IJCTA, 9(39), 2016, pp. 291-296

A New Resonant Based Method for the Measurement of Turbine Blade Tip Clearance

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Abstract : Measurement of turbine blade tip clearance is necessary for active control systems for maintaining the optimized clearance. Improved blade tip clearance can provide a significant reduction in specific fuel consumption and time-on-wing, and improvements in engine efficiency as well as payload capabilities in high pressure compressors and high pressure turbines. Reported works on blade tip clearance measurement in rockets, gas engines and steam turbines has the capability to measure the tip clearance as well as time of arrival. Eddy current sensors, due to their noncontact sensing requirements, low power consumption, insensitivity to contaminants are most viable for detecting the turbine blade parameters. Resonating cantilever beam with piezoelectric excitation and detection with a magnet at the end as tip mass has been reported as eddy current based thickness measurement system. This paper discusses on extending the same principle for eddy current based turbine blade tip clearance measurement system. The work focusses on demonstrating the validity of the concept proposed for measuring tip clearance using a laboratory test apparatus, and to outline future course of action for application in aircraft engines.

Keywords : Piezoelectric, Tip clearance, Eddy current, MEMS, Resonant sensors.

1. INTRODUCTION

Tip clearance measurement is important for active clearance control in rockets and jet engines and steam turbines for improving the engine efficiency and for reducing the fuel consumption, time-on-wing etc. It is always desirable to minimize the clearance between the blade tips and the casing of the engine. However any contact between the blade tips and the engine causes damage to the engine and excessive clearance can cause a reduction in the engine efficiency. Thus the clearance is to be optimized in engines for the efficient performance. The sensors used for clearance measurement must be well durable to have a long service life. The tolerance level must be maximized in terms of temperature capability, vibration and impact,moisture,dirt or combustion product handling tolerance etc. Sensors must also have the capability to be easily demounted for calibration and maintenance in scheduled interval. Some of the technologies used currently for tip clearance measurement are eddy current, X-ray, inductive, capacitive, acoustic etc. The theory of eddy current based measurement systems and the importance of engine clearance control system have been well established[1,2]. Capacitive sensors based on synchronous detection of phase modulated signal has been reported [3,7] which gave a capacitance variation of about 120fF for a clearance variation of 100 μm. The system will have a zero error and higher complexity of fabrication. Capacitive sensors rely on a uniform dielectric material between the sensor and blade. This dielectric needs to be constant and non-contaminated. An eddy current based thickness measurement system has been reported in [4]. The system works with a cantilever as a resonating structure with piezoelectric excitation and detection of the eddy current produced by a magnet at the tip. The system works only for the thickness measurement of non-magnetic and non-conducting sheets. As the turbine blades are made of materials

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of similar characteristics, the same principle is extended for tip clearance measurement applications which has produced reasonable output .A tip clearance measurement method using pulsed eddy current is reported in [6]. The work reports on using a pulsed eddy current generator receiver pair for establishing the calibration curves of eddy current output as function of tip clearance. But the system is prone to errors depending on room temperature variation, ambient vibrations, electromagnetic interferences etc. These conditions are difficult to satisfy in the engine environment.

In this report the authors discuss about a more effective mechanism based on resonant frequency shift of vibrating cantilever beams with respect to the tip clearance of turbine blades. The frequency shift is the cause of eddy currents induced in the blades and is detected by the method discussed in [2]. The piezoelectric excitation has advantages such as strong force, low actuation voltage, high energy efficiency, linear behavior, high acoustic quality, high speed, and high frequency Moreover the system is efficient as it is more feasible to detect the blade's parameters, due to their non-contact sensing requirements, low power consumption, insensitivity to contaminants. The work is a proof-of-concept validation of using eddy current based sensors using a laboratory test apparatus, and to outline future course of action for application in aircraft engines.

2. PRINCIPLE OF DETECTION

The setup for clearance measurement consists of a permanent magnet fixed on a cantilever beam, which is fabricated into a hole in the turbine stator (casing). The tip of the rotating blade passes near the cantilever structure. A Piezoelectric patch is pasted on the cantilever beam. The schematic for the measurement system is shown in Figure1.

