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Rotating Cantilever Beam Dynamic Strain Measurement and Analysis based on FBG

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Abstract

The main form of machine's working principle is rotation. The mechanical properties of rotating component are significant importance to improve the machine's reliability. In the measurement, the difficult thing is to transmit signals form sensors on a rotor to a stationary part . In this paper, using the FBG's(Fibre Bragg Gauge) properties of wireless transmission, author measure the local strains of rotating cantilever beam cantilever by utilizing the strain principle gauge FBG(Fibre Bragg Gauge) and the rotary signal transmit equipment,. The result of analysis showed that rotating cantilever have complicate dynamic phenomenon, dynamic strain not only related to speed but also related to fluid action, the dynamic stiffing phenomenon were observe in the same time. Finally, author offer an improved insight into a strain measurement technique for a rotating mechanical system. The research work could provide an effective way for measuring rotating component's mechanical properties.

Key words: *fiber Bragg grating (FBG) , dynamic stress , measurement , beam*

1. Introduction

Rotating component can be found on almost every unit of machinery equipment, and is the main component for realization of mechanical function conversion. In the development of modern industry, equipment continuously develops towards the direction of large-size, high-speed and flexible, the unit load of rotating component tends to become larger and larger, and factors such as control of machinery vibration, reduction of stress level, and enhancement of usage life of mechanical component and usage reliability are becoming more and more important. Usually, dynamics design will be performed for important components, so as to determine its mode (displacement, speed and acceleration mode), but these parameters reflect overall dynamics performance of structure, and are not sensitive for local change of structure, damage of structure normally occurs at the location of the largest stress, rather than the location of the maximum displacement, speed and acceleration, in recent years, numerous scholars have started to study measurement of dynamic response through stress and strain [1,2].

For rotating component, the key point of strain measurement is how does the signal transmit between rotating component and stationary components, methods available at present include electric slip ring, telemetry, optical fiber slip ring, and FBG collimator. In literature [3-6], researcher measures stress distribution of steam turbine impeller blade and air compressor blade under rotation condition by adopting slip ring, and signal is transmitted through stationary component (electric brush) and rotating component (armature) of slip ring, the disadvantage of this method is the physical contact between electric brush and armature will cause noise, which will overcome signal under circumstance of high rotation speed. The telemetry, was firstly utilized by Westhouse in 1958 for measurement of rotating component [7], rather than uses slip ring, this type of technology enlarges strain signal before transmitting strain signal to a radio frequency transmitter which transmits it in form of frequency-modulated wave, then receives frequency modulated signal by antenna, and then demodulates and enlarges strain signal. The disadvantage of this method is rotation speed of test cannot be high due to the extra weight of radio frequency transmitter, but the transmission distance is large, reaching up to nearly 1000 km. No matter for slip ring or for wireless telemetry, there is a same difficulty-strain response of vibration is different for different excitations, and distributive measurement is required, while each strain gauge needs two pieces of wire, large quantity of wires will cause difficulty of dynamic balance, at the same time, requirements of strain gauge mounting technique are high,

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there are numerous installation difficulties. 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 got more and more attention [8-9]. 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 piece of 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 out from end of rotating optical fiber, and enters stationary optical fiber through air. To realize signal transmission, the disadvantage of this method is friction between pipe wall and optical fiber causes low rotation speed, which is normally lower than 2000rpm. Literature [10] has researched measurement of rotating component stress through FBG-optical fiber slip ring, but its rotation speed is lower than 2000r/m.

In this article, FBG-collimator method is adopted for measurement of dynamic strain of rotary cantilever beam, its theory is similar with literature [], but rotation speed is up to 3000rpm. Through serial connection of 3 FBG strain sensors on rotary cantilever beam modal surface, change of cantilever beam strain under 800rpm has been researched, and dynamic strain distribution and response of rotating cantilever beam under rotation condition has been analyzed, indicating that this method can measure dynamic strain of high-speed rotating component effectively.

