Simulation analysis of grid-type PVD thin film sensor based on COMSOL

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Abstract: On-line quantitative monitoring of fatigue crack sensors is an important part of structural health monitoring systems. A rectangular grid-type PVD (physical vapor deposition) thin film sensor based on the potentiometric method is designed in this paper. First, the sensor finite element model is established through the AC/DC module of COMSOL Multiphysics to verify the feasibility of the sensor to monitor cracks. Second, the effect of the number of sensing channels on the sensitivity of the sensor is studied. Finally, the structural parameters of the sensor are optimized. Significantly improved sensitivity for crack detection. The results show that the rectangular grid PVD film sensor can effectively monitor structural cracks.

1. Introduction
In order to meet the new challenges of safety and reliability, structural health monitoring technology has been gradually developed and applied to the use and maintenance of high-reliability equipment such as aircraft. While ensuring structural safety, it reduces maintenance costs and improves economics [1]. Fatigue crack on-line quantitative monitoring sensors are an important part of structural health monitoring systems. The development of sensors that are easy to integrate with structures and have high sensitivity is the focus of damage tolerance design research based on structural health monitoring technology.

At present, the main methods used in aircraft structure crack monitoring at home and abroad are piezoelectric thin film sensor [2], optical fiber sensor [3], relative vacuum sensor [4], eddy current sensor [5], acoustic emission technology [6], Potential-based sensors, etc. The monitoring method based on the potential method has the advantages of simple system, easy signal processing, and easy integration with the structure. It has great application prospects in the field of aircraft structure crack monitoring, and has become an important branch of structural health monitoring technology research. Bai Baosheng [7] and others used a special process to make a smart coating sensor with a trinity of damage characteristics, insulation, and electrical parameter testability. S.Z. Zhang [8] and others proposed a method to detect the length and location of cracks by measuring the potential difference or resistance value between any two points on the structure surface. Du Jinqiang [9] proposed a research scheme of crack monitoring sensor based on the principle of potentiometric method, and verified the feasibility of the scheme through experiments. At the same time, the finite element model of the sensor was established to simulate the output characteristics of the sensor. The characteristics of the potential difference between the monitoring points with crack growth and the relationship between the crack length and the potential difference are provided, which provides a reference for further research and application of the sensor. Behnam Ashrafi [10] and other experiments verified the application of epoxy nanocomposite thin film sensors in continuous monitoring of crack evolution of metal structures. Bo HOU [11] and others proposed a Ti / TiN conductive thin film sensor based on the potential method for real-time monitoring.
of metal structure cracks. The experimental results show that by analyzing the slope of the sensor output potential value with time, the structure crack generation and the Extended information.

It can be found that the related scholars have done in-depth research on the principle of potentiometry and the preparation method of conductive thin films, but the monitoring technology based on potentiometry still has a significant shortcoming, which is difficult to achieve accurate quantitative monitoring, which needs to be obtained through reference experiments or theoretical derivation. A reference model for the quantitative relationship between the potential / resistance change and crack length of the structure. Therefore, based on previous research [12], a rectangular grid-type PVD (physical vapor deposition) thin-film sensor is designed. The feasibility of the sensor was verified by finite element simulation, and the influence of the number of sensing channels on the sensitivity of the sensor was studied. The structural parameters of the sensor were optimized to significantly improve the sensitivity of crack detection.

2. Rectangular grid type PVD thin film sensor

2.1 Sensor design

The PVD thin film sensor uses the physical vapor deposition (PVD) method in modern surface engineering technology to integrate conductive functional materials on the surface of metal structures, and senses fatigue crack damage of metal structures by monitoring changes in the electric field information in the conductive thin film structure. Structural health monitoring methods [13]. The PVD thin film sensor is composed of three layers of functionally graded materials, which are an insulation layer, a damage sensing layer, and a package protection layer. The principle of PVD film sensor for monitoring the fatigue damage of metal structures is shown in Figure 1. The difference from the traditional DC potential method is that the PVD thin film sensor's monitoring of metal structure cracks mainly depends on the damage consistency between itself and the base structure, that is, when the base metal structure has fatigue damage, the conductive sensing with accompanying damage characteristics also has cracks in the same part, and continuously expands with the base crack, causing the resistance change of the damage sensing layer in the damage area. The damage of the base structure can be obtained by monitoring and analyzing the potential (resistance) information of the damage sensing layer. Since the thickness of the damage sensing layer of a PVD thin film sensor is only micrometers, and generally made of materials such as Cu and TiN, the initiation and propagation of cracks will have a greater impact on its resistance.

As shown in Figure 2, a rectangular grid-type PVD thin film sensor is designed in this paper. The conductive material of the damage sensing layer is Cu. The sensor is composed of an sense channel and a connection channel. When a crack is generated on the structure surface, the crack passes through the sense channel in turn, and the resistance of the sensor changes, so as to monitor the crack.

![Figure 1. Principle of PVD thin film sensor](image1)

![Figure 2. Rectangular grid type PVD thin film sensor](image2)
2.2 Sensor sensitivity
In order to evaluate the ability of grid-type PVD thin film sensors to monitor cracks, the concept of sensitivity is proposed in this paper. The change rate of the sensor output resistance before and after the first grid channel is broken is defined as the sensitivity of the sensor.

\[ S = \frac{R^* - R_0}{R_0} \]  

In the formula, \( R_0 \) represents the resistance before the first sensing channel is broken, and \( R^* \) represents the resistance of the sensor after the first sensing channel is broken.