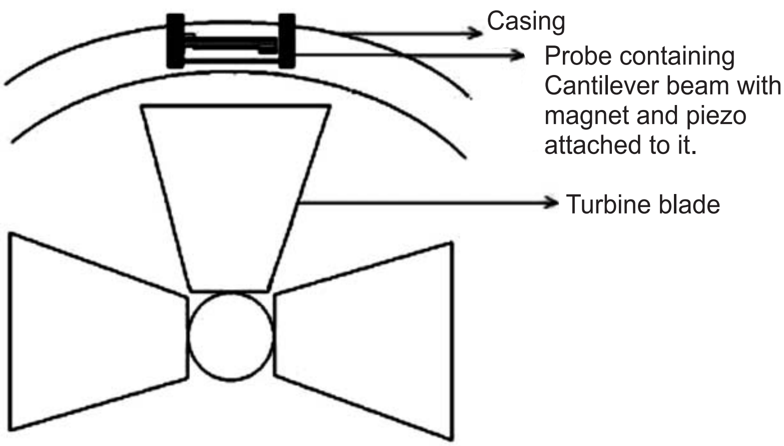


Figure 1: Schematic diagram of proposed measurement system

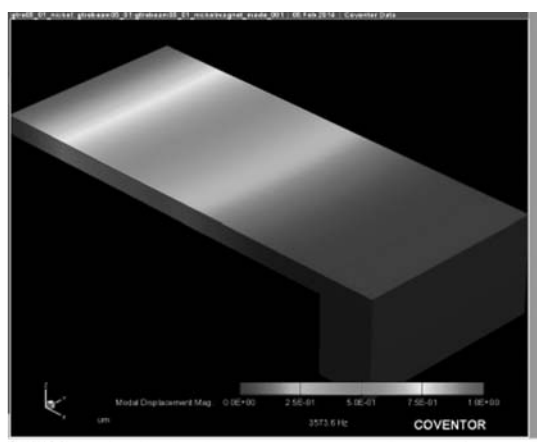


Figure 2: Displacement profile at first Modal Frequency

The rotating blade of the turbine interacts with the magnetic field due to the permanent magnet which is placed on the cantilever beam. Due to this, eddy currents are created in the engine casing that is opposing the permanent magnet's field. The passage of a blade, by the probe location disturbs the magnetic field, and implicitly the eddy current flow in the case wall. This causes a force to be applied to the cantilever beam, which acts as an impulse and causes the beam to vibrate. This vibration continues and damps naturally till the next blade passes through the magnetic field of the permanent magnet, when another impulse is produced and the amplitude of vibration of the cantilever beam rises again. The probe will be enclosed in a case made of non conducting non-magnetic material so that it does not have any impact on the measurement system and at the same time prevent any physical damage to the cantilever and remove effect of stray vibrations die to air drag. The feasibility of the measurement system depends on frequency and material properties of the blade, and the strength of the permanent magnet. It is important that the probe casing is designed in such a way that the temperature inside is significantly lower than the outside temperature to prevent errors due to thermal expansion and varying magnetic field strength of the permanent magnet.

3. MODELLING AND SIMULATION

3.1. Modelling of Cantilever Beam

The beam dimensions were obtained according to holes present in an in-use aircraft turbine. The dimensions chosen were 10mm*5mm*0.5mm. This beam with a permanent magnet attached to one of its ends was simulated using CoventorWare, a MEMS simulation tool. The fundamental frequency was found to be 3.857 kHz, which is not close to the frequency of the rotating turbine blade, (Figure 2) so as to prevent any resonance condition and subsequent damage caused.

3.2. Magnetic Field Simulation

The permanent magnet and the Turbine blade models were simulated using COMSOL Multiphysics software to determine the value of magnetic field at different points on the rotating blade. This is essential as it is not possible to compute the magnetic field theoretically.

