Crack Quantification of Bolted Joints by Using a Parallelogram Eddy Current Array Sensing Film

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Abstract: Crack monitoring at the bolt hole edge is one of the important focuses of aircraft structural health monitoring. In this study, a novel eddy current sensing film based on a parallelogram coil array is developed to quantitatively monitor the crack characteristics near the bolt hole with fewer layers and coils, compared with the existing methods. The parallelogram coil array configuration is designed and optimized to improve the quantitative monitoring ability of the crack. A 3×3 parallelogram coil array is used to quantify the crack parameters of aluminum bolted joints. Finite element simulation and experiments show that the proposed parallelogram coil array could not only accurately and quantitatively identify the crack angle at the edge of the bolt hole, but also track the crack length along the radial direction of the bolt hole and the depth along the axial direction.

Key words: bolted joints; flexible eddy current sensing film; parallelogram coil array; structural health monitoring

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0 Introduction

Bolted joints are widely used in aerospace because of their high reliability, high load-bearing capacity, easy repeated disassembly/assembly, and simple maintenance. However, due to the stress concentration at the hole edge, the complex load, and the harsh flight environment, bolted joints are prone to structural failure. Non-destructive testing technologies commonly used for crack detection include eddy current testing[1], ultrasonic testing[2] and other testing methods. However, for non-destructive testing technologies, it is difficult to monitor the structure state in real time and detect the crack of the inaccessible bolted joints.

For solving this problem, a revolutionary and innovative technology, structural health monitoring (SHM)[3-4] technology, is considered as a solution. Compared with non-destructive testing technologies, the sensors in the SHM system are permanently installed on the surface or embedded in the interior of the structure, which can monitor the structural state online and increase the accessibility. At present, the common structural health monitoring technologies include the structural vibration method[5], the acoustic emission method[6], the ultrasonic guided wave method[7-9], the electromechanical impedance method[10], the comparative vacuum method (CVM)[11], the intelligent coating method[12], the surface-bonded rosette eddy current method[13-15], etc. However, these methods have poor abilities to detect the crack of multiple-plate joints and quantify the multiple parameters of the crack.

Chang's team[16] at Stanford University proposed an eddy current sensing film, which was wound and boned on the bolt, to monitor the hole-edge crack of bolted joints. Then, Sun et at.[17] proposed that in the limited space of the bolt hole wall, a compact eddy current sensor array can be designed to sense as many groups of signals as possible so as to obtain more crack parameters. A one-dimensional rectangle coil array[17], a two-dimensional rectangle

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coil array[18] and two-dimensional interleaving rectangle coil array[19] were proposed successively to quantify the crack parameters. The one-dimensional rectangle coil array is only able to identify the crack depth and length. Furthermore, the two-dimensional rectangle coil array could identify one more crack parameter, that is, simply give the crack angle. Based on this, the two-dimensional interleaving rectangle coil array[19] could accurately quantify the crack angle using two interleaving layers of the two-dimensional coil array[18]. However, the cost of this is that the thickness of the sensing film has been doubled. The installation space of bolts and connectors is limited. The more layers and thickness of the eddy current sensing film, the greater the impact on the installation of bolts and connectors. Reducing the impact of sensor installation on structural mechanical properties as much as possible is not only an effective way for structural health monitoring research to be applied quickly, but also one of the current goals of structural health monitoring research. It is thus very important to reduce the number of layers and thickness of the eddy current sensing film.

In this paper, a parallelogram eddy current coil array is developed to detect cracks, and especially to obtain crack angles with higher accuracy, while the number of layers of the sensing film is half that of the present one.

