The Rotating Rectangular Thin Plate’s Dynamic Stress Experiment (Single Point’s Frequency Research)

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Abstract: Utilizing optical Fiber Bragg Grating’s (FBG) characteristic of transmission optic signals in non-contact way, the measure method of the twisted, variable cross-section, variable thickness, rotating rectangular blade’s local strain has been presented. Firstly, by using the finite element method to obtain the rotating blade’s natural frequency, modal shape and strain modal shape, the mounting location of the FBG on the rotating blade is determined; secondly, using optical fiber non-contact transmission device, the rotating blade’s dynamic strain in different locations can be measured by FBG. In this paper, the author only analyzed the frequency, amplitude and the dynamic stiffening phenomenon of dynamic strain at one point in rotating state. Finally, the author points out that this method can effectively measure rotating blade’s dynamic strain and dynamic response, by result analysis, rotating blade worth further researching. Copyright © 2013 IFSA.

Keywords: Rotating blade, FBG, Dynamic strain, Non-contact, Strain.

1. Introduction

In aviation or steam turbine industry, the blade is the core component of equipment for function transforming. During operation, the force on the blade is more complex, which includes rotating centrifugal force, fluid exciting force, coupling force between blade-fluid and blade-blade. Under the composite effect of these forces, the blade begin distortion, bending deformation and bear enormous stress, which eventually led to the structure’s fatigue damage and failure. At the same time, in effect of these force, the dynamic characteristics of blade also change, such as under the centrifugal force, rotating blade’s bending natural frequency will be greatly increased (Dynamic Stiffening) [1, 2], in effect of Coriolis acceleration, the different vibration models will be coupling together and produce complex vibration model. Thus, the measurement and analysis of rotating blade’s strain is important to improve blade reliability and service life. From dynamic strain point of view, to study the dynamic characteristics of the rotating blades, to research the blade’s stress and strain response in the condition of fluid incentive, are all important in blade design, manufacturing stage and of great significance to prevent flutter phenomenon and blade’s destructive fracture.

In generally study, the researchers usually simplify the blade to beam, early researchers such as Southwell and Gough (1921) studied the vibration of the rotating beam [3]. They proposed a simple equation set to calculate bending natural frequency of rotating beam by application of Rayleigh energy theory, the equation is general called Southwell equation and still is widely used. Later, Schilhansl improved the method by Southwell [4], he deduced
the rotating beam’s partial differential equation and applied the Ritz method in order to obtain more accurate solution. In recent years, with the development of computer technology, researchers can use complex numerical calculation and more accurately calculate the natural frequency, natural model etc. [5-7] of beams.

Although beam can be used as a good model of rotating blade, such model is inaccurate for investigation of higher frequencies and for modelling of short-wide blades. Therefore, researchers introduced the rotating plate model, for more accurate calculation of the blade’s natural frequencies and model shape. By using the finite element method, Dokainish and Rawtani calculated rotating cantilever plate natural frequencies and modal shape mounted on a disc(1971) [8], they studied effect of the aspect ratio, disc radio and setting angle on the natural frequencies, but didn’t consider the gyro effect and Coriolis effect. Karmakar and Sinha also used finite element method to study the rotation laminated composite pre-twisted cantilever plate’s characteristics [9], they considered the effect of pre-twist angle, the thickness ratio, the fiber orientation on natural frequencies of plate. Ramamurti and Kielb [10], Yoo and Kim [11], Yoo and Pierre [12] studied the cantilever beam’s vibration characteristics.

In work environment, the load, stress/strain and the dynamic response at one point of blade are quite different from the calculation results; in this case, the measurement is significant, but the strain of rotating blades is often very difficult to be directly measured. The biggest difficulty lies in the signal transmission between rotating blades and the still measuring instrument. The existing transmission methods include the strain gauge–slip ring method, the strain gauge–telemetry method, FBG–fibre optic rotary joints method, FBG–collimator method. Literature [13] used the strain gauge–electricity slipping method to measure the rotating blade’s strain of steam turbine and compressor, signal transmission from the stationary unit (brush) to the rotating unit (the armature).