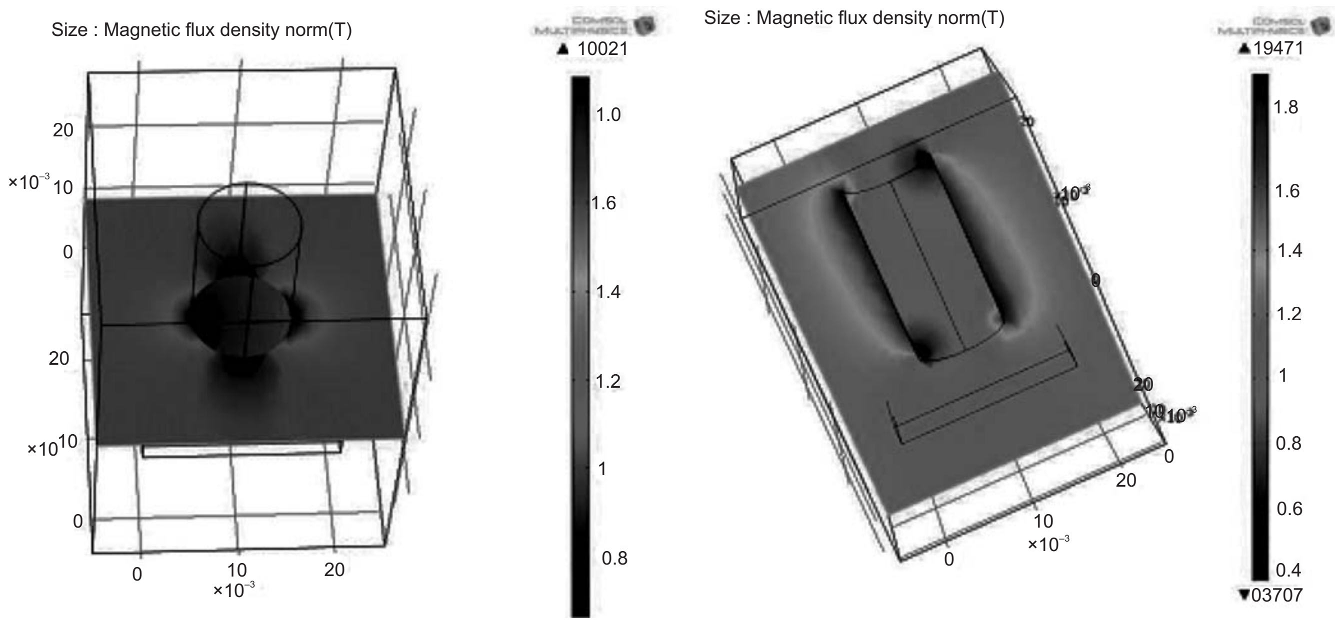


Figure 3: Magnetic field distribution

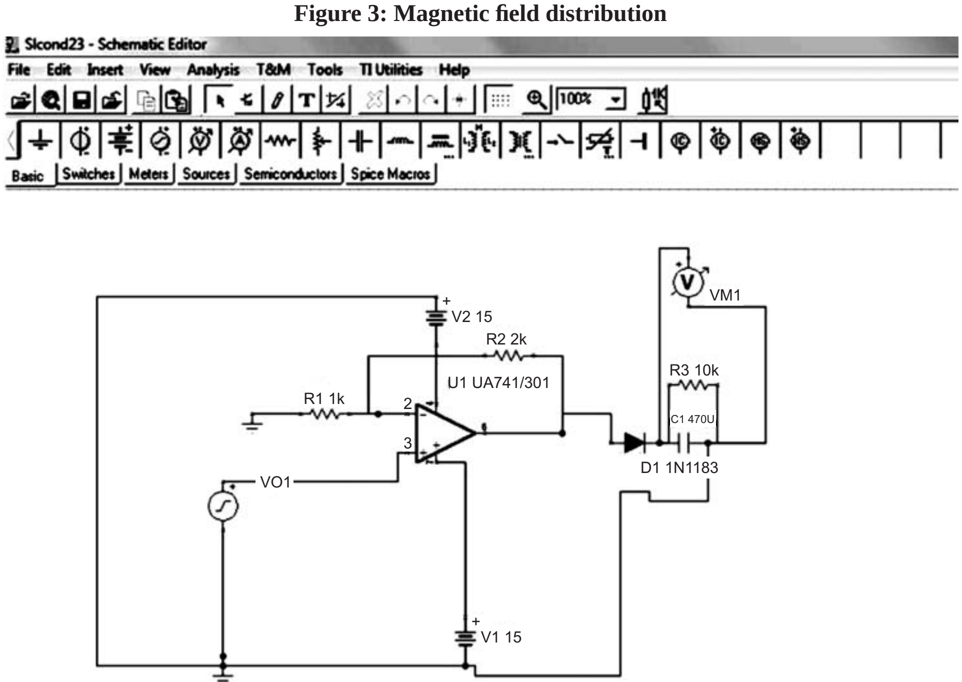


Figure 3:(*a*) Peak detector circuit

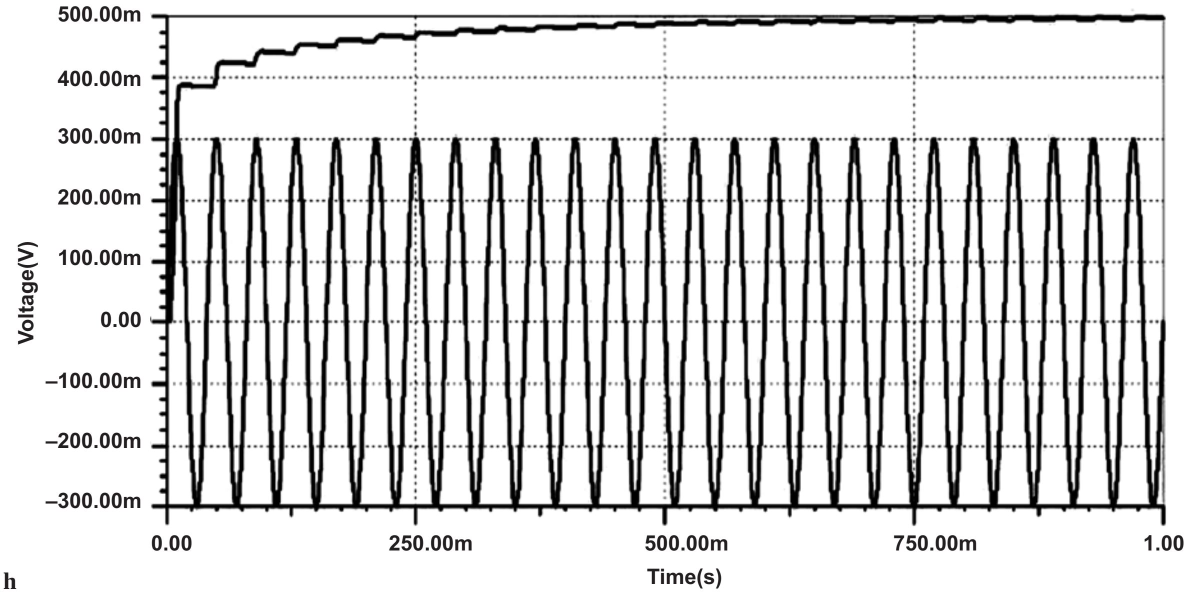


Figure 3: (*b*) Output of peak detector

3.3. Simulation of Signal Conditioning Circuit

The output obtained from the piezoelectric sensor will be oscillating. Hence a signal conditioning circuit is required to convert the oscillating output to a dc voltage that can be directly correlated to the tip clearance of the rotating blade. For this purpose, a charge amplifier circuit, used in conjunction with a peak rectifier was used. A charge amplifier is necessary to amplify the voltage generated in the piezoelectric crystals and to eliminate the noise signal. The peak rectifier is used to isolate the signal generated due to the passage of the blade near the cantilever beam from that natural frequency of the beam. The circuit and simulation results are shown in Fig 3(*a*) and (*b*)

