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Evaluation of the health of riveted joints with active and passive structural health monitoring techniques

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ABSTRACT

Many active and passive structural health monitoring (SHM) techniques have been developed for detection of the defects of plates. Generally, riveted joints hold the plates together and their failure may create accidents. In this study, well known active and passive methods were modified for the evaluation of the health of the riveted joints between the plates. The active method generated Lamb waves and monitored their propagation by using lead zirconate titanate (PZT) disks. The signal was analyzed by using the wavelet transformations. The passive method used the Fiber Bragg Grating (FBG) sensors and evaluated the spectral characteristics of the signals by using Fast Fourier Transformation (FFT). The results indicated that the existing methods designed for the evaluation of the health of individual plates may be used for inspection of riveted joints with software modifications.

1. Introduction

All composite and aluminum parts have defects created by three different mechanisms [1]. First, the process-induced defects may be created during the manufacturing of the part. These defects include foreign inclusions, porosity and delamination. Second, defects may be initiated during the assembly by drilling bad holes and/or fitting parts with excessive forces. Third, during the service, loads and environmental effects create additional defects and enlarge the existing ones. These defects grow by time and structure fails. To minimize the risk, structures have traditionally been designed with safety factors and maintained with regular inspections. Since the loading and operating conditions vary, the actual life of the identical parts is not the same. Structural health monitoring (SHM) methods have been proposed to monitor the condition of the parts and to replace them in a timely manner without causing accidents. SHM methods improve reliability while the operating costs are reduced by minimizing regular maintenance and inspections. The SHM studies mainly concentrated on the evaluation of the condition of plates, which are used at the fuselage of aerospace vehicles. In this study, the same methods will be modified to evaluate the health of the riveted joints.

The non-destructive-testing (NDT) techniques including radioscopy, eddy current, ultrasonic and visual inspection have been used for the evaluation of the structural integrity of aerospace structures periodically at the maintenance facilities [2–4]. These methods use large and expensive transducers, which are not suitable for installation to the structures in large quantities and stay there during the service [5,6]. SHM methods prefer light, small and cheap sensors, such as accelerometers, piezoceramic materials, fiber-optic wires, smart paint, strain gages and

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acoustic emission sensors. Creating and monitoring the guided Lamb waves have been found very advantageous in SHM applications since they propagate over large distances with little loss of amplitude [7,8]. Passive acoustic emission sensors [9] may detect the propagation of a crack while active piezoceramic materials may be used to obtain the frequency response functions (FRFs) for more accurate inspections [10] thanks to surface waves.

Two widely used SHM methods in aerospace applications are the Lamb wave [11,12,1] and fiber Bragg grating (FBG) approaches [13–15]. The Lamb wave-based methods may directly estimate the severity and location of the defects with finer resolution if several PZT elements are properly attached to a plate [16]. The FBG sensors use fiber optic cables. These cables are cheap, light, take up a small amount of space, are immune to electro-magnetic-interference, have high sensitivity and many sensors may be attached to single cable [17]. The FBG approach may estimate localized strain. The location and severity of the damage should be separately estimated from this information. The SHM community has used many other methods for academic studies [18–32]. The studies on the detection of rivet cracks and monitoring of their growth are limited [33–38]. For analysis of the sensory signals, the most popular approach is calculation of the spectrum by using the fast Fourier transformation (FFT). Many popular instruments such as digital oscilloscopes calculate the FFT of the signals. If the characteristics of the signal changes with time, FFT cannot represent them. More popular approaches for these complex signals are two-dimensional time–frequency [39] and time-scale analysis [40–42] procedures. Wavelet methods were used to prepare scalograms, wavelet spectras, compression of data, and denoising [43].

The body of the aerospace structures is built by joining thin plates with thousands of rivets. The riveted joints create severe stress concentration and plastic strain. In addition, secondary bending and surface damage (fretting wear) shortens the life of the structure [44,45]. The condition of thousands of riveted joints is an important consideration for the health of structures.

In this paper, the condition of the riveted joints was evaluated with active and passive methods. The active method used lead zirconate titanate (PZT) sensors to create surface waves and monitored their progress. The analysis of the data by using the wavelets simplified the interpretation of the sensory signals. For the passive method, the fiber Bragg grating (FBG) sensors monitored the dynamic strain and FFT of the signal was calculated.

2. Theoretical background

In this section, wavelet transformation and the Lamb wave method will be briefly introduced.

2.1. Wavelet transformation

The wavelet transformation (WT) represents a signal with the help of a mother wavelet $\psi(t)$, which satisfies certain mathematical criteria [46]. The original signal is represented with the dilation and translation of this mother wavelet [47]. The continuous wavelet transform (CWT) of a real function $x(t)$ is represented with the family of wavelets $\psi_{a,b}(t)$,

$$\begin{aligned} x(t) &\to X_{a,b} = (x, \psi_{a,b}) \\ X(a,b) &= \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(x)\psi\left(\frac{x-b}{a}\right)dx \end{aligned} \tag{1}$$

where a and b are the scale and the position parameters, respectively. The family is created by the dilation and translation of the mother wavelet $\psi(t)$ based on the following expression,

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{2}$$

In this study, the wavelet transformation tool box of the MATLAB program was used.

2.2. Lamb wave method

The Lamb wave concept was introduced by Horace Lamb in 1917 [48]. Researches started to use this concept in engineering applications after several decades. Generation of the Lamb waves with desired qualities and monitoring of their propagation is necessary to detect the defects. The part thickness and material should be considered in the selection of the excitation frequency to control the dissipation and resolution of the analysis [49]. It may be beneficial to excite the system at relatively low frequencies to generate the zeroth antisymmetrical mode (A0) and the zeroth symmetrical mode (S0). Previous studies have observed that the dominant components of the A0 mode oscillate out-of-plane and create shear stress in the vertical direction while the displacements are in the horizontal plane [50]. The resolution of the A0 mode is higher and may detect the smaller damages better since its wavelength is shorter than the S0 mode at the same frequency. On the other hand, the dispersion of the A0 mode is more than the S0 mode. The S0 mode is widely used when the PZT disks are used at the SHM applications to transmit the surface waves with little dissipation. The graphical representation of the antisymmetric and symmetric modes is presented in Fig. 1. The PZT disks were used in this study and both modes were excited individually at separate experiments.

3. Experimental setup

The experimental setup was prepared to evaluate the performances of active and passive methods. Two Al 2024 plates with $500\,\text{mm} \times 300\,\text{mm} \times 4.5\,\text{mm}$ dimensions were attached to each other with a single butt joint (Fig. 2) by using eight C2 4X10 Fe TS 10468/1 rivets (Fig. 3). Numbers were assigned to the rivets joining the plates to identify them in the rest of the paper. These numbers are shown in Fig. 3.

Three PZT disks were attached to the surface for implementation of the active method. One of the PZTs was used as an exciter to create surface waves and the others monitored the propagation of the waves at sensors. The diameter and thickness of the PZT disks were 12 mm and 0.2 mm, respectively. The location of the PZT elements at the