2. Research Method

2.1 The FBG Sensor

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, know 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:

$$\lambda_B = 2 n_{eff} \Lambda \quad (1)$$

Where λ_B is the Bragg wavelength of FBG, n_e is the effective refractive index of the fiber core, Λ is the grating period.

If the grating is exposed to external perturbations, such as strain and temperature, the Bragg wavelength will changes. 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:

$$\Delta\lambda_B = a_\varepsilon \varepsilon + a_T \Delta T \quad (2)$$

Where a_ε is the strain sensitivity coefficient, a_T the temperature sensitivity coefficient, with the assumption of no pressure change and no temperature change, we can measure the strain from wavelength shift as:

$$\Delta\lambda_B = a_\varepsilon \varepsilon \quad (3)$$

2.2. Working Principle Of Non-Contact Optical Signal Transmission

Figure 1 shows the working principle of the non-contact optical signal transmission, broadband light emitted from a light source and 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.

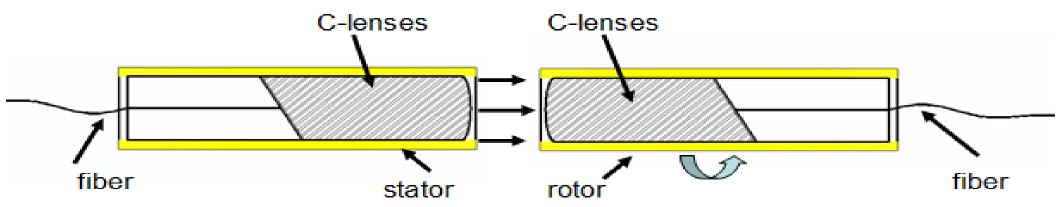

Figure 1. Working Principle for Rotary Optic Signal Transmission

2.3. Working Principle Of Dynamic Strain Detection

Dynamic strain testing system of rotating rectangular sheet consists of personal computer, interrogator, optical fiber rotating joint, FBG, rotating shaft and blade.

After coupling, light emitted by wideband light source in FBG demodulator enters optical fiber, move forward in polylines, 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 after passing optical fiber rotating joint, 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.

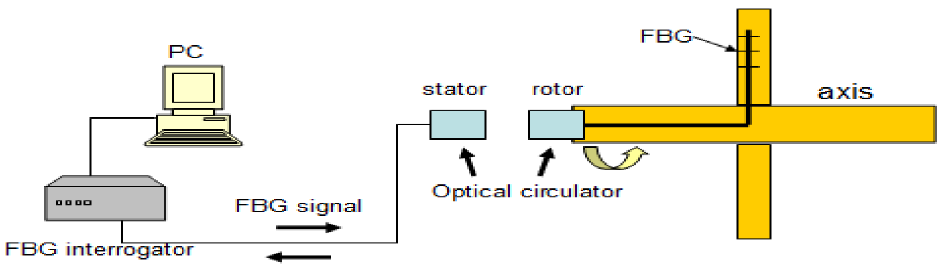

Figure 2. Experimental Set-Up for Dynamic Strain Detection by FBG

3. Simulation

Dynamic strain response of rotary cantilever beam will change under excitation of different rotation speeds, in order to mount FBG at the position of maximum strain, and enhance measurement effect, strain mode of cantilever beam has been analyzed, as shown in the figure, dimension of analytic model and material property are described in 2.1, model boundary conditions are configured as: complete solid connection at ends without consideration of deformation along direction x, i.e. deformation along cantilever beam width direction, its 1st, 2nd and 3rd natural frequency are respectively 60.199Hz, 375.2Hz and 1045.6Hz, the maximum strain positions are respectively 0mm, 159.3mm and 90.4mm, with consideration of actual length of FBG, the actual installation positions of FBG are respectively 5mm, 159.3mm and 90.4mm, as shown in Figures 3-5.

