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Analysis of Resonance in Blade Vibration

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Abstract— the gas turbine operates at different range of speeds. When the natural frequency of the blade becomes equal to the rotor frequency, resonance is said to occur. The gas turbine should not operate at this frequency because it will result in increase in wear and tear of the turbine. The purpose of this paper is to find the resonant frequency using an optical sensor measurement. A pulse generated from reference probe is used to test the vibrations under given conditions.
Here, Optical sensor output is synthesized with respect to the reference probe with and without blade vibration. With vibration, sensor output gets modulated with the natural frequency. Thus in this paper we extracted the natural frequency for different rotor speeds and found the resonance.

The mean square error is estimated for each of the rotor speed. The same analysis is also concluded for noise corrupted sensor output.

Index Terms—Blade Vibration, Optical Sensor, Resonant Frequency, mean square noise, signal to noise ratio.

Introduction

To develop a tip measurement system it is important to observe, understand and predict the vibration of turbo machine blades [1].The life and durability of the blade is limited by High Cycle Fatigue (HCF). Problems like blade failure have expensive consequences to the engine. Blade fatigue and maximum vibration levels, a blade can withstand must be monitored and controlled before failure occurs. Failure is determined by off-rig tests which are expensive and time consuming. High temperature and centrifugal loading are the criteria taken into consideration while designing the test [5].Destructive testing is done to determine fatigue testing. A comparison between the fatigue strength findings from the off-rig trials with the highest vibration level detected in the engine under consideration is used to predict blade life or durability.

Pressure distribution causes alternating aerodynamic forces in the compressor blade of the gas turbine. Air flow through inlet guide vanes, up streams, down streams and stator vanes causes pressure distribution. This may cause the blade to vibrate. When the rotor frequency matches with the natural frequency of the blade vibration, resonance occurs. This may cause the blade to vibrate more.

The conventional method of measuring vibration level of rotor blades involves usage of strain gauges attached to the surface of the blades. The resultant signals exit the engine through slip rings or radio telemetry systems. The disadvantage of this method is that it results in high failure and degrades the performance of the engine since gages and wiring are located inside the engine. Moreover, for this instrumentation many engine parts have to be modified which leads to high cost and delay.

The alternate method for measuring vibration level on rotor blades is non contact measurement from the casing mounted probes [1], [3]-[5]. The transmission methods between rotor and stator have been removed and concurrent measurement of all blades ensures no instrumentation effects. Cost is reduced as well as preparation time is economized. This system uses 15millwatt He-Ne lasers, optical fibers and associated electronics. This system can monitor the rotor blade vibration under engine running conditions. Due to fragile hardware, it must be installed in a measurement room to avoid shock and vibrations caused by the running engine. Long optical fiber bundles are required to connect the probes on engine case and He-Ne laser light source in the measurement room.

This paper is organized as follows section I gives introduction of blade vibrations and its occurrence. Also, the conventional methods and non-contact measurement is explained in this section. Section II explains the principle and operation of optical sensor. Section III illustrates the mechanism behind measurement of blade vibration. The simulated output obtained is displayed in IV. The inference and future scope is stated in V. Finally conclusion is given in VI.

Operation of optical sensor

Three optical probes have been mounted and spaced equally around the turbo machine casing. These probes receive the optical pulses from the rotor blade tips and then convert the optical signal into an electrical signal. The probes are connected by long optical fiber bundles on engine case and He-Ne laser light source in the measurement room. Reflected pulse train from rotor blade tips are converted into electrical signal as voltage pulse train and sent to data analyzer system by using a photo multiplier [2].The first probe is used to measure the number of revolutions of the blades. The second probe is used as the reference probe. The third probe is used to measure blade vibration. Durability and small size is achieved by intensive use of semiconductors such that the system can be directly mounted on engine case and only one meter long optical fiber bundles are used.

