Research on the Pulsed Eddy Current Sensor of the Crack Depth of Turbine Disk

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1. Introduction
The aeroengine is known as the “heart” of aircraft, its performance seriously affects flight safety, a little problem can cause the plane to crash. The high-pressure turbine disk in the aeroengine, as the connecting part of installing and fixing blades, is a very important power transmission rotating part. It is driven by high-pressure gas in the combustion chamber of the engine, which converts the heat energy of the gas into mechanical energy, and drives the engine to run. It can be seen that the load on the turbine disk is very complex. When the turbine disk rotates at a high speed, it is affected by its centrifugal force. The centrifugal force is generated when the blade rotates and reflected on the connecting groove. The rapid combustion of fuel makes it affected by high temperature and gas power. Besides, the change of the external environment makes the turbine disk easy to produce fatigue cracks under the action of various multistage and amplitude cyclic loads [1].

At present, the common nondestructive testing methods of crack depth are ultrasonic testing, ray testing, eddy current testing, potential difference testing and AC field testing, which can achieve the quantitative measurement of crack depth, but they are not enough for the high-precision requirements of turbine disk crack measurement [2]. (1) In ultrasonic testing, it is much more difficult to measure the depth of defect by ultrasonic than by using it to measure the length of defect. The measured depth of defect is the only equivalent depth of defect. When measuring the defect with smaller depth, the accuracy is worse, and the measurement needs the couplant [3]. (2) X-ray inspection, an experimental technology that uses X-ray technology to observe, study and inspect the microstructure, chemical composition, surface or internal structural defects of materials, can penetrate the thicker parts, but usually can not detect the smallest cracks [4]. (3) Eddy current testing is usually to select a certain frequency and a certain power alternating signal to the excitation coil of the detection probe, so that eddy current is induced in the tested body. This eddy current also produces an alternating magnetic field which is opposite to the original magnetic field, which makes the impedance and induced voltage of the
measuring coil of the detection probe change, so as to realize the measurement of the defect depth. The quantitative analysis of the defect by using eddy current method can rely on the standard test piece to calibrate the defect, or can be deduced by a fixed proportion relationship between the depth and length of the defect. However, there are some shortcomings in the above two methods, so eddy current testing is called the lowest efficiency nondestructive testing method. (4) The potential difference method is used to detect the surface defects of good conductors. When the surface is perpendicular to the defect, the direct current or alternating current is connected, and the defect depth is obtained according to the voltage change between the beginning and the end of the defect. Based on the reasonable position relationship between the excitation electrode and the detection electrode, and the good contact between the voltage electrode and the test piece, the measured voltage drop has a linear relationship with the depth of the defect. But the surface of the workpiece should be clean, otherwise, the error is large, and the error is large when testing non-ferromagnetic materials.

According to the comprehensive analysis, the above nondestructive testing methods are either not accurate enough to detect the crack depth, or high environmental requirements, and the testing equipment is complex and hard to carry. Aiming at these problems, this paper designs a miniaturized and high-precision PEC sensor. The following three aspects will be analyzed from the principle of PEC testing, the design and testing model of the sensor, and the testing of the sensor in titanium alloy components. So the feasibility of the sensor is further illustrated.

2. Principle of PEC Testing
The principle of PEC testing is similar to that of conventional eddy current testing, and the working process can be explained by Maxwell equations. The excitation signal of the conventional eddy current testing system is the sine wave, while that of the PEC testing system is a square wave. The Fourier transform can be regarded as a myriad of sine signals with different frequencies, which has more abundant information. The general process is to load the pulse signal onto the excitation coil, and the excitation coil itself will generate an attenuated pulse excitation magnetic field, which will generate transient eddy current in the conductor, and the eddy current in the tested body will generate a rapidly attenuated magnetic field. The magnetic sensor will obtain these two superimposed magnetic fields, and the defects on the tested body will cause the change of eddy current density, which causes the change of magnetic field, and then obtains the defect information through the sensor.

