Technological Analysis on Vibration Measurement Method of Turbine Blades by Eddy Current Sensor Made from Low Temperature Co-fired Ceramics

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Abstract: In this paper, a wireless high temperature eddy current sensor based on LTCC technology is proposed to measure the vibration response of turbine blades. Firstly, the development technology of wireless high temperature eddy current sensor based on LTCC technology is introduced, and the frequency characteristics and high temperature characteristics of the sensor are analyzed; On this basis, the speed of turbine rotor and vibration displacement of blade monitoring method based on the high temperature eddy current sensor is proposed, and the specific scheme and expected test results are given, the vibration measurement of turbine blade at high temperature is realized. The test results show that the eddy current sensor has good sensitivity at high temperature and can be used to measure the vibration displacement at high temperature, the sensor can be used to monitor the rotor speed and blade vibration.

Keywords: High temperature eddy current sensor; Turbine blade; Vibration measurement; Speed of the rotor

1 Introduction

In the development and application of high-end thermomechanical equipment represented by aeroengines, a large number of high-temperature sensors that can adapt to high-temperature environments and other harsh conditions are required to meet the needs of control and performance status monitoring, including the state of structural parts with the engine at high temperature and even the temperature, pressure and vibration of the combustion chamber components. Low temperature co-fired ceramic (LTCC) technology is a kind of highly integrated packaging technology that uses co-

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fired ceramic substrates to realize the processing of extremely small-sized products on its surface, forming a three-dimensional high density circuit, making the products miniaturized and low cost. Using LTCC technology, a variety of sensor structures can be designed on the co-fired ceramic substrate, combined with advanced MEMS processing technology, heat resistant temperature, pressure, displacement sensor sensitive components can be made.

Due to its heat resistant temperature, low cost, insulation, self-encapsulation and other characteristics, as well as low-temperature co- fired ceramic (LTCC) process，it has unique advantages in making stereoscopic structure. LTCC material and technology are selected to make pressure sensor, which can meet the application in high temperature environment of about 400 ~ 600 ℃[1-5]. The Allen M G team of Georgia Tech has studied the LTCC wireless high temperature sensor, proposed the ‘sandwich’ structure of the LTCC pressure sensor for the first time, and the sensor has high sensitivity. A research team in Serbia has improved the structure[2], but the performance is far worse than before, and the sensitivity of the sensor is only 25.6 kHz / bar. G. Radosavljevic conducted deep study on LTCC wireless passive pressure sensor in 2009 and 2010, proposed an embedded structure that improves the stability of the sensor and improves the static characteristics of the sensor such as sensitivity and linearity at room temperature [6,7].

This paper introduces the main progress in literature [8], including the application of LTCC technology in the development of high temperature eddy current sensor. Low temperature co-fired ceramic is a multilayer glass-ceramic composite material, which can withstand high temperature up to the melting point of conductor metal. The eddy current sensor based on LTCC technology made according to the characteristics of eddy current can realize the measurement of vibration displacement under high temperature conditions. Therefore, this paper proposes to use the sensor to measure the turbine blades on the turbocharger, and gives the specific scheme and expected test results.

2 Design of the eddy current sensor

2.1 General principle and design factors

The working principle of the high temperature eddy current sensor is that when the magnetic line of force produced by the inductance coil passes through the metal conductor, the metal conductor will produce the induced current, and the size of the output signal will change with the distance between the probe and the surface of the measured body. The eddy current sensor is based on this principle to measure the vibration displacement of metal objects, as shown in Figure 1, the structure of the high temperature eddy current sensor is designed.

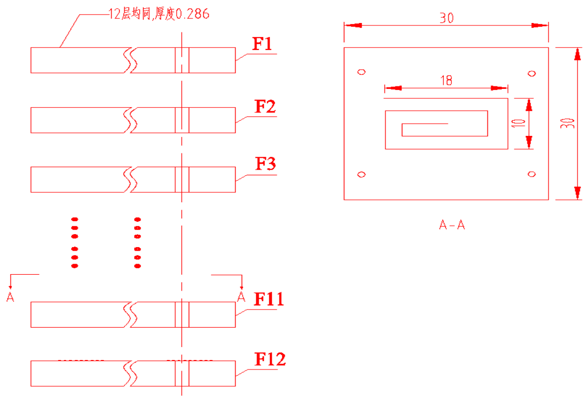

Fig. 1 Structure diagram of high temperature eddy current sensor based on LTCC technology.