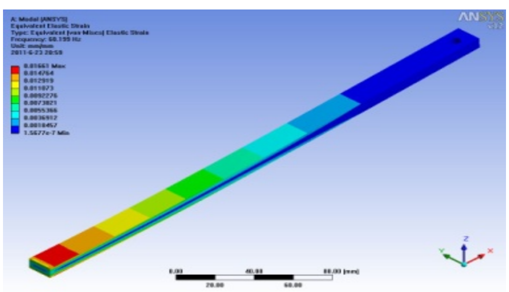

Figure 3. The 1st Strain Mode Shape

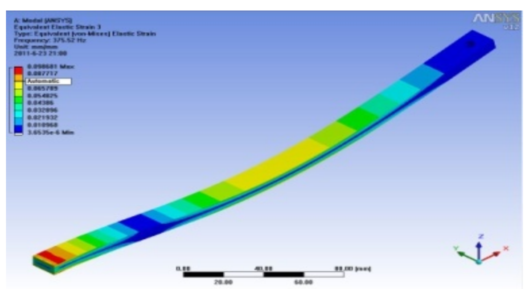

Figure 4. The 2nd Strain Mode Shape

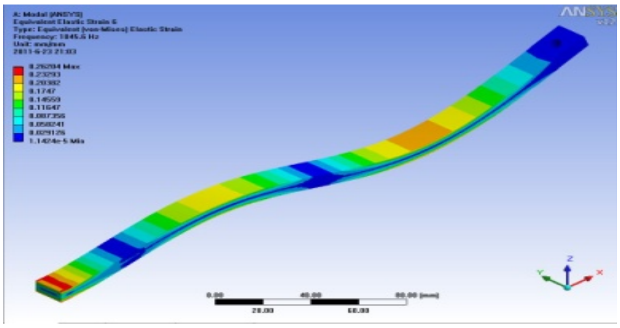

Figure 5. The 3rd Strain Mode Shape

4. Dynamic Strain Measurement Of Rotating Blade

4.1. Experimental Set-Up

As constitution of dynamic stress measurement system of rotary cantilever beam shown in figure 7, the driving device is a AC variation frequency motor of 45KW and rotation speed 30~3000rpm, rotation speed can be adjusted by speed regulation software of industrial control computer, or by manual adjustment of adjustable resistance, motor drives a speed-increasing gear box, of which gear ratio is 1:5, gearbox drives bearing box, cantilever beam is installed on end face of bearing box, and is built in-house, with length 280mm, thickness 6mm and material Q235, modulus of elasticity 2.09E11 and density 7800kg/m, specific shape as shown in figure 6, rotary collimator holding device is installed on end of high-speed shaft of speed-increasing gear box, so that optical shaft center of rotary collimator is located at the rotating center of rotating shaft, adjust the stationary collimator on five-dimension fine adjustment bracket fixed on foundation, so that optical shaft centers of two collimators coincident with each other, thus optical signal communication can be realized between rotary-stationary collimators.

