Aircraft distributed structural health monitoring based on φ-OTDR

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INTRODUTION

Fiber optic sensors for aircraft health monitoring allow evaluating both: new avionic materials and the behavior of avionic structures under harsh environmental conditions of pressure, temperature and acoustic disturbance (Di Santi, 2015). Distributed sensors based on optical time-domain reflectometry (OTDR) are suitable for aircraft due to electromagnetic interference immunity, small dimensions, low weight and flexibility. These features allow the fiber to be embedded into aircraft structures in a nearly non-intrusive way (Degrieck, 2011) to sense and measure vibrations along every point along the fiber length (Masoudi, 2014). The capability of measuring vibrations on avionics structures is of interest when concerning the study of the material fatigue (Apinis, 2004) or the occurrence of undesirable phenomena like flutter (Krishnamurthy, 2010).

In this work, we present a φ-OTDR technique to locate acoustic disturbances on structures and estimate their frequencies. In order to do so, we embedded 125 μm standard single mode optical fiber into a composite material board and applied to this board vibration whose frequency ranged from 0 to 1000 Hz. Using the φ-OTDR technique, we were able to correctly measure the applied vibration frequencies.

METHODS

The φ-OTDR method uses a coherent laser source to generate Rayleigh backscattered light that is coherent inside the pulses. When vibrations impose a phase-shift to the reflected optical signal in the fiber, it translates to intensity variation of the backscattered signal and is detected with a photodiode (Masoudi, 2014). The experimental setup shown in Fig. 1 comprises a narrow linewidth laser (NLL), a semiconductor optical amplifier (SOA) to both amplify and trigger the laser light into optical pulses, an optical circulator and a 50 m of single mode optical fiber, so that 2 m of the fiber was embedded into a 50 x 50 cm area 3 mm thick board made of composite material and used as the fiber under test (FUT). The backscattered light from the FUT is detected by an avalanche photodetector (APD) and acquired by an analog-to-digital converter (ADC).

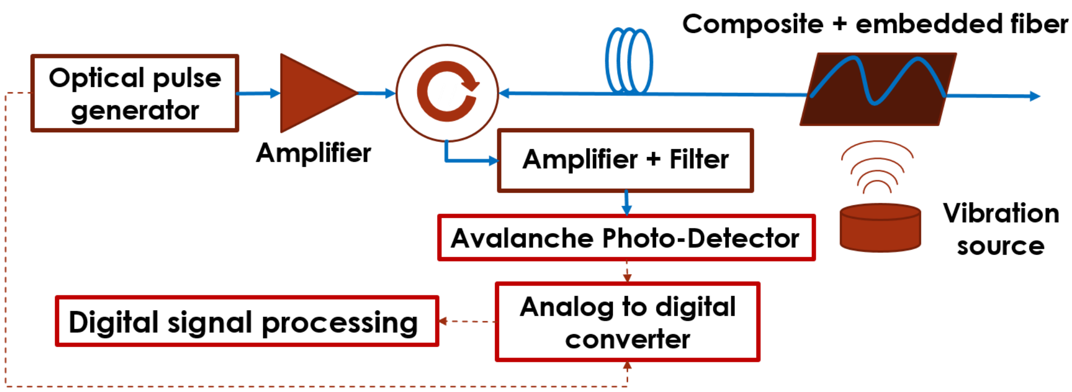

Figure 1. Experimental setup comprising the φ-OTDR apparatus and the composite board with embedded optical fiber.

The composite board was made of 24 superposed plies of composite material according to the following stacked sequence: (45°/-45°/0°/90°/45°/-45°/0°/90°/45°/-45°/0°/90°)$_{\text{mirrored}}$.
Fig. 2 shows the composite board, its embedded fibers insertion points and a transversal cut view of a sample of composite with embedded fiber in its 90°/90° mid layer. Although four optical fibers were embedded in the composite in different layers, we used only the one embedded in the mid layer, the other three were left as back up.
A mini shaker controlled by a sine generator was placed beneath the composite board and used as a vibration source. The frequency was swept from 0 to 1000 Hz and for each value of applied frequency, we used the φ-OTDR to measure the vibration frequency of the composite board. The results obtained in these experiments are presented in the next section.

Figure 2. (a) Composite board with embedded optical fibers; (b) detail of the embedded fibers insertion point; (c) transversal cut view of a composite sample with embedded fiber in its 90°/90° mid layer.

RESULTS AND DISCUSSIONS

As previously explained, vibrations were applied to the composite under test and their frequencies were measured with the proposed φ-OTDR method. Fig. 3 shows the squared differential φ-OTDR traces obtained when applying vibration to the composite. It is visible that the disturbed track of the fiber is between 45.5 and 48 m, which is the fiber section embedded into the composite.