1 New Configuration Design

The principle of the eddy current sensing film for crack detection can be interpreted using Fig.1. The eddy current coil wound on the bolt surface produces an eddy current on the hole wall when it is excited by an alternating current. When a crack exists at the hole edge, it will cause eddy current disturbance, and then generate some changes in the magnetic field, which can be sensed by the eddy current coil. The interference of the hole-edge crack to the eddy current around the hole wall is mainly reflected in two directions: (1) Flowing around the crack tip in the radial direction; (2) flowing around the crack tip in the axial direction of the hole. The influence of flowing in the radial direction on the induced voltage

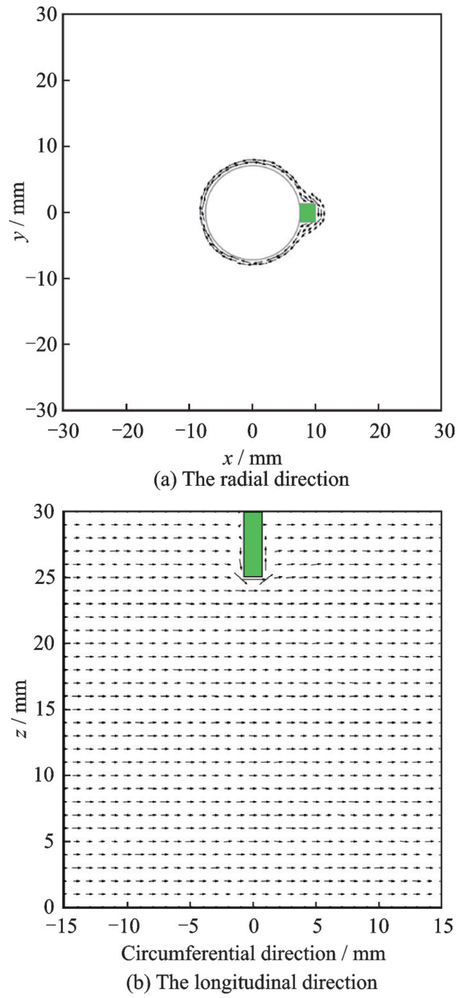

Fig.1 Principle of eddy current sensing film for crack detection

of the eddy current coil is significantly higher than that in the axial direction[17].

As shown in Fig.2, Sun et at.[18] proposed a two-dimensional sensing film consisting of an interleaving rectangle coil array to quantify the crack parameters, especially the accurate angle of bolted joints, which is helpful to identify the failure mode of joints. This is mainly due to the fact that when the crack angle changes, the induced voltages of the two interleaving rectangular coils present exactly the opposite linear change trend. However, it is obvious that the sensing film consisting of multiple layers has a larger thickness, which may influence the installation of bolted joints.

As shown in Fig.3, a parallelogram eddy current coil array, taking a 3×3 array as an example, is considered to characterize the hole edge cracks. The detailed configuration of the parallelogram coil

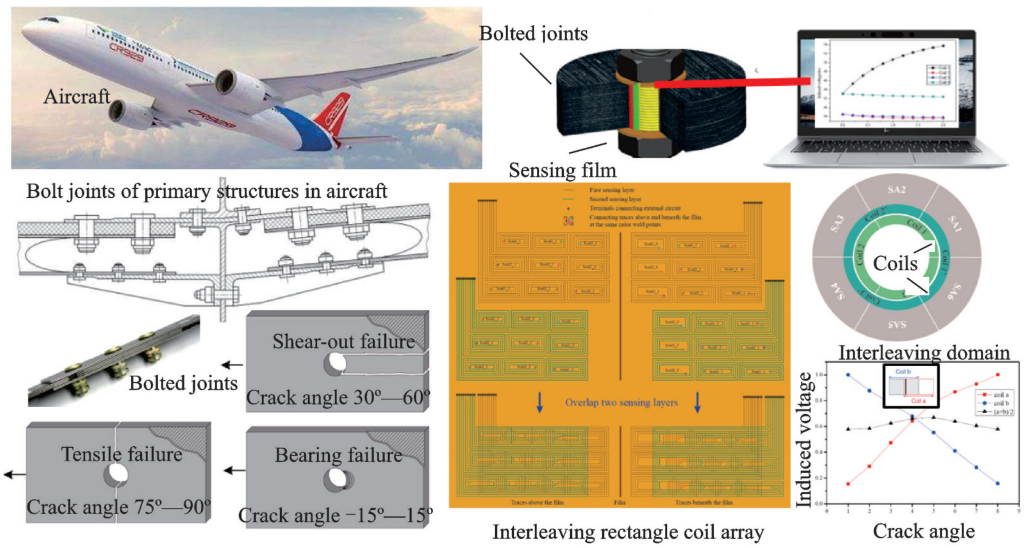

Fig.2 Interleaving rectangle eddy current coil array-based sensing film and its application

