and loosened fasteners. Heterodyne effect may be utilized for the evaluation of debonded area when the linear characteristics of the system changes to nonlinear as a result of light contact in the bonding zone and this nonlinear system responds to appropriate bitonal excitations with new frequencies. Nonlinear elastic wave spectroscopy (NEWS) methods are using the same concept although they are limited to the combination of a high and a low frequency. Heterodyne method allows the engineers to have control over the new output frequencies as indicators of nonlinearity in the target structure. In this study, implementation of the heterodyne method is proposed for identification of the debonded region and evaluation of the compressive forces applied to facing plates. The proposed SHM method proved to be effective in both scenarios.

1. Introduction

Composite materials have gained popularity in high tech applications due to their high strength-to-weight ratio and durability against corrosion. Composite parts may be joined by using adhesive bonding and/or fasteners including rivets and bolts. Weakening or partial separation of bonded regions or their delamination drastically reduce the strength of the structure and may lead to failure [1–3]. Similarly, fasteners may loosen during the service life of structures and cannot hold the parts with the required strength. Structural health monitoring (SHM) methods have been developed for early detection of growing defects and/or for scheduling maintenance operations at the right time to minimize the process cost and downtime. Although several SHM methods already exist, developing new methods to simplify the instrumentation, signal processing, and data management are crucial. In this paper, implementation of the heterodyning method is proposed for inspection of the composite joints that are bonded with adhesives or held together with fasteners. The proposed SHM method is used for identification of the debonded regions and evaluation of the compressive forces applied to the plates by fasteners.

Typically, SHM methods can be divided into two primary groups, these are termed active or passive, depending on if an exciter is used during inspection [1–7]. Among the passive methods, Acoustic Emission (AE) is one of the most popular methods for identification of developing defects in planar composite materials [8–11]. Acoustic Emissions are created by the generation of transient waves due to the rapid release of strain energy within the damaged composites after a defect is developed. Active methods, however, excite the system using appropriate excitation signals and monitor the response of the system. These methods are the most effective SHM methods for estimating the location, severity, and type of defects [12–17]. Active methods can furtherly be categorized into linear and nonlinear methods. The majority of active linear methods compare the characteristics of the data taken from a system in a pristine condition with the data at a later time for identification of defect [18–33]. In these type of methods, linear characteristics of structures, such as time of flight of the excitation waves between the actuator and the sensor, reflections from the defects and changes of the impedance of the attached Lead zirconate titanate (PZT) transducers are considered as main parameters for fault detection.

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However, using these methods for damage detection in early stages of defect growth and nucleation can be problematic and challenging.

Recently, researchers have shown that some types of damage including debondings, cracks, and delaminations change the linear behavior of structure into nonlinear. It is possible to detect the development of these defects by recognition of the nonlinear behavior [34–39]. In these methods, there is no need for collection of the reference (baseline) data from the pristine structure for further processing. Nonlinear elastic wave spectroscopy (NEWS) methods are most prevalent approaches in this area and are able to detect the nonlinear behavior of structures at early stages [40–52]. non-linear wave modulation spectroscopy (NWMS) and non-linear resonant ultrasound spectroscopy (NRUS) are well-known NEWS methods. In NWMS approach, two different actuators are used to excite the structure at very low and high frequencies. Although the selection of appropriate excitation frequencies plays a pivotal role in the progress of damage detection, researchers were not able to come up with a practical and efficient approach for an assortment of proper frequency combinations.

In linear SHM systems, the primary focus is on monitoring the response in excitation frequencies. A certain type of damages, such as cracks, debonding and delamination cause the structure to behave as a nonlinear system and respond with newer frequencies. When these non-linear systems are excited with bitonal excitation, the new frequencies appear in the response of the system at the difference, summation and some other harmonics of the two excitation frequencies. This phenomenon is known as the heterodyne effect [53–57] and has been effectively used by electrical engineers to create new frequencies at desired frequency range in communication systems. This method uses relatively low voltage excitation signal and it is not limited to the combination of a high and a low frequency which can simplify the selection of excitation frequencies.

A theoretical background for the heterodyne effect is explained in the following section by considering a simple experimental setup including two plates staying on top of each other to simulate weak bonds. Debonding and weakness of compressive forces are evaluated experimentally through monitoring the development of new harmonics at the difference of the excitation frequencies.