Measurement of blade vibration

i. Detection of signal

The He-Ne laser tube emits light into rotor blade tips through the optical fiber with the help of the two probes. The two optical probes are separated from each other are installed on the engine case (fig 1). A reference signal is picked up by an eddy current in proximity probe. In order to measure the time interval accurately, signals are amplified and passed through a threshold circuit to form a sequence of pulses. If the rotor does not vibrate, when the rotor speed remains constant, the time interval remains constant for each blade. Probe 1 is mounted on shaft and probe 2 and 3 is mounted on surface casing. Probe 1 gives a complete revolution of the blades and probe 2 and 3 are used to measure the blade frequency.

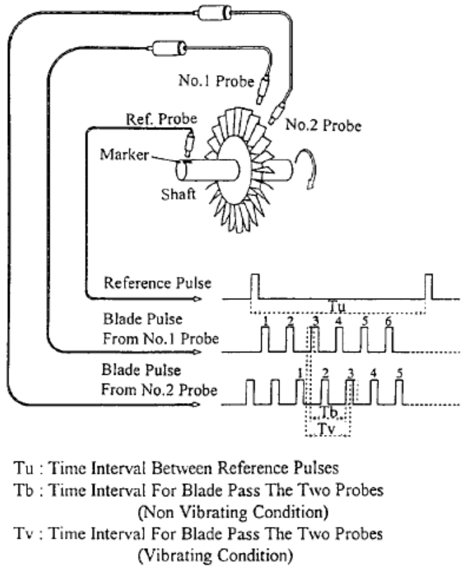


Fig.1. Schematic diagram of Optical Blade Vibration Monitoring Systems. Courtesy [1].

T_b represents the time interval of blades travelling between two probe positions. The pulse interval (T_b) fluctuates around the non-vibrating interval whenever any blade vibrated.

Blade vibration is the passing time difference between one blade to another with and without vibration. Shaft frequency is the number of shaft rotations in a minute.

$$Shaft\ frequency = \frac{rpm}{60}$$

$$Blade\ pass\ frequency = \frac{rpm * N}{60}$$

Where N is the number of blades and rpm is number of rotations per minute of the blades in the gas turbine.

But due to the vibrations occurring in the blade, different blade path frequencies will be observed. Different blade path frequencies occur due to operation of the turbine in various speeds. Mathematically blade frequency can be expressed as

$$Blade\ pass\ frequency\ (with\ vibration) = actual\ blade\ frequency - measured\ blade\ frequency$$

In theory, constant rectangular pulses will be obtained when there is no vibration. But in case of vibrations, the pulse position will be shifted based upon the magnitude of vibrations. According to the literature, the shift in the pulse position follows few cycles of sinusoidal shape. Phase and the magnitude of this sine signal will vary while the shaft speed varies. When the sinusoidal signal phase shift is 90 degree with maximum magnitude then the natural frequency of the blade becomes equal to the rotor frequency, resonance is said to occur.

This paper mainly focused to synthesis the phase shifted pulse position modulated sine signal for different shaft speed. Then to develop an algorithm to estimate the phase shifted sinusoidal signal for different shaft speed. Finally resonance frequency needs to be identified.

Simulated Results

i. Observed Output

A sine wave with 72 samples with each sample representing the amplitude of each blade will have a time period of two and half cycles. These 72 samples are taken with different rpm such that the pulse position is changed. The output of the probe which is taken from the sensor is synthesized when there is blade vibration. From the measured data, the magnitude of the blade vibration is extracted. Pulse position demodulation is used to extract the magnitude from the received wave.

ii. Retrieved Output

In this method the distance between two blades corresponds to the width of the pulse. The first two pulses of the probe are taken into consideration. On time is the duration where the pulse has amplitude of 1 and off time is the duration where the pulse has amplitude of 0.The distance between the transitions from 1 to 0 and 0 to 1 gives the value of off time. Due to vibrations, there will be a shift in the off time of time of the pulse and the difference between the shifted value and the reference value gives the amplitude of sinusoidal signal. This procedure is repeated for consecutive pulses to get the amplitude of vibration for all the blades. The peak vibration amplitude is constant at probes mounted position. As vibration passes the resonance speed, the vibration amplitude changes and concurrently vibration phase changes by 90°.

iii. Resonance

Resonance detection is considered more important than the detection of non-integral order vibration. Theoretically it is not possible to detect resonance vibration using the casing mounted probe if the engine keeps steady rotor speed. These difficulties are solved when the system is used to detect resonance vibration during slow acceleration [2].