array can be designed as shown in Fig.3(b), and its typical feature is that the traces of the coil contacted by the crack at each angle are different. With the change of crack angle, this coil has exactly the opposite change trend of induced voltage with the two adjacent coils in the circumferential direction. Thus, as the crack angle changes, the induced voltages of the two adjacent coils in the circumferential direction may have the opposite change trend, which is similar to the interleaving rectangle coil array[17].

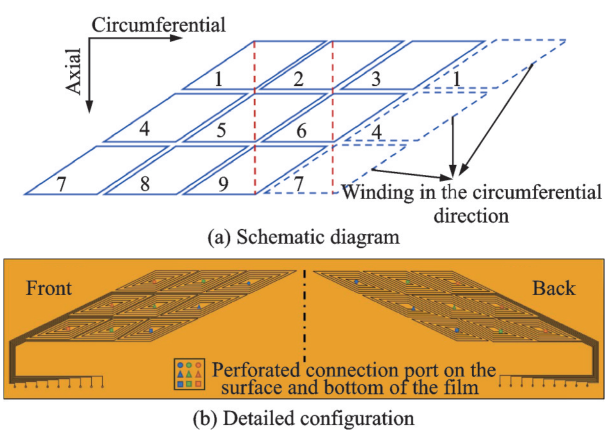

Fig.3 Parallelogram coil array-based sensing film

2 Finite Element Analysis

A simulation is carried out to assess the ability of the proposed parallelogram coil array to identify hole-edge cracks of bolt joints. The existence of cracks and the parallelogram coil configuration in this paper destroy the axisymmetric characteristics of the bolt hole edge, so it is difficult to analyze the influence of cracks with analytical solutions. Thus, the finite element method is used to solve the following Maxwell equations.

$$\nabla^2 \varphi - \mu\varepsilon \frac{\partial^2 \varphi}{\partial t^2} = -\frac{\rho}{\varepsilon} \tag{1}$$

$$\nabla^2 \boldsymbol{A} - \mu\varepsilon \frac{\partial^2 \boldsymbol{A}}{\partial t^2} = -\mu \boldsymbol{J} \tag{2}$$

where $\boldsymbol{A}$ is the magnetic vector potential, φ the electric scale potential, ρ the free charge bulk density, μ the permeability, ε the dielectric constant, and $\boldsymbol{J}$ the conduction current density.

2.1 Finite element model

The finite element software Ansoft Maxwell is employed. In the paper, only the hole-edge crack of the jointed structure is considered to change the induced voltage of eddy current coils, while the bolt is intact and its existence has little effect on the induced voltage change. Hence, the bolt is not considered in the simulation. As shown in Fig.4, an aluminum sample with the dimension of 6 mm×4 mm×9 mm (hole diameter×radial length×height), the conductivity of 3.8×10^7 S/m, and the relative magnetic permeability of 1.000 21, is considered. In Fig.4, r, θ and z denote the radial, circumferential and axial directions, respectively. A parallelogram eddy current coil array (3×3), the same as the one in Fig.3(b), distributes in both the circumferential and axial directions. Each parallelogram coil covers two thirds of the circumferential length. The receiving coil and the excitation coil have the same configuration. The width and spacing of traces are both 0.1 mm. The exciting coil is loaded with a sinusoidal signal with the frequency of 1 MHz.

