Dynamic strain distribution monitoring of 5.5 m CFRP blade using 5 m FBGs interrogated by optical frequency domain reflectometry

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Key words: Composites, Distributed strain measurement, Dynamic measurement, Optical fiber sensor.

Abstract
We have developed an optical frequency domain reflectometry (OFDR) system which is capable of conducting distributed strain measurements with a sampling rate of 150 Hz, a spatial resolution of less than 1 mm and a sensing range of 20 m. In this study, we applied this technique to monitor dynamic strain distributions along a 5.5 m helicopter blade structure with carbon fiber reinforced plastics (CFRP) skins and shear webs. We used 5 m fiber Bragg grating (FBG) which were bonded on the CFRP blade, and measured the strain distributions along the FBGs. We hung up and released the blade at several points and applied several cases of vibrations. The time variations of strain distributions were monitored by the OFDR-FBG system. In order to validate the results, we attached 16 strain gauges along the FBGs, and compared time variations of measured strains at individual locations. The comparison results validated the accuracy of the results, and demonstrated a promising capability of the optical fiber distributed sensing system to monitor vibrations of the CFRP blade.

1 INTRODUCTION
Moving parts of structures, such as helicopter blades, are often exposed to the most severe loading conditions. Therefore, structural monitoring especially at such moving parts is essential to predict and prevent the fatal fracture of the whole structural system. Optical fiber sensors possess promising characteristics for the purpose of such structural monitoring. Representative characteristics of optical fiber sensors are light-weight, which allows minimum intrusion to structures, and distributed sensing capability. By measuring detailed distribution of strains, the accurate detection of fractures and estimation of deformations can be expected [1,2]. Not a few optical fiber distributed sensing techniques have been demonstrated so far, however, it has been a challenge to apply them to dynamic monitoring of moving parts of structures. This is mainly because it has been difficult to both achieve distributed and dynamic measurements due to their system configurations, the calculation costs and so on [3-5].

We have developed an optical frequency domain reflectometry (OFDR) which is capable of conducting distributed measurements with a spatial resolution of less than 1 mm [6-9]. In this study, we constructed a high-speed OFDR system to achieve a sampling rate of 150 Hz.
and a sensing range of 20 m. We applied this technique to monitor dynamic strain distributions along a helicopter blade structure with carbon fiber reinforced plastics (CFRP) skin and shear webs with a length of 5.5 m. The experimental results demonstrated the validity of the measurements and a promising capability of the optical fiber distributed sensing system to monitor vibrations of the CFRP blade.

2 SENSING SYSTEM

The distributed sensing system based on OFDR allows us to interrogate reflected spectra at arbitrary locations along an optical fiber. When long-length fiber Bragg gratings (FBGs) whose length is typically more than 100 mm are aligned, we obtain distributions of Bragg spectra within the FBGs. The schematic of the OFDR system is shown in figure 1. The signal observed at Detector 1 works as an external clock signal. The clock interval is defined by the optical path difference between Reflector 1 and 2, which is \( LR \). The sensing range of the OFDR system is defined as \( L_i \leq LR/2 \). In this study \( LR \) was 40 m. The signal observed at Detector 2 is demodulated to the distribution of the Bragg spectra based on signal processing of short-time Fourier transform. The demodulation results are expressed as spectrograms. Figure 2 shows an example of the spectrograms obtained through numerical simulations [9]. The horizontal axis represents the wavelength, the vertical axis represents the position and the color represents the amplitude of the reflected spectra. In this case we can see a 10 cm FBG at \( 3.0 \, m \leq L_i \leq 3.1 \, m \).

In this study, the Bragg spectra were obtained with a spatial resolution of 1 mm and with a sampling rate of 150 Hz. The shift of the Bragg wavelengths were converted to the strain variations. The long-length FBG was approximately 5 m. This FBG was manufactured by sequentially inscribing 10 cm FBGs into a fiber with minimum gaps between each.