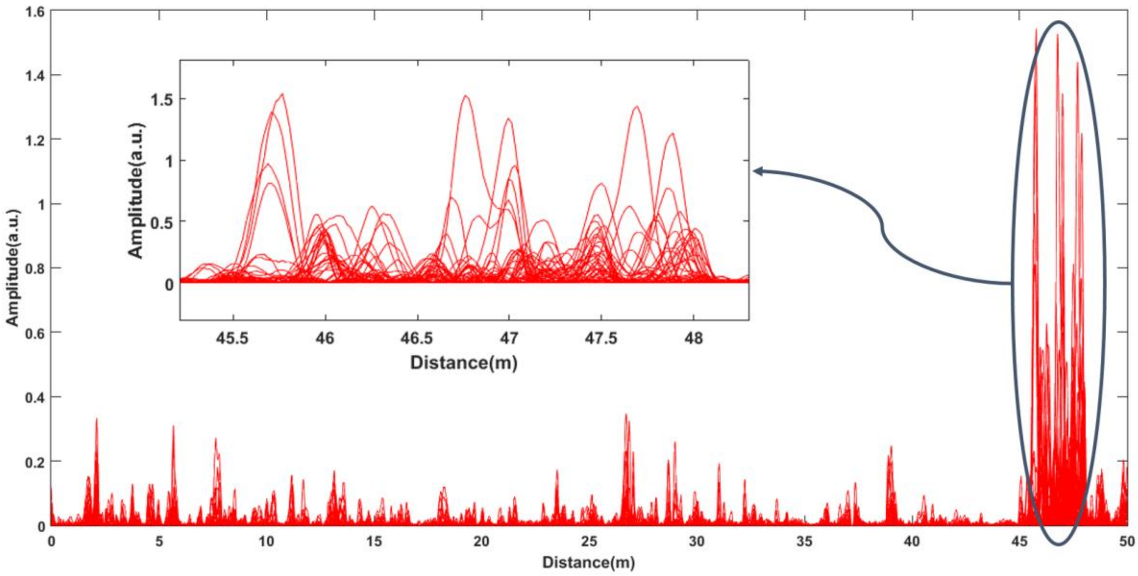

Figure 3. Squared differential φ-OTDR traces, highlighting the fiber section embedded into the composite submitted to periodic disturbance (inset).

One can recover the disturbance signal in time-domain by sampling the consecutive obtained φ-OTDR traces in one point among the localized disturbed section. For example, Fig. 4 exhibits the recovered time-domain disturbance signal of 1000 Hz from 393 consecutive φ-OTDR traces. In order to obtain the frequency profile of the disturbance signal, a fast Fourier transform is applied to its time-domain signal.

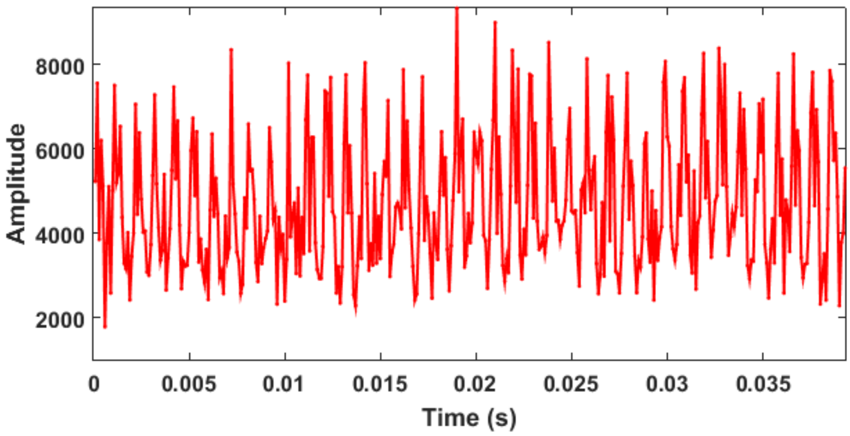

Figure 4. Measured time-domain disturbance signal of 1000 Hz from 393 consecutive φ-OTDR traces.

Fig. 5 exhibits the frequency measurements for each vibration frequency applied to the composite board. It is noticeable that the value of the frequencies measured by the φ-OTDR technique are similar to the frequency of the vibration applied to the composite. The slight differences between applied and measured frequencies may be due to the mini shaker – composite – fiber coupling and can be considered subject of further investigations in future works.

It is also noticeable the capability of the sensor to measure low frequency vibrations around 0 to 100 Hz. Since the natural frequency of airplane wings and the undesirable flutter phenomenon can range around some dozens of herz, it is important for the proposed sensor to be able to detect vibrations with these frequency values. Also, the capability to measure higher frequencies might be also of interest, since fatigue tests can occur at frequency ranges beyond 100 Hz.

