

Measurement of Rotating Blade Tip Clearance with Fibre-Optic Probe

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Measurement of Rotating Blade Tip Clearance with Fibre-Optic Probe

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Abstract. This paper described a tip clearance measuring system with fibre-optic probe. The system is based on a novel tip clearance sensor of optical fibre-bundle mounted on the casing, rotating speed synchronization sensor mounted on the rotating shaft, the tip clearance pre-amplification processing circuit followed by high speed data-acquisition unit. A novel tip clearance sensor of trifurcated optical fibre bundle was proposed and demonstrated. It is independent of material of measured surface but capacitive probe demands target conductive. Measurements can be taken under severe conditions such as ionization. Sensor circuitry and data acquisition circuit were successfully designed. With the help of Rotation synchronized sensor, all the blades can be detected in real-time. Because of fibre-optic sensor, the measuring system has commendably frequency response, which can work well in high rotating speed from 0-15000rpm. The measurement range of tip clearance is 0-3mm with 25 μ m precision.

1. Introduction

Blade tip clearance is one of main parameters governing the efficiency of turbine engine. Large tip clearance leads to large leakage flows, hence low efficiency; small tip clearance leads to rotor blades touching static case, hence insecurity. Therefore for improving efficiency and security of engine, the real time and non-contact tip clearance measurement system plays an important part especially in rotating turbo-machinery [1].

The traditional methods of tip clearance measurement include discharging probe measurement, eddy current measurement, capacitance measurement and so on [2]. The discharging probe measurement demands electricity conducting blades, which only measures the least clearance of rotational blades. The eddy current measurement demands that the blades must conduct electricity, and the tip end face must have some thickness. Because the output of sensor will change with the tip shape, setting state and environment temperature, so it must be calibrated in advance. The capacitance measurement has badly frequency response; it demands that the blade must be iron material. The traditional measurement methods have some limitations. So recent years, much research and development has gone into investigating the ability of optical probes to achieve this goal [3].

This paper proposed a tip clearance measuring system with fiber-optic probe, which share the same characteristic with Reflective optical fiber displacement sensor. The kind of sensor offer great advantages particularly in non-contact and difficult measurement environment with high resolution and wide bandwidth [4].

2. Optical fibre tip clearance measurement system

Figure 1 shows the composing of tip clearance measurement, which comprises the tip clearance sensor mounted on the casing, rotating speed synchronization sensor mounted on the rotating shaft, the tip clearance pre-amplification processing circuit followed by high speed data-acquisition unit. Blade tip clearance is sensed by the photo-detector as receiving light power. The tip clearance sensor plays an important role in the measuring system. Speed synchronization sensor is applied to measure rotate speed of turbo-machinery, whose signal is also as the synchronization one of the tip clearance sensor. The highest pulse frequency of speed synchronization sensor is 250Hz when rotate speed is not more than 15000rpm. Magneto-electric tachometric sensor can achieve this.

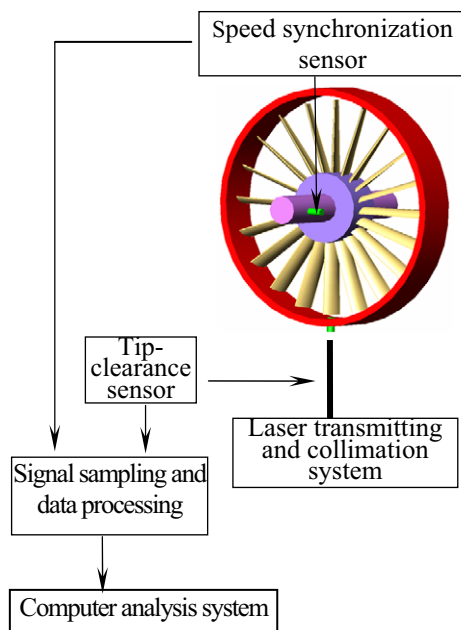


Figure 1. Configuration of tip clearance measurement system on turbine blade.