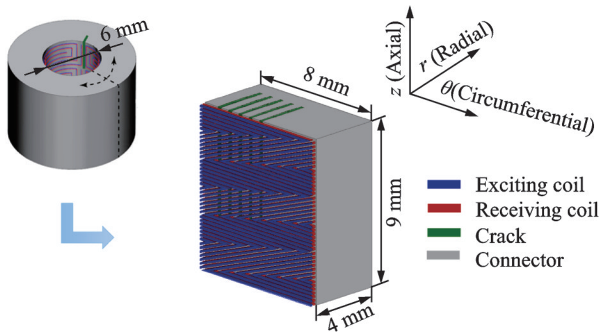

Fig.4 Finite element simulation model

2.2 Configuration of exciting coil

Based on the previous knowledge, the excitation and receiving coils must have the same configuration, which can cause the receiving coil to have a high sensitivity to the crack-induced magnetic field and generate a relatively more orderly change of induced voltage. Moreover, in order to ensure that the traces at each position have the same excitation current and improve the detection efficiency, each parallelogram coil is connected end-to-end as a large coil when used as an excitation. There are four exciting configurations, named Configurations Ⅰ—Ⅳ, respectively, as shown in Fig.5. The difference among the four configurations is whether the directions of electric current at the edge of adjacent coils in both the circumferential and axial directions are the same or not.

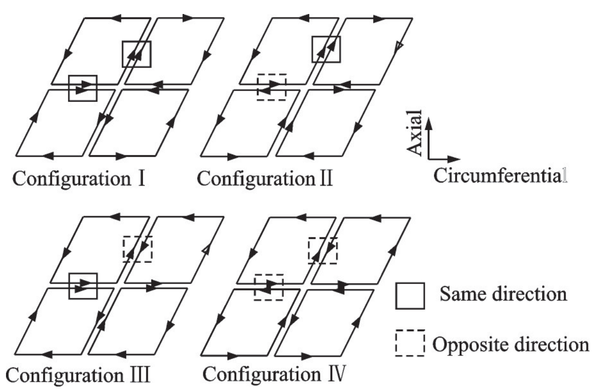

Fig.5 Configurations of exciting coil

Fig.6 shows the eddy current field of the bolt hole wall at the cross region of circumferentially adjacent coils generated by four excitation coil configurations. It can be seen that the eddy current fields generated by Configurations Ⅰ and Ⅱ are relatively uniform compared to Configurations Ⅲ and Ⅳ, and have much larger strengths at the edge of adjacent coils in the circumferential direction. As shown in Fig.6, the circumferentially adjacent coils are named as S1 to S6, and a crack, with the dimension of 0.2 mm× 3 mm×1 mm (width×axial length× radial length) is set in the middle of S1 and S2. Fig.7 shows the induced voltage change caused by the four configurations. It can be seen that Configurations Ⅰ and Ⅱ are more sensitive to cracks than Ⅲ and Ⅳ. Therefore, it is much better to select Configurations Ⅰ and Ⅱ with the same exciting current directions at the edge of adjacent coils in the circumferential direction.

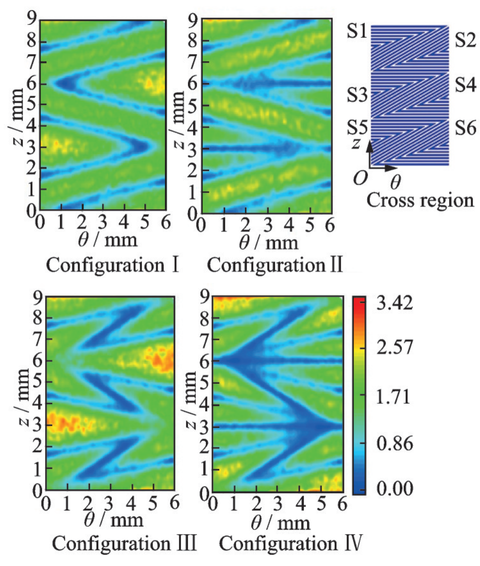

Fig.6 Eddy current field at the cross region

On the other hand, the current direction of axially adjacent coils is important to identify the crack depth, which has been discussed in detail in Ref. [15]. It has been concluded that the opposite exciting current directions between axially adjacent coils are suitable for identifying the damage of metal structures with strong conductivity, while the same excitation current directions are suitable for identifying the damage of composite structures with weak