Literature [14, 21] used strain gauge–telemetry method to measure the rotating part’s strain, due to the added mass, the speed is not very high, but the transmission distance can amount to thousands of kilometers. Whether the slip ring or telemetry method, both facing the same problem in the measurement of rotating machinery–the strain response of the vibration will change with exciting source, therefore, distributed measurement is needed, as two wires are required for each strain gauge, these wires will lead to the difficulty of dynamic balance. As a new type of sensor device, optical fiber Bragg grating (FBG) features small volume, integration of sensing and transmission, explosion-proof, fire-proof, electromagnetic interference resistance, easy constitution of FBG intelligent sensing network by adoption of wavelength division multiplex, time division multiplex and interval multiplex technology, and has attracted more attention [16-17]. Usage of FBG for equipment strain measurement can solve problems such as remote data transmission, electromagnetic interference resistance and distributive measurement, and requirements on strain gauge mounting technique are substantially lower. Main methods used in FBG dynamic stress measurement are optical fiber slip ring method and optical fiber–collimator method, optical fiber slip ring method is to place two pieces of optical fiber in one thin pipe, in which one piece of optical fiber rotates with rotating component, the other piece of optical fiber stands still, optical signal is transmitted from the end of rotating optical fiber, and enters stationary optical fiber through air, thus signal transmission is realized, the disadvantage of this method is that optical fiber is controlled and aligned through the thin pipe, but the friction between pipe wall and optical fiber causes low rotation speed, normally lower than 2000 rpm. Literature [18] has researched measurement of rotating component stress through FBG–optical fiber slip ring, with its rotation speed is lower than 2000 r/m.

In this paper, the author use FBG/C-Lens method to measure the cantilever blade dynamic strain, with similar theory as that of Literature [18]. By mounting eight FBG on two distortion/variable cross-section/variable thickness/rotating rectangular blade surfaces, dynamic strain change of cantilever beam at 77 ~ 847 RPM is measured. This paper analyzes dynamic strain, dynamic frequency and dynamic stiffening phenomenon of one point, the analysis of multi-point dynamic strain will be present in future paper.

2. Measuring Principle

2.1. Strain Measurement Using FBG Sensors

A FBG is composed of periodic changes of the refractive index that are formed by the exposure to an intense UV interference pattern in the core of an optical fiber. When light from a broad band source interact with the grating, a single wavelength, known as Bragg wave length, is reflected back while rest of the signal is transmitted. A FBG shows sensitivity to strain and temperature changes. The Bragg condition is expressed as:

$$\lambda_B = 2n_{eff} \Lambda$$

(1)

If the grating is exposed to external perturbations, such as strain and temperature, the Bragg wavelength will change. By measuring the wavelength change accurately, the physical properties, such as strain and temperature, can be measured. The shift of a Bragg wavelength due to strain and temperature and pressure can be expressed as:

$$\Delta \lambda_B = a_s \epsilon + a_T \Delta T$$

(2)
where $a_\varepsilon$ is the strain sensitivity coefficient, $a_T$ is the temperature sensitivity coefficient. With the assumption of no pressure change and no temperature change, we can measure the strain from wavelength shift as:

$$\Delta \lambda = a_\varepsilon \varepsilon$$  \hspace{1cm} (3)

### 2.2. Working Principle of Noncontact Optical Signal Transmission

Fig. 1 shows the working principle of the noncontact optical signal transmission. Broadband light emitted from a light source propagates along an optical fiber, the C-lenses change the light in the fiber to collimated beam of parallel light, and collimation light transmit between air gap, then, the optical signal could transmit between stationary part and rotating part.

![Fig. 1. Working principle for rotary optic signal transmission.](image)

### 3. Simulation

This section presents the simulation result based on the ANSYS. The plate’s physical properties and Mechanical properties are shown in Table 1. The 3d geometric model is complete in Pro-e. The boundary value is that the displacement of the surface of tenon is 0 mm.

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density 2.75 g/cm³</td>
<td>Young Modulus 70.6 GPa</td>
</tr>
<tr>
<td>Thickness 6 mm</td>
<td>Poisson Ratio 26.5 GPa</td>
</tr>
<tr>
<td>Length 305 mm</td>
<td></td>
</tr>
<tr>
<td>Width 25 mm</td>
<td></td>
</tr>
</tbody>
</table>

Select 20 node95 units and mesh the geometric model, full finite element model of the bladed comprises about 15000 DOFs. By using this model, the natural frequency and model shape are obtained. Figs. 2, 4 show 1st and 2nd natural model shape of blade, Figs. 3, 5 show the 1st and 2nd natural strain model of blade. The 1st natural frequency is 219 Hz, far beyond the maximum operational frequency 28 Hz, therefore, only consider 1st model shape. By comparing the magnitudes of the 1st natural strain model, the location of FBG can be established. As shown in Fig. 6, four FBG are mounted on the surface of the blade, the other four FBG are mounted on the same location of other blade.

![Fig. 2. The first mode shape of blade.](image)

![Fig. 3. The first strain mode shape of blade.](image)

![Fig. 4. The second mode shape of blade.](image)

![Fig. 5. The second strain mode shape of blade.](image)
4. Dynamic Strain Measurement of Rotating Blade

4.1. Experimental Set-up

Dynamic strain testing system of rotating rectangular sheet consists of personal computer, interrogator, optical fiber rotating joint, FBG, rotating shaft and blade (Fig. 7), of which interrogator is made by Wuhan University of Technology, interrogator frequency is 2000 Hz, optical fiber rotating joint is made by Wuhan University of Technology, sensing length is 7 mm, there are 8 FBGs, the Bragge wavelengths are 1298.190041 nm, 1300.839359 nm, 1302.321735 nm, 1303.233038 nm, 1305.884722 nm, 1309.729094 nm, 1312.060959 nm, 1313.672056 nm, and all FBGs are of series connection in one piece of optical fiber.