Low temperature co-fired ceramic (LTCC) technology can be defined as a method of producing multilayer circuits under a substrate, which is used to apply conductive, dielectric and resistance paste. The technological process flow suitable for the preparation of LTCC high-temperature vibration sensor includes punching, via filling, screen printing, lamination, hot cutting and co-firing. The LTCC eddy current sensor is made of DuPont 951 raw porcelain, the printing conductor paste is DuPont 6142d silver paste, and the via filling paste is DuPont 6146d silver paste. Finally, the vent hole of the sample is blocked, and the glass slurry is coated on the vent port of the sample, which is placed in the sintering furnace at room temperature to 700 ℃ and evenly raise the temperature to room temperature. After curing, the glass slurry can well block the vent hole, so that the sensor capacitor cavity can form an airtight structure. Finally, the molded sensor sample is obtained. Observe the cross-sectional line of each layer in the left image through a microscope as shown in Figure 2 (a), and the top view of the sensor as shown in Figure 2 (b) on the right.

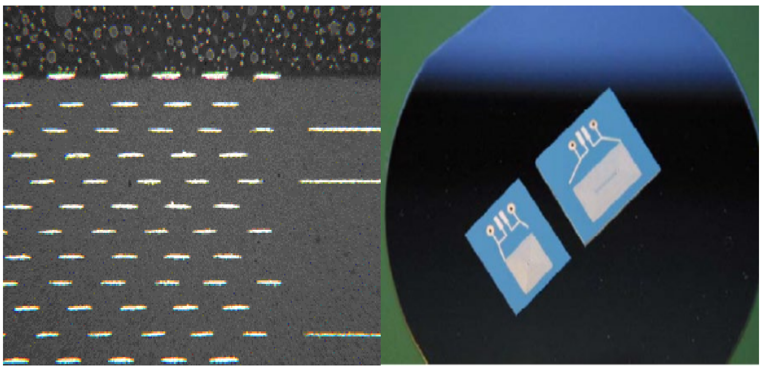

Fig. 2 Preparation processing (a: Cross section of LTCC coil under microscope; b: 2 Top view of LTCC eddy current sensors) (see [8])

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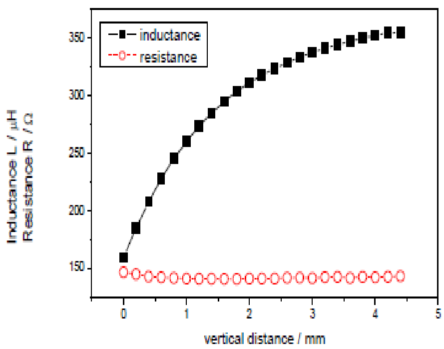
2.2 Electrical characteristics of LTCC high temperature eddy current sensor

Firstly, the static test of the high temperature eddy current sensor is carried out. The influence of eddy current on the coil impedance of high temperature sensor is different between the vertical approach direction and the horizontal channel direction. For proximity measurement, when the target surface area is larger than the sensor, the change of inductance is obvious, while the effect of resistance can be ignored. If the target surface area is smaller than the target surface area of the sensor, the eddy current is cut on the narrow surface. Then, the change of inductance is very small, and the change of resistance is equivalent to the change of inductance. The actual design of measurement circuit must be considered, and the different distance. The test results are shown in Figure 3(a) and Figure 3(b).

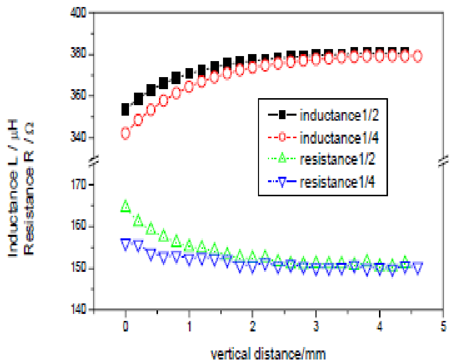
Secondly, the frequency characteristic of the high temperature eddy current sensor is analyzed. The excitation frequency is set as 1MHz, and the width of the plane of the conductor to be measured is 30mm. The frequency of the excitation source has a great influence on the performance of the sensor. Through a wide frequency range of excitation sources, the influence of frequency on sensor performance is studied, as shown in Figure 3(c) and Figure 3(d).

Finally, the temperature characteristic of the high temperature eddy current sensor is analyzed. The oven produced by Capolit company is used to provide different temperature environment for this experiment, and the maximum temperature can reach 600 ℃. The temperature characteristic curve of the impedance and inductance of the high-temperature eddy current sensor is shown in Figure 3(e) and Figure 3(f).