Analysis and Reference

In this paper, speeds ranging from 2400rpm to 4800rpm at the interval of 300rpm are taken into consideration. The speed at which resonance occurs is assumed to be at 3600rpm [6] and the gas turbine should not be operated at this speed [4]. At this speed, the natural frequency of rotor is matched with the blade vibration frequency and at this frequency; it had been found that maximum blade vibrations occur. At these speeds (2400rpm to 4800rpm), the change in phase had been noted and their relationships had been observed. There had been an increase in phase with increase in speed and at the resonant frequency the phase was found out to be 90 °.

In fig 2(a) the sensor output mounted on the shaft is displayed. It is the number of rotations of the blade in one cycle. In fig 2(b) the output of probe 2 is shown. It is observed that when there are no vibrations there is no change in pulse position i.e. equal spacing in each pulse.

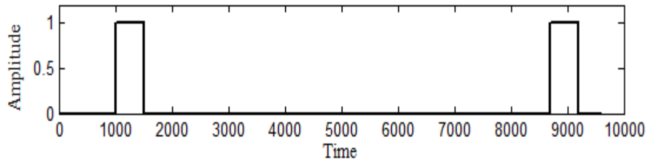
In fig 3(a), when blade vibrates, the pulse position will change. Each pulse in the graph gives the output of an individual blade which is shifted linearly. In Fig 3(b) these pulse positions when plotted as a magnitude, it follows two and a half cycles of sine wave theoretically at every instant [1].

Fig 4 shows the graph of different speeds each with different phase. As the rpm increases, the amplitude and phase angle of the sine wave increases till resonance, and after resonance, amplitude decreases with phase still increasing. A peak amplitude has been observed in the sine graph where the speed at which the gas turbine is operated is 3600 rpm, having a 90 ° phase shift(in Fig(4)).

In fig 5 a white Gaussian noise is added to the sine wave and its SNR (sound to noise ratio) is varied. The mean square error is calculated and analyzed. Mathematically mean square error (MSE) is calculated by using the formula:

$$MSE = E[(x' - x)^2]$$

Where x' is the amplitude of each blade in the measured signal and x is the amplitude of each blade in the actual signal.
The mean square error at various speeds is calculated and the variation of mean square error at various speeds is observed from the graph in fig (6).