4. EXPERIMENTAL RESULTS

Table 1
Magnet and beam properties

Symbol	*Description*	*Value*	*Units*
B_r	Residual flux density	1.2	T
l	Length of the magnett	15	mm
r	Radius of magent	5	mm
μ_0	Permeability of intervening medium (air)	1.256×10^{-6}	Hm^{-1}
E	Young's modulus of the beam	71	Gpa
I	Moment of inertia of the beam	2.219×10^{-12}	mm^4
l_b	Length of the beam	200	mm
b	Width of the beam	13	mm
h	Thickness of the beam	1.27	mm
m	Effective mass of the beam	8.9154×10^{-3}	kg
l_p	Length of the piezo	70.5	mm
b_p	Width of the piezo	13	mm
t_p	Thickness of piezo electric Layer	0.5	mm
d_{31}	Piezo electric strain constant	-247×10^{-12}	mV^{-1}
g_{31}	Piezo electric stress constant	-9×10^{-3}	VmN^{-1}
K_3^T	Dielectric constant	3100	–

A model beam of dimensions 10cm*2cm*0.1cm was used for the testing purpose. A permanent Nd-Fe-B magnet was used of Height 2.5mm and diameter 1.5mm. The properties of the magnet and the beam are given in Table 1. The apparatus used for test can be seen in Fig. 4

4.1. Testing

For modelling the turbine rotor, many arrangements were tried out, and experiments were conducted to measure tip clearance. Finally a two blade model with blade tip surface area analogous to the aircraft turbine blade was selected to conduct the final experiments.

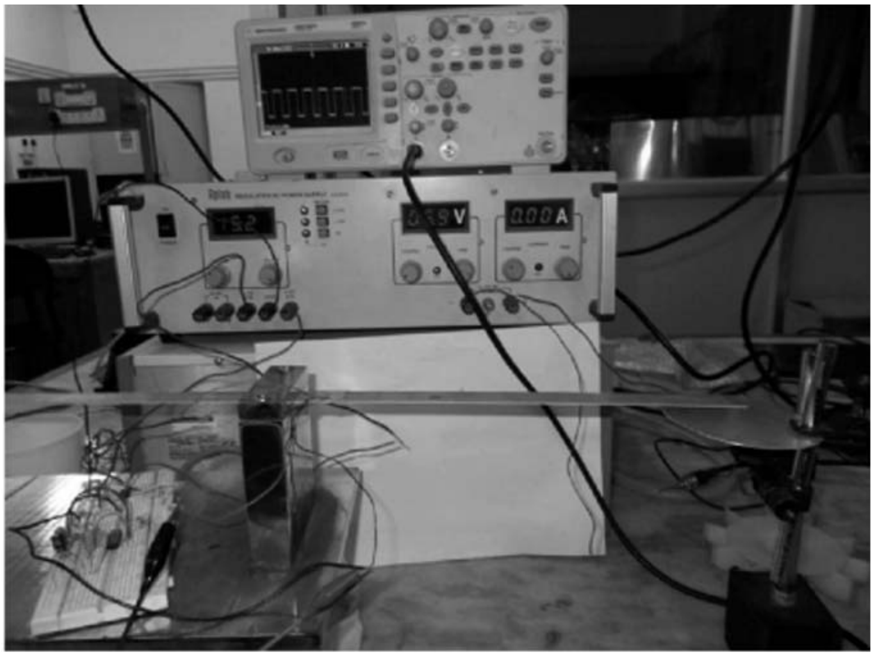
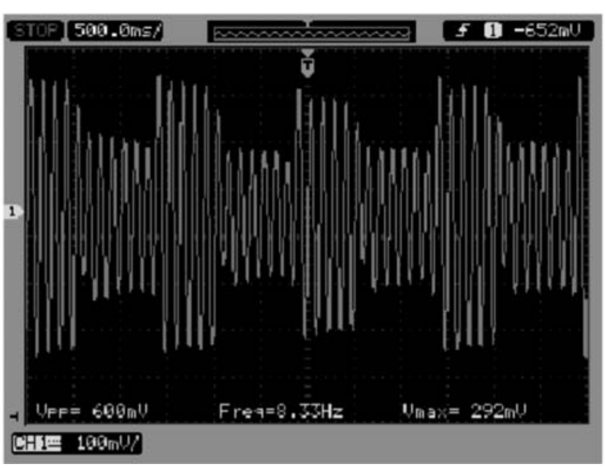