Thus, this experimental validation proved the capacity of the presented method to evaluate vibration frequencies in composites with embedded optical fibers, which highlights the suitability of the technique for aeronautic applications.

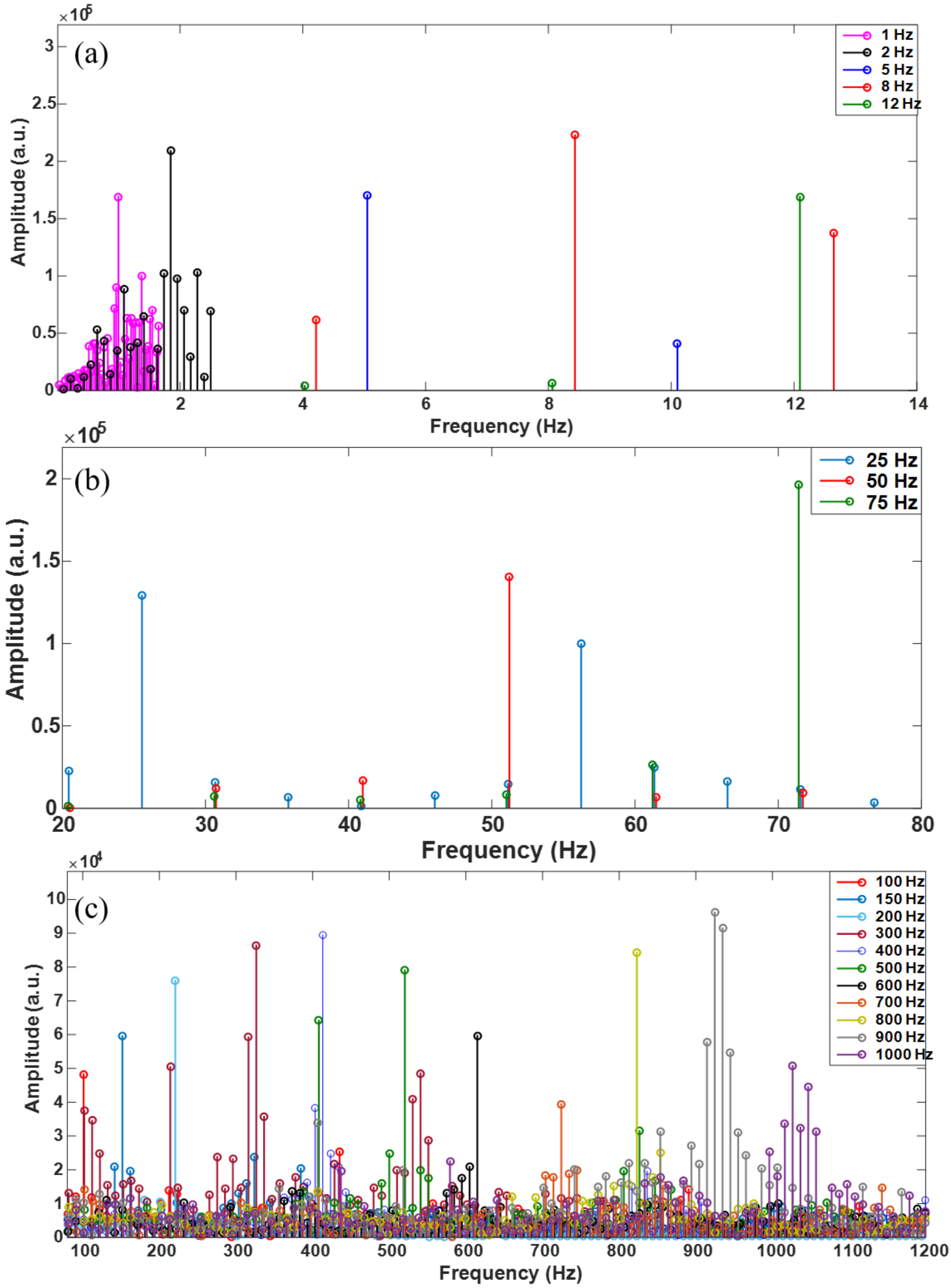

Figure 5. Vibration frequency measurements using the φ-OTDR technique: (a) 0 to 12 Hz; (b) 50 to 75 Hz and (c) 100 to 1000 Hz.

CONCLUSIONS

We proposed and validated experimentally a φ-OTDR technique to localize and measure vibration frequencies in composite materials. In order to do so, we embedded standard single mode fiber into aircraft composite material and applied the proposed φ-OTDR method to measure frequencies from 0 to 1000 Hz. According to the experimental results, we proved the capacity of the presented method to evaluate vibration frequencies in composites with embedded optical fibers, which highlights its usefulness for aeronautic applications.

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