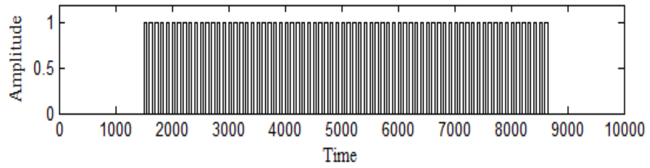


Fig.2.a Sensor output of the shaft probe

Fig.2.b Received output of probe 2

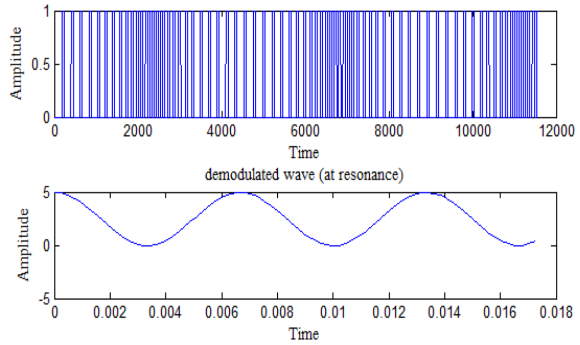


Fig.3.a Modulated pulse with blade vibrations

Fig.3.b Retrieved pulse with blade vibrations

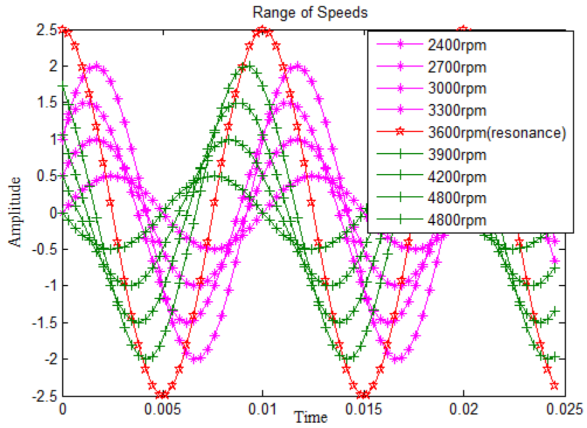


Fig.4. Different speeds with different phase

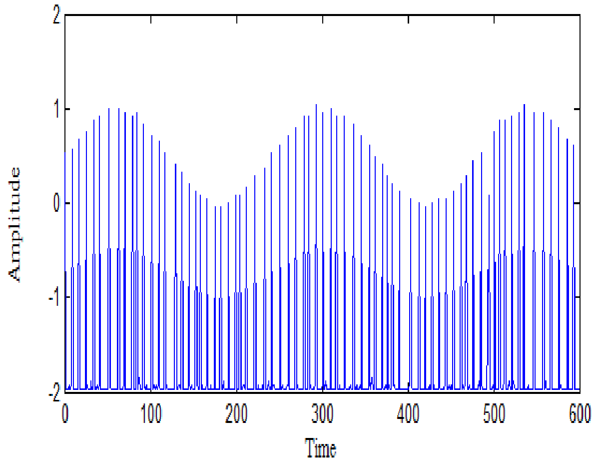


Fig.5. White Gaussian noise added to signal

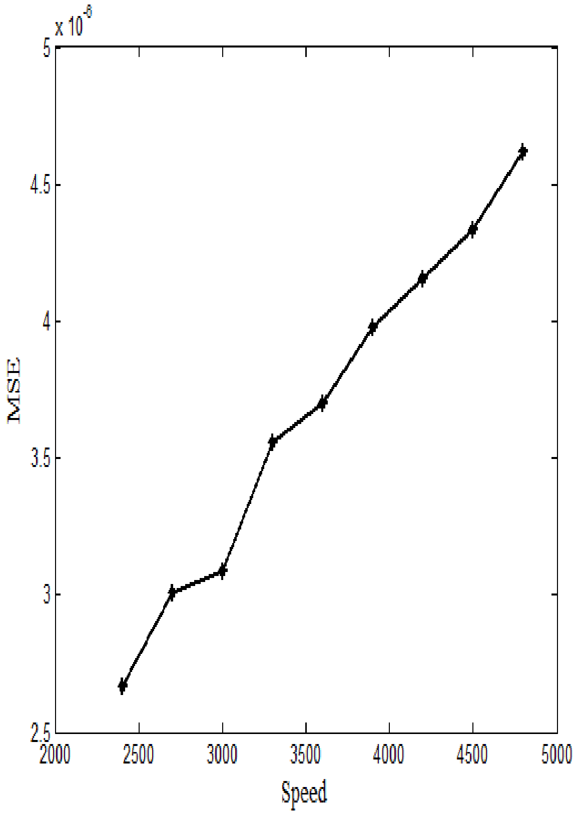


Fig.6. Plot of MSE at various speeds

Conclusion

The relation between phase and rotor speed was observed and analyzed. It is anticipated that there will be a severe resonance vibration in particular operating rotor speed range. The result shows that the resonance vibration is detected in the operating rotor speed range. The gas turbine should not be operated in this resonant frequency because it can cause wear and tear of the blade and mistuning. Moreover, 90˚ phase shift of the retrieved sine waveform shows that at that particular rpm it gets resonated, so it is instructed that this particular rpm should not be used. A white Gaussian noise was added to the modulated wave and the analysis of this noise was performed by varying the signal to noise ratio. The mean square error was computed mathematically for different speeds. It is observed that as speed increases MSE is also increased. In future, when the observed signal is corrupted with noise, a filter needs to be designed to remove the noise.

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