Figure 4: Experimental setup

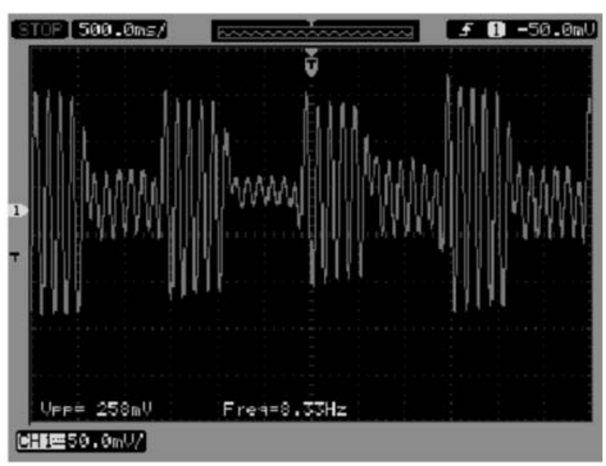
Figure 5: (*a*) Frequency of vibration at 2mm Figure 5: (*b*) Frequency of vibration at 4mm

4.2. Experimental Results



(*a*)

Figure 6: (*a*) Output at clearance *xmm*



(*b*)

Figure 6: (*b*) Output at clearance *x* + 2*mm*

Due to constraint in measuring dynamic tip clearance, the experiments were performed using two clearances x and $x + 2$ mm. This was achieved by raising the cantilever beam by 2mm. The turbine blade was rotated at an Rpm of about 150-200. The sensor output, from the piezo patch for both these clearances are shown in Fig 6(*a*) and (*b*). As can be seen, the desired sensor output Vpp rises from 250mV to 600mV. Also there is no change in the frequency of the beam, which remains at 8.33 Hz. This frequency depends only on the properties of the beam and the Rpm of the rotor.

To increase the voltage output, a gain of 10 was used for the charge amplifier in the signal conditioning circuit. The output after the signal conditioning circuit is a DC current. The Voltage level is significantly increased due to the charge amplifier. The table of sensor outputs obtained for various tip clearance is shown below in Table 2. As can be seen, the expected results of Increasing Sensor Output with decreasing tip clearance are obtained.

Table 2
Output voltage with respect to tip clearance

Sr. No.	*Tip Clearance*	*Sensor Output(V)*	*Final Output(V)*
1.	Minimum (Just before contact)	0.95	8.65
2.	Intermediate	0.564	4.73
3.	Maximum (Before vibrations stop)	0.225	1.40
4.	No moving table	0.040	0.00

5. CONCLUSION

Tip clearance measurement and control in rockets, gas engines and steam turbines is crucial for the efficient working of the system. Given the presence of holes in the aircraft turbines, this offers a novel non invasive and cheap method of measuring tip clearance. The paper illustrates the use of eddy current based piezo cantilever sensing principle for the measurement of clearance between a non magnetic rotating conducting material (for *e.g.* a turbine blade) and a cantilever beam. The experimental results show that the amplitude of vibrations produced is inversely proportional to the tip clearance while the frequency of vibrations is independent of the clearance, and in turn depends upon the physical properties if the beam. Another advantage of this method is that it can measure both blade timing (frequency) and tip clearance using the same sensor, which is not possible using any other sensing technology. All outputs are obtained as electrical voltage quantities and can be directly read out without any high end electronics on the sensor side. Some challenges to this method include the need for developing an effective protective cover for the setup so that the temperature inside is low enough so the properties of the beam and the magnet are not altered. Furthermore,

6. REFERENCES

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