2. Theoretical background

Many communication systems and optical measurement devices use the heterodyning method to transfer information between different frequency bands without any information loss. The main component of a heterodyne system is the nonlinear component which is called the mixer. Diodes and transistors are the typical nonlinear components of electrical engineering applications, which are used as the mixer. For the implementation of the heterodyning method in SHM applications, the structure is excited at two different frequencies. As long as the structure is in pristine condition, these two frequencies are the main components in the response of the structure to the excitation. That is, when two metal plates are held together with well-tightened bolts, the contact surfaces have elastic deformations and behave like a unit solid plate. Well-built composite plates also behave in a similar manner either they are used as a single panel or they are held together with well-built joints. Adhesives or fasteners may be used for holding composite plates together. The following equation represents the general form of the excitation signals and also response signals:

$$v_0 = av_1 \pm bv_2 = a\sin(\omega_1 t) \pm b\sin(\omega_2 t) \quad (1)$$

Where a and b are the amplitudes of the signals and ω_1, ω_2 are the angular frequencies of the excitation signals. If a defect such as a crack, loose bolt or delamination exists in the system, there is not a perfect contact between surfaces of plates or layers and very small gaps appear at the debonded or delaminated regions of the composite plates. In the absence of the appropriate surface pressure, the surfaces of plates held together with the bolts are in light contact with each other. Therefore, the waves created by the excitation signals on one plate propagate to the other surface after going through some certain alterations which cause the nonlinear behavior of the structure when it is subjected to bitonal excitation. The signals which move to the mating plate or layer with the influence of the defect will have nonlinear characteristics. The following equation represents the general expected form of the response in the second plate:

$$\begin{aligned} v_0 &= av_1 \pm bv_2 \pm c(v_1 \pm v_2)^2 \pm d(v_1 \pm v_2)^3 \pm \ldots \\ &= a\sin(\omega_1 t) \pm b\sin(\omega_2 t) \pm c\cos(2\omega_1 t) \pm d\cos(2\omega_2 t) \pm e\cos((\omega_1 \\ &+\omega_2)t) \pm f\cos((\omega_1 - \omega_2)t) \pm \ldots \end{aligned} \quad (2)$$

Eq. (2), represents the nonlinear response of the structure which contains the harmonic signals at two original excitation frequencies (ω_1, ω_2) and the new frequencies at the summation and subtraction of the original excitation frequencies. The schematic of wave transmission process between the surfaces of two adjacent plates with a small gap is presented in Fig. 1 and it is explained via numerical simulation.

Two harmonic signals $v_1 = \sin(\omega_1 t)$ and $v_2 = \sin(\omega_2 t)$ were added in order to generate the surface waves at the bottom plate. The top surface will be subjected to excitation only if the waves of the bottom plate reach it. The transferred waves to the top surface are indicated with dark blue lines in Fig. 1a. The frequency spectrum of the transferred wave was calculated and presented at the bottom of Fig. 1b. in this graph, the new frequency components at the summation and subtraction of the excitation frequencies in addition to the original excitation frequencies can be seen.

3. Implementation of the heterodyne effect into SHM

In this study, the implementation of the heterodyne method for SHM of composites is proposed. Two approaches were considered for joining composite plates: Bonding with adhesives and fasteners. The proposed SHM method was employed to detect the debonding and weakening of the joints.

For the implementation of the heterodyne effect in SHM, one of the plates was excited with two and also three excitation frequencies. Identical PZT disks were used as excitation source and sensors in this study. Two harmonic signals may be applied to two different exciters or in order to reduce the number of exciters, a modulated signal containing the required frequencies may be applied to a single exciter. The transmitted signal is then measured in the adjoining plate. The frequency spectrum of the monitored signal is calculated. When the system is linear, spikes are not expected at new frequencies. However, development of the new spikes corresponds to the presence of the debonding or having weakly held plates with fasteners.

Different frequency combinations and modes interact differently with a potential defect. Therefore, different levels of nonlinear mixing occur when different frequency combinations are used. Selection of the appropriate excitation frequencies is critical for ensuring an accurate and effective monitoring process. In this study, initially, a sweep sine wave in a broad range of frequencies was applied to one of the exciters on the system with an artificially made defect. Then the response signal was sampled and the time-frequency plot was obtained. Noticeable spikes were observed in