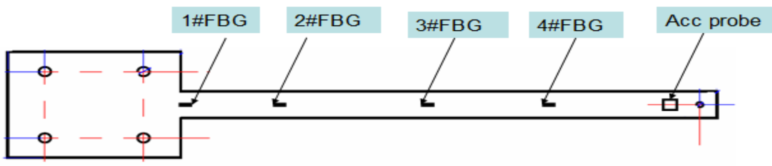

Figure 6. The Cantilever Beam and FBG

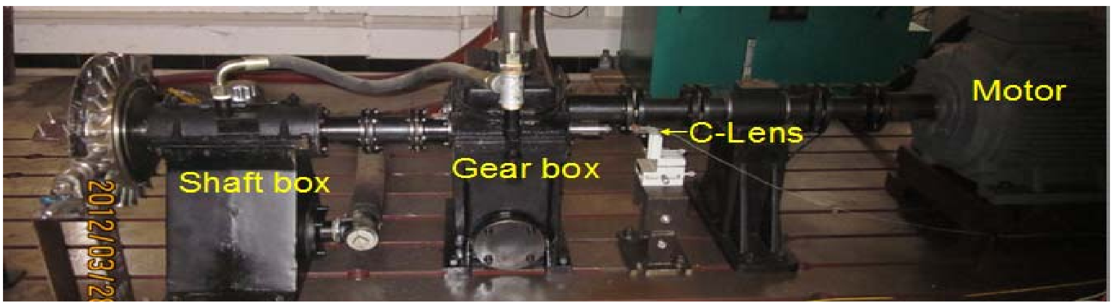

Figure 7. Experimental Set-Up

4.2. Result

Under environment of room temperature 20□, perform measurement test of dynamic stress, firstly in order to avoid discrepancies between boundary conditions of simulation analysis and actual conditions, impact test is performed for cantilever beam under static condition, to determine natural frequency of cantilever beam, as shown in the figure, the 1st order frequency is 54.9Hz and the 2nd order frequency is 331.8Hz.

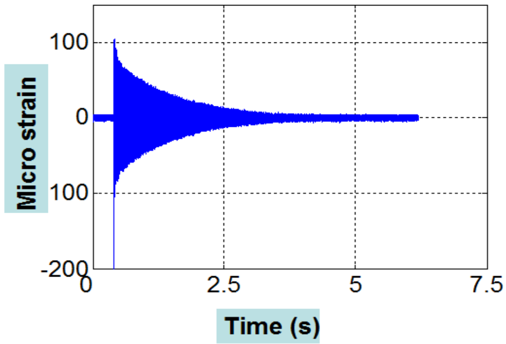

Figure 8. Impact signal of Cantilever Beam

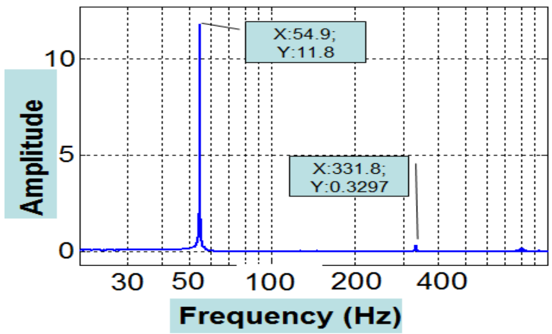

Figure 9. Analysis of Impact Signal Response Spectrum

Rotation speed test starts from 100rpm, and rotation speed rises to 800rpm stably as per interval of approximately 100rpm point by point, recording FBG output value of all recording points in turn, after reaching 800rpm, decreases to 0rpm stably as per interval of 100rpm point by point, make records of retracting stroke FBG output value of all test points in reverse order, and repeat the cycle as per the above mentioned method for 3 times, then subtract the average value of Bragg wavelength of all gratings from FBG Bragg wavelength of all channels, the results are plotted in figures as follows, figure 10 shows the change of micro strain of cantilever beam under constant rotation speed 420 rpm, and figure 11 shows analysis of response spectrum of signal in figure 10, in which, frequency 7.26Hz is a frequency related to rotation speed, 14.53Hz is doubled-frequency of 7.26Hz, normally doubled-frequency related to rotation speed exists in rotary system driven by motor, 55Hz is 1st order natural frequency of rotary cantilever beam.