![Figure 1. A typical pulsed eddy current time-domain response signal.](image)

Metal materials are divided into ferromagnetic and non-ferromagnetic materials. For ferromagnetic materials, eddy current has a magnetizing effect on them. In the detection signal, there are both eddy current signals and magnetic leakage signal. For non-ferromagnetic materials, the detection signal only exists in the PEC signal. Generally speaking, the material of the turbine disk is titanium alloy, which
belongs to non-ferromagnetic material. There is zero crossover point (the time from the rising edge of the excitation signal to the first reduction signal to zero). According to the principle of PEC testing, the volume of the defect is related to the peak value of the response signal without considering other factors; the position and size of the defect are related to the peak time of the response signal; the depth of the crack is related to the zero crossover time of the detection signal [10,11].

3. Sensor Design and Detection Model
The sensor consists of an excitation coil and a detection element. Due to the small size of the sensor, the excitation coil and the detection element are only composed of a coil. To facilitate operation, the pen-type probe is adopted, and the flexible plane sensor is installed at the front end, as shown in Fig. 2 the structure of sensor, with a size of about 5mm × 5mm. When the single turn rectangular coil is excited by a pulse, the central region will produce a changing magnetic field, and the multi-turns detection coils can obtain the detection signal. The pen probe (as shown in Fig. 3) contains a slender circuit board, which is used to pre-amplify the detection signal. The pen probe is connected to the host through 4-core cables (excitation current, ground, DC power, detection signal).

3.1. Establishment of Simulation Model
COMSOL finite element analysis software is used to simulate the PEC detection of the plane sensor. The established model is solved and analyzed in the electromagnetic field environment under the AC / DC module, and the established PEC detection model is shown in Figure 4. In the model, the length, width, and height of the tested body are set as 18mm * 14mm * 5mm, the overall dimension of the
sensor is 5mm * 5mm, the outer ring is a single turn rectangular excitation coil (width 0.5mm), the coil and line spacing of the detection coil is 0.1mm, the direct lifting height of the sensor and the tested body is 0.1mm, and the air domain is a cube of 100mm * 100mm * 50mm. The model meshes and voltage pulse excitation is introduced in the form of function. The tested body is titanium alloy, the excitation coil, and the detection coil are copper wire, and the parameter performance of the material is shown in Table 1.

| Materials       | Conductivity $\sigma$(S/m) | Relative Permeability $\mu$ | Relative Permittivity $\varepsilon$ |
|-----------------|-----------------------------|-----------------------------|-----------------------------------|
| Air             | 0.1                         | 1                           | 1                                 |
| Copper          | $6\times 10^7$              | 1                           | 1                                 |
| Titanium Alloy  | $1\times 10^6$              | 1                           | 1                                 |

Figure 4. Model of plane sensor by pulsed eddy current testing.

3.2. Analysis of Detection Model
The sinusoidal AC signal and square wave are added to the excitation coil of the sensor respectively. The excitation signal of the conventional eddy current is the sinusoidal AC with the effective value of 1a, the frequency is 5KHz, and the excitation signal of the pulsed eddy current is the square wave with the amplitude of 5V. The simulation results of the sinusoidal signal are shown in Fig. 5 and Fig. 6, and the simulation results of the square wave signal are shown in Fig. 7 and Fig. 8.

Figure 5. Flux density under sinusoidal.
Figure 6. Flux density in Z direction under sinusoidal.