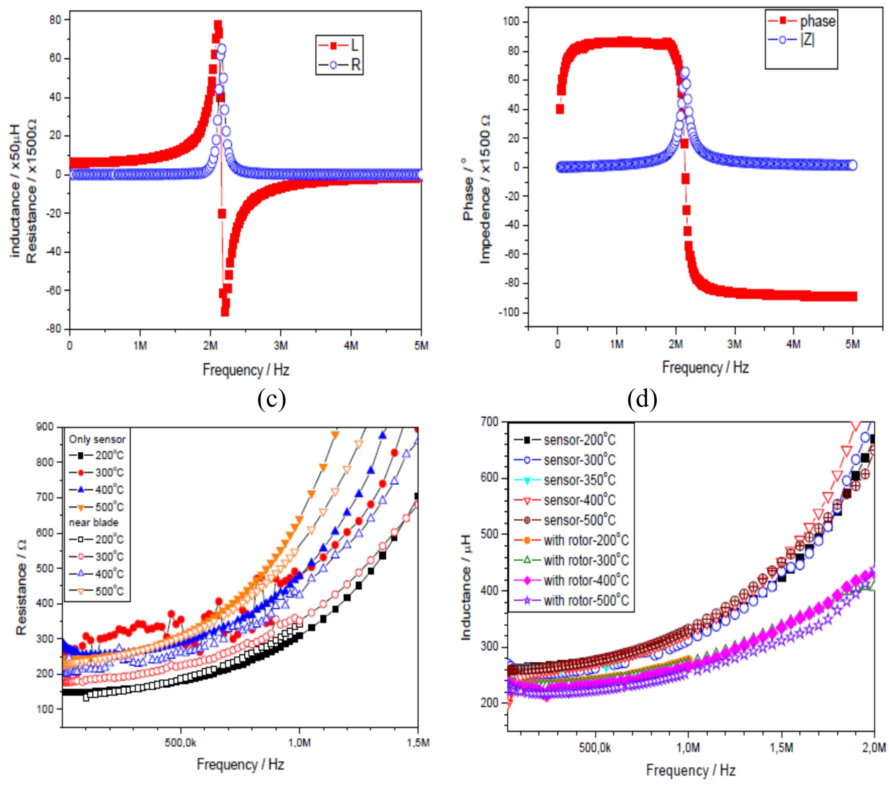
It can be seen from Figure 3 that the eddy current sensor has very good sensitivity at high temperature.



(a)



(b)



(c) (d)

(e) (f)

Fig. 3 Electrical characteristics (a: The relationship between resistance, inductance and proximity distance for copper target with 30mm surface width; b: The relationship between resistance, inductance and proximity distance for copper target with 1mm surface width (The thin plate lies over the center and up ¼ of sensor coil); c: Change of inductace and resistance of sensor with frequency; d: Change of impedance amplitude and phase angle of sensor with frequency; e: The resistance of a sensor with an aluminium target blade from 200 to 500 ºC and the resistance of a sensor without target in same temperature range. Both were tested in the oven with maximum temperature 600 ºC; f: The inductance of a sensor with an aluminium target blade from 200 to 500 ºC and the inductance of sensor without target in same temperature range. Both were tested in the oven with maximum temperature 600 ºC) (see [8])

3 Experimental system and methods

As shown in Figure 4, the turbine dynamic test system built in this paper consists of three main parts, namely turbine system, signal measurement and acquisition system and test object.