3. Finite element simulation of influence of sensor parameters on sensitivity

3.1 Simulation model
This article uses the AC / DC module of COMSOL Multiphysics to build a finite element model of the sensor. The sensor material is Cu, and the structural parameters are shown in Table 1. The surface crack is set as a rectangular crack, the crack position is located at the midpoint of the conductive channel, and the width is 0.1mm. The crack length is parameterized and scanned. A freely split tetrahedral regular grid was used. A voltage of 1 V was applied to one end of the test block and the other end was grounded. The meshing of the simulation model is shown in Figure 3 (a). For the sensor finite element model with different structural parameters, the sensor resistance was calculated by the global solver derived from COMSOL software. Figure 3 (b) shows the voltage distribution of the sensor.

| parameter       | Induction channel | Connected channel | Conductive layer |
|-----------------|-------------------|-------------------|------------------|
| Value /mm       | Length | Width | Pitch | Length | Width | Thickness  |
|                 | 12   | 0.2   | 0.8   | 10   | 2   | E-3       |

![Meshing of simulation model](image1)

![Voltage distribution](image2)

Figure 3. Sensor finite element model

3.2 Sensor feasibility verification
As shown in Figure 4, the resistance of the sensor increases as the crack grows. When the crack length reaches 1mm, the fatigue crack spreads to the first sensing channel, and the sensor resistance increases stepwise. The jump in resistance is due to a crack that causes the corresponding first sensing channel to break and cannot conduct electricity, thereby increasing the sensor resistance. As the crack passes through the first sensing channel, the resistance of the sensor stabilizes again. When the crack spreads to the next sensing channel again, the resistance jumps again. By analyzing the characteristic phenomenon of the jump in the sensor resistance change, it can be inferred that the cracks propagate through the corresponding sensing channels, so that the quantitative monitoring of the cracks is achieved. The simulation results show that the grid-type PVD film sensor can better monitor the entire process of structural cracks.
3.3 Effect of number of sensing channels on sensitivity

The sensing channel is an important part of the sensor in the grid-type PVD film sensor, which plays a role in inducing crack damage. When the spacing of the sensing channels is the same, the more the number of sensing channels, the larger the monitoring range of the sensor; and when the monitoring range of the sensor is constant, the more sensing channels, the smaller the spacing between the channels, and the resolution of monitoring fatigue cracks. The higher. Therefore, the more the sensing channels of the sensor, the better it is to improve the resolution of fatigue crack detection by the sensor and increase the monitoring range of the sensor. However, according to Ohm's law, the greater the number of sensing channels, the smaller the impact of a sensing channel break on the change in sensor output resistance, that is, the smaller the sensor's sensitivity.

As shown in Figure 5, the simulation results show that the number of sensing channels greatly affects the sensitivity, and the sensitivity of the sensor decreases as the number of sensing channels increases. When the number of sensing channels is 2, the sensitivity is 60.04%; when the number of sensing channels is 5, the sensitivity is less than 10%, which is 9.31%; when the number of sensing channels is 7, the sensitivity is less than 5%, which is only 4.75%.

3.4 Influence of sensor structure parameters on sensitivity

In order to analyze the influence of the structural parameters of the conductive grid sensor on the sensitivity, a sensor model with 5 sensing channels was established in this paper. In the simulation
analysis, a single variable is controlled, and the effects of the length of the sensing channel, the width of the sensing channel, the length of the connecting channel and the width of the connecting channel on the sensitivity of the sensor are studied. Set the connection channel length to 10, 15, 20, 25, 30, 35, and 40 mm, and the width to 1, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, and 1.7 mm respectively; the length of the sensing channel is 6, 8, 10, 12, 14, 16, and 18 mm, with widths of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 mm, respectively. When studying the influence of a certain parameter on the sensitivity, the remaining structural parameters remain the same, as in Table 1. The sensitivity of the sensor calculated under various conditions is shown in Figure 6. It can be seen from the figure that the sensitivity of the sensor increases with the increase of the length of the sensing channel and the width of the connecting channel, and decreases with the increase of the width of the sensing channel and the length of the connecting channel.

Simulation results show that reducing the width of the sensing channel, increasing the width of the connecting channel, increasing the length of the sensing channel, and reducing the length of the connecting channel, that is, increasing the resistance of the sensing channel and reducing the resistance of the connecting channel, is conducive to improving the sensitivity of the sensor.

![Figure 6](image)

4. Conclusions
This paper presents a rectangular grid-type PVD thin film sensor based on the potentiometric method. Through finite element simulation analysis, the following conclusions are obtained.

(1) The resistance of the sensor will increase stepwise when the crack is expanding, which indicates that the grid-type PVD thin film sensor can better monitor the entire process of structural fatigue cracks.

(2) The number of sensing channels greatly affects the sensitivity. The sensitivity of the sensor decreases as the number of sensing channels increases.

(3) Increasing the resistance of the sensing channel and reducing the resistance of the connecting channel are conducive to improving the sensor of sensitivity.
The rectangular grid PVD thin film sensor proposed in this paper can provide a new method for the quantitative monitoring of fatigue cracks.

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