After coupling, light emitted by wideband light source in FBG demodulator enters optical fiber, move forward in polyline, and reaches FBG on rotating blade through optical fiber rotating joint, in which, light meeting Bragg condition are reflected, light of other wavelength are transmitted through FBG, the reflected light returns back to FBG demodulator through optical fiber, FBG demodulator modulates/demodulates wavelength signal of FBG, and communicates with PC through TCP/IP protocol, thus signal attached on rotating cantilever beam and detected by FBG can be measured and recorded.

4.2. Results

Under circumstance of temperature 20°, perform measurement test of dynamic strain of rotating blade, start verification test firstly from 3.3 V, then raise to 24 V stably as per interval of 0.1 V, verify positive travel outputs of all recording points in turn, after reaching 24 V, decrease quickly and stably to 0 V, make records of retracting stroke output of all recording points in reverse order, repeat the above method for three times, make records of output of each verification result, Figs. 8-15 show the representative results.
4.3. Discussion

As shown in Fig. 8–9, dynamical strain signal contains a frequency 1.282 Hz related to rotation speed (corresponding rotation speed is 76.92 rpm, and the measured rotation speed is 77 rpm), a double frequency 2.625 Hz related to rotation speed, the first natural frequency 219.9 Hz of blade, and a frequency cluster excited by fluid, of which frequency scope is approximately 56 to 84 Hz.

As shown in Fig. 10, with the rise of rotation speed, cycle of dynamical strain signal is shortened prominently, as shown in spectral analysis Fig. 11, frequency related to rotation speed has risen to 4.151 Hz (corresponding rotation speed is 249.06 rpm, and the measured rotation speed is 250 rpm), and double-frequency 8.301 Hz related to rotation speed still exist, frequency cluster excited by fluid rises rapidly, and frequency scope is approximately 160-194 Hz.

In Fig. 12, dynamic strain frequency borne by blade rises, and amplitude tends to grow, as shown in frequency analysis Fig. 13, the frequency related to rotation speed is 12.36 Hz (approximately 741 rpm), and double-frequency 24.72 Hz related to rotation speed exits, first natural frequency of blade rises to 222.7 Hz due to the rise of first natural frequency of blade caused by centrifugal force, meanwhile, frequency cluster related to fluid disappears due to
the fact that the first natural frequency of blade is scattered in frequency cluster excited by fluid, causing self-exciting vibration of blade of which the vibration amplitude is 20.68 με and rises by approximately 170 times in comparison with the work mode of 77 rpm.

In time domain signal of Fig. 14, the maximum dynamic strain amplitude borne by blade is decreased in comparison with Fig. 15, but signal is irregular, in analysis of frequency, there is frequency 14.1 Hz (approximately 846 rpm) related to rotation speed, and frequency 28.23 Hz related to rotation speed, with the rise of rotation speed, first natural frequency of blade rises by 2.1 Hz to 224.8 Hz, but in comparison with Fig. 12, amplitude of frequency 224.8 Hz is decreased substantially, as frequency cluster excited by fluid in this rotation speed rises gradually and is higher than the natural frequency of blade (a small cluster of frequency can be seen to the right of frequency 224.8 Hz), the resonance effect has been substantially weakened.

5. Conclusions

A new strain measurement technique, using FBG and rotary optic coupler, was introduced for determining the strain distribution on a rotating blade for a turbo-jet engine. Eight FBG sensors are mounted on two blades for purpose of measuring the local strain at different speed, strain condition in terms of strain frequencies and strain amplitude was determined within a region, the results show that:

1. To a rotating blade’s frequency response, the influence from fluid is more complex than the existing knowledge, rotating blade’s first natural frequency is stimulated at speed of 77RPM, and at speed of 741 RPM, the first natural frequency of blade is scattered in frequency cluster excited by fluid, the dynamic strain maximum peak-peak value come to 100 με (Fig. 2).
2. For rotating blade, it is convenient to measure the natural frequency and easy to verify the theoretical calculation result involving rotating blade.
3. At the speed of 846 RPM, time domain dynamic strain shows the feature of shock. The characteristics are not antique on the theoretical analysis.
4. At the speed of 77 and 249 RPM, spectrum analysis of dynamic strain shows existing a frequency cluster, which increase exponentially with the speed and influence the frequency response of rotating board (lead blade self-excited vibration at 741 RPM), we can foresee that the high order natural frequency will be motivate at higher speed, this have important influence to the fatigue life and will be taken into account in the future research.

Acknowledgements

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