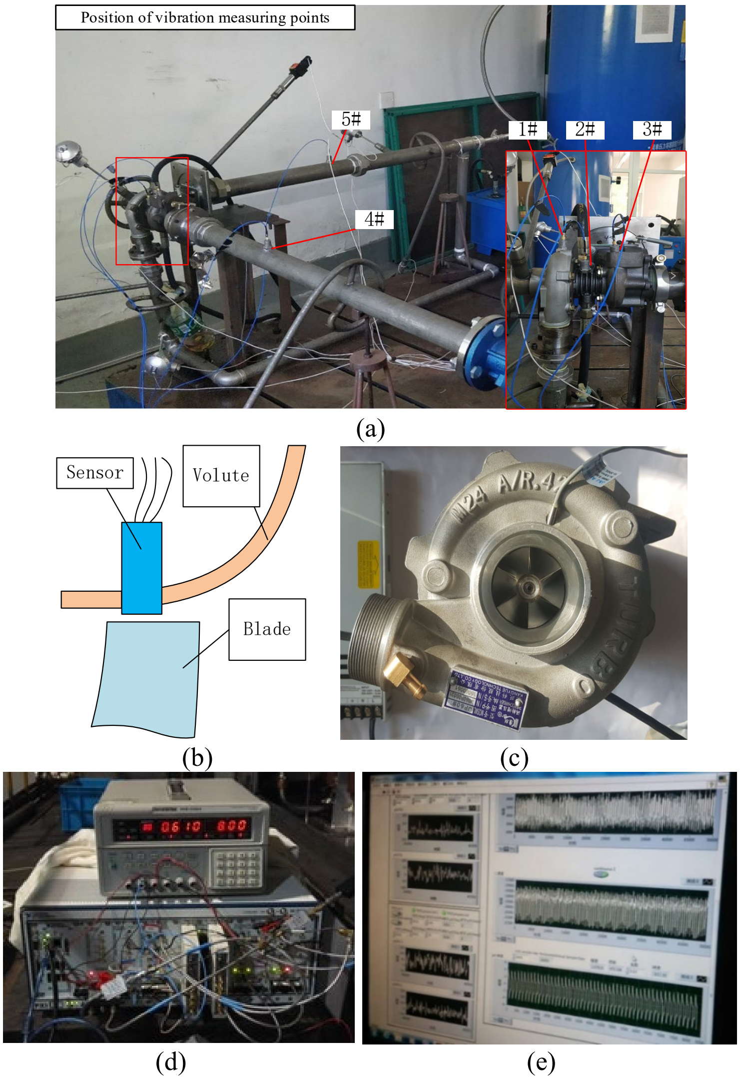


Fig. 4 Turbine dynamic test system (a: Turbine test system and Position of vibration measuring points; b: Microwave detector and installation manner; c: Installation of the dec-tors on the turbine body, d: Data collection system; e: System working interface)

3.1 Response of the sensor to rotation of the rotor

The high temperature eddy current sensor can be used to measure the speed of the impeller rotor. The gap between the surface of the sensor and the measuring end of the rotor is 1mm, the capacity of sensor test can reach 400Hz (12000rpm).

During the test, start the turbine normally, Increase the rotor speed to 10000 r/min slowly, and record the rotor speed data in this period; the rotating speed of the rotor is stable at 10000 r/min, and the running time is 10s, record the blade vibration data and rotating speed data in this period; slowly reduce the rotating speed of the rotor from this working condition, and record the rotating speed data of the rotor.

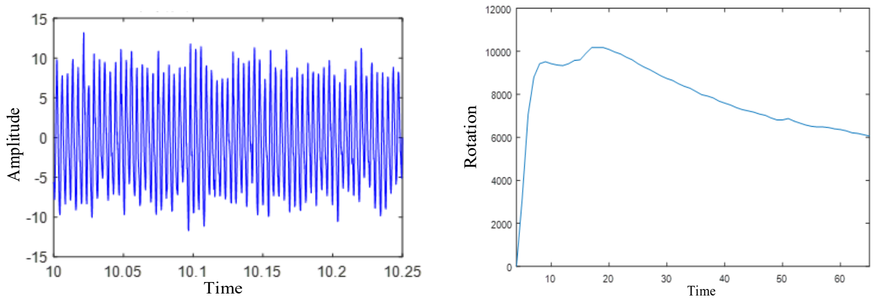


Fig. 5 Response of the sensor to rotation of the rotor (a: Original signal wave; b: Rotation of the rotor)

The sensor test signal is shown in Figure 5 (a), which can accurately reflect the rotor speed, as shown in Figure 5 (b). One finds that the testing signal can reflect the rotating speed of rotor exactly. Therefore, the function of sensor to test rotating speed of rotors was identified.

3.2 Influence of the clearance between sensor surface and tip of blades

In this section, the clearance between sensor surface and tip of blades was changed from 1.5 to 3.5 mm. The amplitude of peaks is the object we focus on. As shown in Figure 6, the amplitude of the negative peak changes abruptly with the clearance. The testing results and sensitivities of the sensor are listed in Table 1.

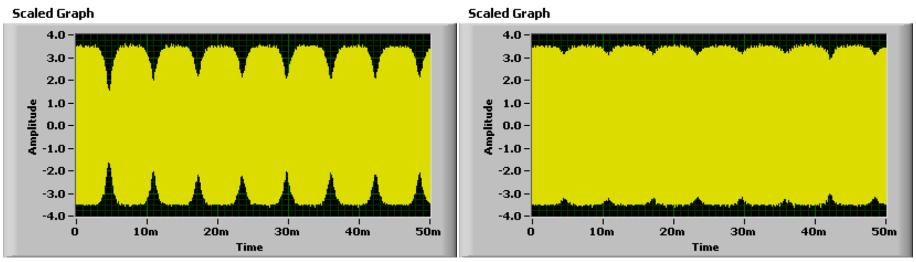


Fig. 6 Testing results of a sensor with different clearance (a: 1.5mm; b: 3.5mm) (see [8])

Table 1 Testing results of a sensor with different clearance (see [8])

Clearance (mm)	Amplitude of modulation signal p_k-p_k(v)	Amplitude of testing signal p_k-p_k(v)	Sensitivity of sensor (%)
1.5	6.91	3.83	44.573
3.5	6.91	5.98	13.459

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From this figure, some conclusions can be made. The sensitivity decreases with the clearance, if we want to get higher and linear sensitivity, the clearance should be set shorter than 2 mm.