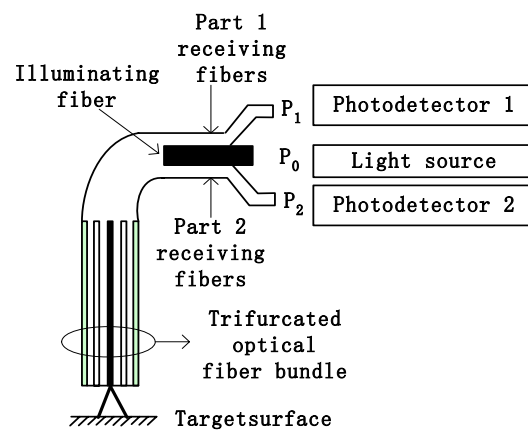


Figure 2. (a) Schematic setup of the differential optical fibre sensor.

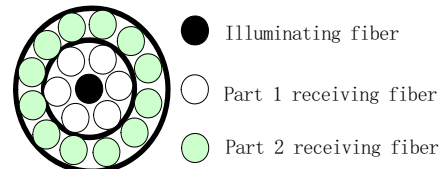


Figure 2. (b) Cross section of probe.

2.1. Optical fibre tip clearance sensor

As is shown in figure 2(a), tip clearance sensor consists of a laser diode light source, a trifurcated optical fiber-bundle probe and two photo-detectors [5]. The light radiated from the light source enters the illuminating fiber, radiates to a target and forms a diverging cone on the target surface. The light reflected from the target is differentially subtended as a function of target distance by receiving fibers and transmitted to a photo sensor. As a rule, an optical isolator is employed between the LASER and illuminating fiber to improve performance of the whole measuring system because light feedback may interfere the LASER as light source and even break the stability of the system.

Cross section of trifurcated bundle probe of figure 3 is composed of a centrally positioned fiber for illumination and the first neighbored circle of receiving fibers(part 1),the second circle of receiving fiber(part 2). This kind of sensor can eliminate the influence of light source fluctuation, target surface reflectivity, optical fiber loss and misaligned angle between probe surface and target surface. That can be proven by followed formula.

In addition, probe surface is usually required to do some rubbing and polishing in order to assure position array precision of optical fiber of probe surface while axes of the probe should be vertical to probe surface.

2.1.1. *Mathematic model analysis* [6]. When we take into account of light source fluctuation, target surface reflectivity and optical fiber loss, the receiving light power detected by photo-detector 1 and photo-detector 2 can be expressed as followed (1) and (2):

$$p_1 = I_0 \rho_0 \rho_1 \rho_R f_1(d) \quad (1)$$

$$p_2 = I_0 \rho_0 \rho_2 \rho_R f_2(d) \quad (2)$$

In the formula, I_0 is light intensity radiated from illuminating fiber, ρ_R is the effect coefficient of reflectivity variety of measured tip surface to measurement results, ρ_0 is effect coefficient of light source fluctuation to the measurement results, ρ_k is the effect coefficient of receiving fiber loss. $f_k(d)$ Is the function relationship of tip clearance, d .

We will obtain the following equation (3) by dividing operation on (1) and (2).

$$\frac{p_1}{p_2} = \frac{\rho_1 f_1(d)}{\rho_2 f_2(d)} = k * g_1(d) \quad (3)$$

For the same optical fibre sensor, ρ_1 and ρ_2 are constant so that the ratio is also constant. From the above expressions, we can find that the ratio of part 1 and part 2 receiving light power is independent of light source fluctuation and target surface reflectivity, but dependent of tip clearance, d [7].

3. Designation of tip clearance signal pre-processing circuit and data acquisition circuit

Block diagram of the sensor circuitry and data acquisition circuit is shown in figure 3. It mainly consists of photo-detectors, pre-amplifiers and post-amplifier filter circuit, A/D converter and two pieces of FIFO [8].