Figure 7. Flux density under square

Figure 8. Flux density in Z direction under square

Fig. 7 and Fig. 8 are the superposition situations of Fig. 5 and Fig. 6 at different frequencies. It can be seen that the magnetic flux density at the centre of the coil is the largest, and almost all of them are in the Z direction. Therefore, it can be concluded that the plane sensor is the most suitable place without an included angle when it contacts the tested body, and the miniaturization and flexible materials of the sensor will better fit the tested body, to detect the maximum voltage induced by the coil.
4. Detection and Analysis of the Sensor in Titanium Alloy Components

Observing the detection signal under the pulse excitation signal is equivalent to the superposition of many sinusoidal AC excitation signals with different frequencies, and the transient voltage is obtained by simulation. As shown in Fig. 9, the time sequence comparison diagram of the typical PEC response signal and the excitation signal is shown. The bottom half of the figure is the square wave excitation signal of PEC. The top half is the response signal of PEC, which is generated by the transient change of excitation signal [12].

![Image of time sequence comparison](image1)

**Figure 9.** Time sequence comparison of typical impulse eddy current response signal and excitation signal

![Image of square wave excitation](image2)

**Figure 10.** Square wave excitation of pulsed eddy current

The excitation coil is loaded with a square wave excitation signal with an amplitude of 5V, a cycle of 10ms, and a duty cycle of 50% (as shown in Fig. 10). The crack with length, width, and depth of 10
mm * 0.1 mm * 1 mm are directly below the sensor. The situation of the tested object and the sensor in transient 10ms (time step is 0.1ms) is simulated. The flux density and current density in figures 11, 14, 15, and 16 are 4.9ms, 5ms, 5.1ms, and 5.6ms respectively. Time 5ms is the step point of the excitation signal, so this point and the front and back time points are selected for observation.

**Figure 11.** Flux and current density at 4.9ms

**Figure 12.** Flux and current density at 5ms
Figure 13. Flux and current density at 5.1ms

Figure 14. Flux and current density at 5.2ms

Before the step signal, until 4.9ms the excitation signal is 5V DC without change, it is impossible to generate eddy current in the measured body, and the magnetic induction intensity generated by the conduction current is the largest, as shown in Fig. 11. When the excitation signal reaches 5ms, there is a jump, so the conduction current generates an attenuated magnetic field, and the changing magnetic field generates eddy current in the measured body. At the same time, the magnetic field generated by the eddy current is opposite to the direction of the last magnetic field, as shown in Fig. 12, it can seem that the magnetic flux density is reduced compared with Fig. 11. By 5.1ms, there is no conduction current excitation, but the attenuated magnetic field continues, and the eddy current still reacts with the former magnetic field, as shown in Fig. 13. When the flux density reaches 5.6ms, it almost can be ignored.
Figure 15. The transient voltage of the detection coil

The voltage of the detection coil can be obtained by deriving the magnetic flux of the detection coil, as shown in Fig. 15. Blue is the detection voltage when there is no crack, green is the detection voltage when there is a 1mm deep crack. The peak value without crack is larger than the peak value with crack, which conforms to the physical characteristics. However, the peak value of voltage in the figure is also a direct jump, and the peak value time and zero crossover time are not gradually changed. The reason is that the magnetic flux is not gradually changed, it is directly calculated with the excitation signal, and the magnetic field provided by the eddy current in the tested body is not calculated. It can be seen from Fig. 14 that at this time, the flux density has been reduced to negligible, but the eddy current is not small. The direction of flux provided by the eddy current is opposite to that of the excitation coil, while the flux density in the simulation is always in the same direction. Therefore, the approximate voltage peak value can be obtained by simulation, and the size of the peak value is convenient for signal processing.

5. Conclusion
Through the simulation analysis of the sensor under the pulse electromagnetic detection, the following conclusions are obtained: The PEC sensor with plane placing is the best for measuring the crack depth of turbine disk, The graph and data obtained from the simulation under the impulse excitation meet the theoretical requirements, so the plane sensor is feasible to detect the crack depth of the turbine disk. In the next step, experiments will be carried out to verify the practicability of the plane sensor. The PEC detection system is composed of a signal generating unit, signal detection unit, signal acquisition unit, and signal processing unit. At last, the response signal and the depth of turbine disk crack are visualized based on the software interface of the detection system.
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