3.3 Measurement for the changes of blades geometry

One of the seven main blades of the impeller has been ground so that the blade is 0.3mm shorter than the other six blades, this modification of the blade can be considered that the tip of the blade moved away from the sensor surface, therefore the clearance between the blade and the sensor is lengthened. The amplitude of signal peaks for this modified blade should be higher than the others and the peak will appear one time in the signal every 7 peaks. The testing waveform (see Figure 7) shows this modification for one blade. The amplitude of the one peak in the signal was changed, but the frequency is the same.

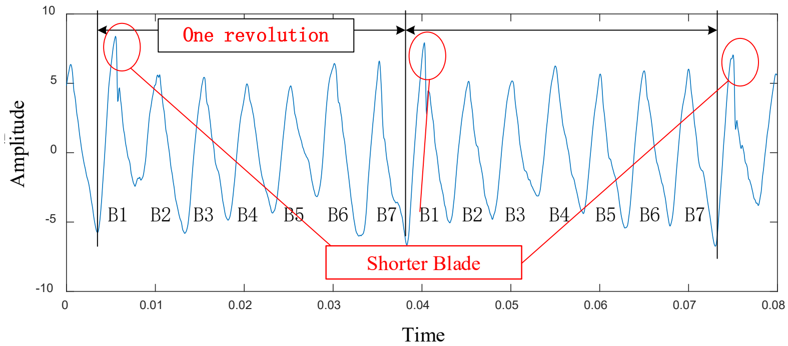

Fig. 7 The test waveform for the rotor with one shorter blade

According to the results, when the length of a blade is shorter than others, the clearance between the sensor and the blade is longer, therefore the electromagnetic interaction between them is weaker and inductance of the sensor increases more quickly. The corresponding peak 'intensity' is reverse to the original peak, therefore it is proportional to the length of blade.

4 Conclusions

In this paper, LTCC technology is applied to the design and manufacture of eddy current sensor to improve the feasibility and reliability of displacement measurement in harsh and high temperature environment. The test results show that the sensitivity of sensor decreases with the clearance between sensor surface and tip of blades, when the clearance is set to less than 2mm, higher and linear sensitivity can be obtained, the sensor can also be used to monitor the speed of rotor and the length changes of blade. The eddy current sensor based on LTCC technology can measure the rotor speed and the vibration displacement of turbine rotor at high temperature.

References

1. Li Y, Design, Fabrication and Measurement of LTCC capacitive high-temperature pressure sensor, ***Transducer and Microsystem Technologies***, 2013, 32 (4): 101-105.
2. Fonseca M A, English J M, Arx M V, et al, Wireless micromachined ceramic pressure sensor for high-temperature applications, J***ournal of Microelectromechanical Systems***, 2002, 11(4):337-343.
3. Edward D B, Jin W P, Mark G A, Wireless ceramic sensors operating in High Temperature Environment. ***40th ALAA/ASME/SAE/ASEE Joint Propulsion Conference***, 2004.1.
4. Stanley R L, Elizabeth J O, Michael C H, et al, Evaluation of Ultra-High Temperature Ceramics for Aeropropulsion Use, ***Journal of the European Ceramic Society***, 2002, 22: 2757–2767 .
5. Sheehan J E, Oxidation protection for carbon fiber composites, ***Carbon***, 1989, 27(5):709-715.
6. Radosavljevic G J, Zivanov L D, Smetana W, et al, A Wireless Embedded Resonant Pressure Sensor Fabricated in the Standard LTCC Technology, ***Sensors Journal, IEEE***, 2009, 9(12):p.1956-1962.
7. Radosavljević G, Smetana W, Marić A, et al, Micro Force Sensor Fabricated in the LTCC Technology, ***International Conference on Microelectronics. IEEE***, 2010.
8. Lai Y Q, ***Eddy Current Displacement Sensor with LTCC Technology***, Albert-Ludwigs-Universität Freiburg, Freiburg, 2005.

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