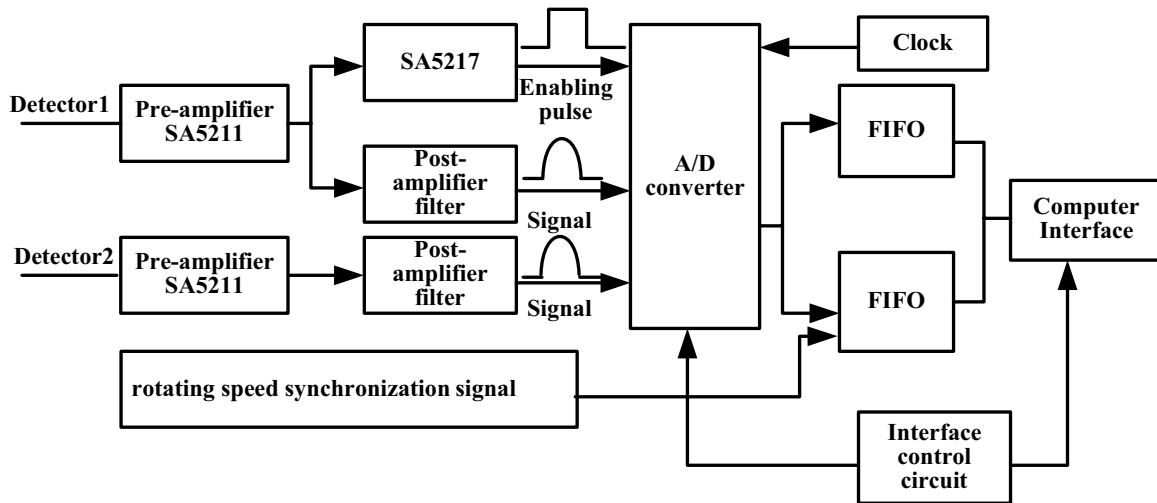


Figure 3. Schematic diagram of tip clearance signal processing circuit.

GT101 PIN Photoelectric diode is employed as photo-detector, which can convert photo signal to electrical one. After two channel electrical simulate signals are respectively amplified and filtered, they are converted to digital signal by A/D converter and then acquired to computer by interface circuit. Two piece of FIFO, followed by A/D converter, work as data buffer. SA5211 and SA5217, designed by Philips Co, are respectively employed as pre-amplifier and post- amplifier, which are specially applied in optic-communication aspect. SA5211 is a 28K trans-impedance, wide-band, low noise amplifier with differential outputs, particularly suitable for signal recovery in fiber optic-receivers. Differential outputs greatly enhance Signal-to-Noise of the whole circuit.

The SA5217 is a 75MHz post-amplifier system designed to accept low level high-speed signals. The SA5217 can be DC coupled with the previous trans-impedance stage using SA5211 trans-impedance amplifiers. SA5217 includes differential amplifier and threshold comparator.

When every blade passes the optical fiber probe, SA5217 outputs high level that enable A/D converter to work. At the same time, two channels of analog signal are converted digital signal through FIFO entered computer for further processing. All the blades can be detected with the help of rotating speed synchronization signal.

In addition, circuit board is required special filter and layout and because the band width is more than 75MHZ.

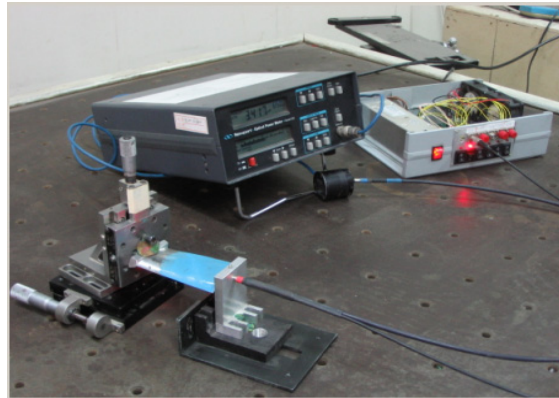


Figure 4. The static experiment setup for measuring tip clearance with optical fiber probe

4. Experiment

Figure 4 shows the static experiment setup for measuring tip clearance with optical fiber probe. Firstly, we adopted Y type tip clearance sensor of the fiber bundle to measure target distance. It consists of one centrally positioned fiber for illumination with numerical aperture (NA) 0.11; core/clad, 400/440 μ m, and the other six receiving fibers around the illuminating fiber, with numerical aperture (NA) 0.22, core/clad 566/600 μ m.