![Figure 1: Schematic of the OFDR sensing system.](image1)

![Figure 2: Example of a spectrogram of a 10 cm FBG obtained by STFT.](image2)
3 EXPERIMENTAL SETUP

We prepared a helicopter blade structure with CFRP skin and shear webs. Figure 3 shows the schematic of the blade and the experimental setup. The blade has a rigid structure at the root section with glass fiber reinforced plastics at the core to increase the stiffness. The 5 m FBG was bonded at the surface of the blade, and 16 strain gauges were bonded along the FBG with 300 mm intervals. The blade was set as a cantilever beam. Figure 4 shows a picture of the setup. We applied three cases of loadings at individual locations as shown in figure 3 (b). The beam was hung by a rope, and the hanging load was released by cutting the rope.

At individual loading cases, we observed the optic signal of the FBG by the OFDR system. Figure 5 shows the observed spectrograms. The Bragg spectra observed when the hanging load was not applied showed non-uniform distribution. One of the reasons is that after the bonding of the FBG, the blade was deflected by its own weight when the blade was set as a cantilever beam. The right figure of figure 5 shows the spectrogram of the initial condition in loading case 1, which is when the hanging load was applied at the position of 4940 mm as depicted in figure 3 (b). The profile of the Bragg spectra shifted towards shorter wavelengths. This is because the compressive strain was applied to the FBG, which was bonded on the compressive side of the blade. We monitored the shift of the Bragg wavelengths distributions when the hanging load was released, and measured the time variations of strain distributions.
Figure 4: Picture of the blade.

Figure 5: Spectrogram of the 5 m FBG bonded to the blade. (Left: without hanging load, Right: with hanging load in case 1.)
4 RESULTS

Figure 6 shows the measured strain distributions when the hanging loads were applied in the three loading cases. The strain values express the strain variations from the initial condition where the blade was deflected by its own weight. The black dots express the measured values by the OFDR system, and the red plots express those by the strain gauges. The results of the OFDR showed “spike” patterns at some locations. This is because the gaps between each 10 cm FBGs, as explained in the sensing system description, existed at these locations, and therefore appropriate signal was not observed. The strain distributions of the OFDR system agreed well with the strain values of the strain gauges, which demonstrated the validity of the distributed measurement capability of the OFDR system. In the loading case 1 the strain distributions showed the typical profile of cantilever beams over the position from 1410 mm to approximately 5000 mm. At the position from 0 mm to 1410 mm the stiffness was designed to be higher towards the root of the beam, therefore the strain values became smaller. The strain distributions indicated the locations of the loadings as clearly seen in the loading case 2 and 3. These results demonstrated the usefulness of the distributed sensing technique with high spatial resolutions.

The OFDR system measured the strain distributions with the sampling rate of 150 Hz. In order to discuss the dynamic measurement performance, we chose one location at 1940 mm as shown in figure 3(b), and compared the time variations of the strain values measured by the OFDR system and one strain gauge bonded at the location. Figure 7 shows the comparison of the time variations of the strain in the loading case 1. The hanging load was released at 0 seconds. The measurements were agreed well between the OFDR system and the strain gauge, which demonstrated the applicability of the OFDR system to the dynamic monitoring. Figure 7 showed the measurement results only at a single location, however, it is noted that the OFDR system was measuring all the other locations within the 5 m FBG simultaneously. This dynamic monitoring performance is expected to be effectively applied to structural monitoring of various moving parts.

![Graphs showing strain distributions](image-url)

(a) Loading case 1

(b) Loading case 2
5 CONCLUSIONS

We conducted the dynamic strain distribution monitoring of the blade structure using the 5 m FBG and the OFDR system. The measurements were conducted with the spatial resolution of 1 mm and the sampling rate of 150 Hz. The FBG was bonded to the blade which was fixed as a cantilever beam. The vibration was applied to the blade by releasing the hanging loads. The spatial distributions and the time variations of the measured strains agreed well with the strain gauges. These results demonstrated the applicability of the OFDR system to dynamic strain distribution monitoring.
REFERENCES