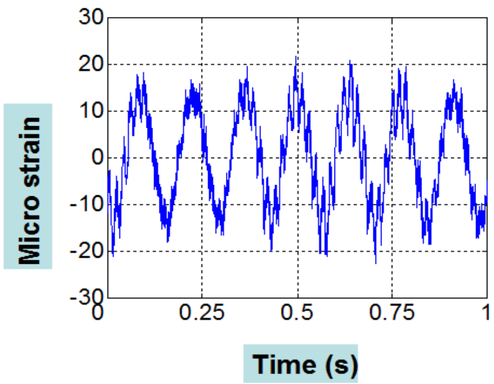

Figure 10. The Rotating Cantilever Beam Dynamic Strain Data From 1#FBG in 420RPM

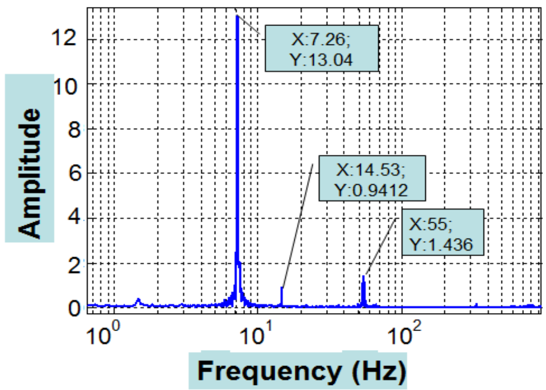

Figure 11. The Rotating Cantilever Beam Dynamic Strain From 1# FBG in Frequency Domain in 420 RPM

Figure 12 shows the micro-strain change of cantilever beam under 660rpm,figure 13 shows analysis of frequency spectrum in figure 12, which shows existence of frequency 10.93Hz related to rotation speed, existence of frequency spectrum 21.85Hz related to rotation speed doubled-frequency, and existence of a large amplitude frequency 55.18Hz near natural frequency 54.9Hz of cantilever beam, the reason for appearance of frequency 55.18Hz is dynamic stiffening of cantilever beam under the action of centrifugal force, which make natural frequency of cantilever beam raise approximately 0.28Hz, the reason for rapid rise of dynamic stress amplitude of cantilever beam at 55.18Hz is similarity between natural frequency and 4-time-frequency of rotation speed, and resonance occurs , meanwhile, with the rise of rotation speed, effect of fluid embodies gradually, the 2nd natural frequency 333.8Hz of cantilever beam and its double frequency are excited, but its frequency value is larger than static value, which is also a phenomenon of dynamic stiffening.

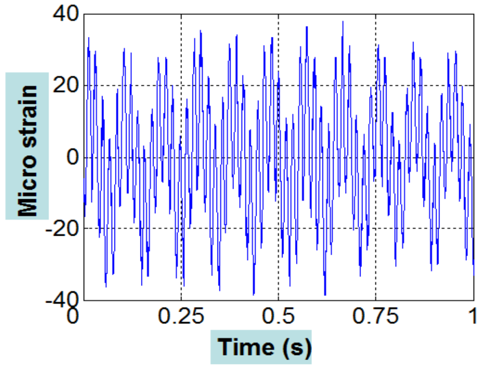

Figure 10. The Rotating Cantilever Beam Dynamic Strain Data From 1#FBG in 655RPM

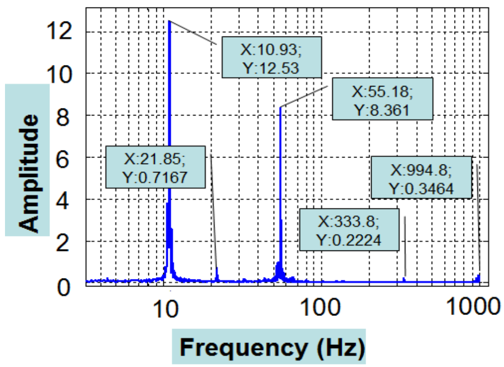

Figure 11. The Rotating Cantilever Beam Dynamic Strain From 1# FBG in frequency domain in 655RPM

5. Conclusion

This article introduces a new strain measurement method of rotating component, strain of constant section cantilever beam under rotary condition is measured through complex structure of FBG-optical coupler, dynamic strain of constant section cantilever beam under high-speed rotary condition is measured through the characteristics of FBG such as multiple-point with one line ,distributive measurement and non-contact transmission of optical signal, meanwhile, test results are analyzed, as indicated in test analysis, cantilever beam embodies abundant kinetic characteristics under rotary condition, substantial theoretical researches have been performed on some of these kinetic characteristics, while research on other characteristics has just been started. This article has provided some fundamental experiment helpful for these researches, and these theories can be verified in experiment. Due to restriction of experimental conditions, the highest rotation speed reached in this thesis is only 800rpm, but it is possible to reach 20000rpm in theory, and stress measurement requirements of existing machinery equipments can be met basically.

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