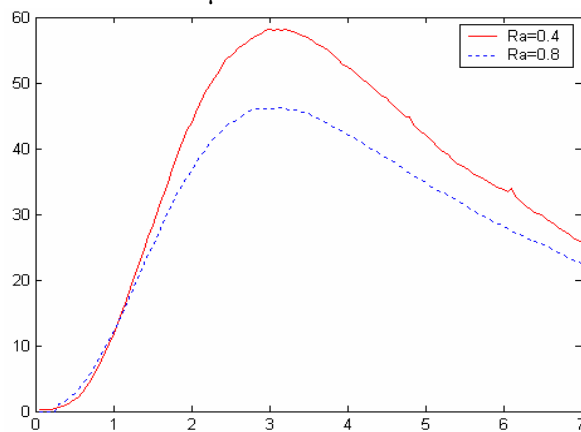


Figure 5. Relationship curve of receiving light power and tip clearance on different target surface.

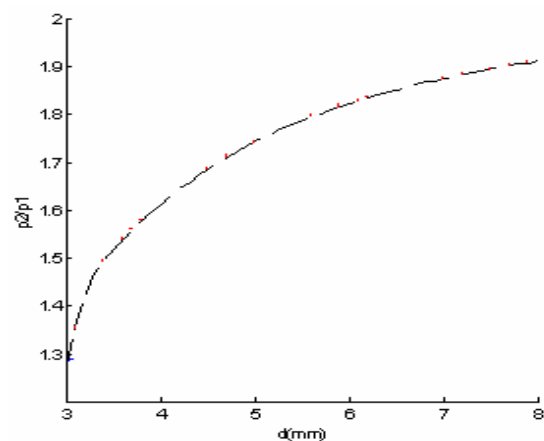


Figure 6. Ratio curves of part 1 and part 2 receiving light power and tip clearance.

The relationship curves of receiving light power and tip clearance on different target surface are as shown in figure 5. When metal surface of roughness $Ra=0.8$, was measured, we got the dotted line; when metal surface of roughness, $Ra=0.4$ was measured, we got the actual line. They have the same characteristic, the receiving light power increased when tip clearance was less than 3mm, and then decreased when tip clearance was more than 3mm.

The difference of two experiment curves illustrates that effect of reflectivity variety of measured surface to measurement results cannot be ignored. In the same manner, effect of light source fluctuation to the measurement result is also not ignored.

In order to eliminate measurement errors resulted from reflectivity variety of measured surface and light source fluctuation, from above Mathematic model analysis, Tip clearance sensor of trifurcated optical fiber bundle was manufactured. Two target surface with different roughness ($R_a=0.4$, $R_a=0.8$) were respectively detected. Two parts of receiving fibers lead to two relationship curves between receiving light power and tip clearance on the same target surface.

Ratio curves of part 1 and part 2 receiving light power and tip clearance were obtained when two parts of receiving light power values were respectively divided. As shown in figure 6, the two curves are coincident. This illustrated that effect of reflectivity variety of measured surface to measurement results had been basically eliminated. In the same manner, effect of light source fluctuation to the measurement result can also be eliminated.

Additionally, receiving fibers are aligned concentrically and receiving fiber NA is greater than illuminating fiber NA, which can contribute to reduce measurement error caused by inclination and torsion of blade tip.

5. Conclusion

From above theoretical analysis and experiments of lab, it is obvious that tip clearance sensor of bifurcated optical fiber bundle has some drawbacks. Its measurement result is easily affected by reflectivity variety of measured surface and light source fluctuation and so on. Hence the tip clearance sensor of trifurcated optical fiber bundle has been employed to overcome the above drawbacks. It is also demonstrated by experiments. This kind of sensors can attain the best resolution, large measurement range, the highest system bandwidth. However, compared to other kinds of sensors, they are often expensive and are sensitive to contamination. Despite these drawbacks, Optical fiber sensors have the best potential to be successfully adapted for measurement of high rotating blade tip clearance. SA5211+SA5217 are successfully employed to achieve designation of circuitry. With the help of Rotation synchronized sensor, all the blades can be detected in real-time. Because of fiber-optic sensor, the measuring system has commendably frequency response, which can work well in high rotating speed from 0-15000rpm. The measurement range of tip clearance is 0-3mm with 25um precision.

Acknowledgements

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