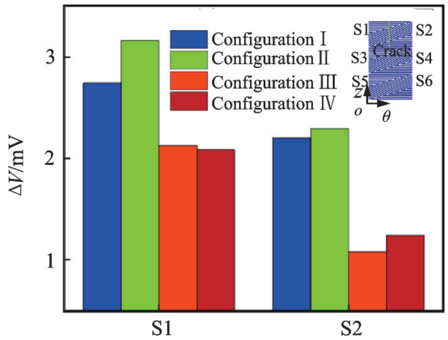

Fig.7 Crack sensitivity of Coils S1 and S2 for four exciting configurations

conductivity. It can also be found from the comparison of Configurations Ⅰ and Ⅲ with Configurations Ⅱ and Ⅳ in Fig.5 that Configurations Ⅰ and Ⅲ have high strengths at the edge of adjacent coils along the axial direction, while Configurations Ⅱ and Ⅳ have a clear line of demarcation.

In summary, Configuration Ⅱ is the best for the crack quantification of metal bolted joints.

2.3 The ability of identifying the crack angle

In order to verify the capability of the proposed coil to identify the hole-edge crack angle of bolted joints, the crack position in Fig.6 is changed from the middle of Coils S1 and S2 to the left tip of Coil S2 four times, and the five positions of the crack are recorded as C5 to C1, respectively.

Fig.8 shows the induced voltage change of each coil as the crack angle changes. In Fig.8, the induced voltages of Coils S1 and S2 at the crack location change significantly, while those at other locations are basically unchanged. The induced voltage changes of Coils S1 and S2 are almost linear. When the crack is at the circumferential location C1

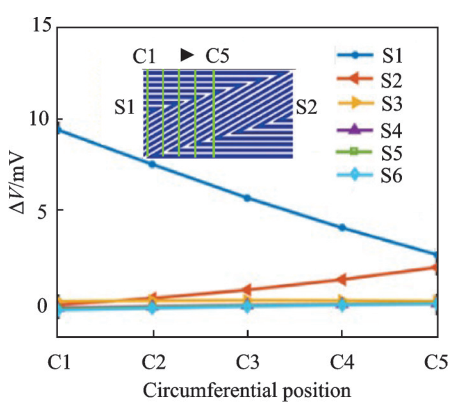

Fig.8 Induced voltage versus crack angle

or C2, the induced voltage change of Coil S2 has a small amount, almost zero, due to the mutual cancellation of the eddy current field generated by the excitation current at the tip of Coil S2, as can be seen from Fig.5.

The difference between the induced voltage changes of Coils S1 and S2 at different crack angles is calculated as shown in Fig.9. Through the linear fitting, it can be found that the induced voltage changes of Coils S1 and S2 show a linear trend with the crack angle, and the fitting curve is expressed as

$$y = -2.3x + 12 \tag{3}$$

where x and y denote the crack angle and the difference between induced voltage variations of Coils S1 and S2, respectively. The determination coefficient, the R-square value, of the linear fitting curve is as high as 0.999 8. Hence, the difference between the induced voltage changes of the crossed parallelogram coils is a good feature parameter that can be used to quantitatively characterize the crack angle.

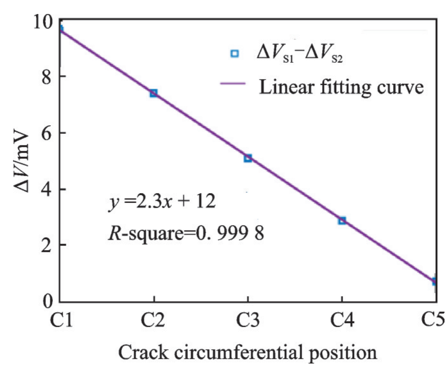

Fig.9 Difference between the induced voltage changes of Coils S1 and S2 versus crack angle

2.4 The ability of tracking the crack length

After identifying the crack angle, the capability of detecting the radial growth of cracks at the five circumferential positions in Fig.7 is also investigated. In the simulation, the cracks at the five circumferential positions are expanded to 3 mm with 1 mm steps in the radial direction, which are labeled as R1, R2, R3.

The induced voltage changes of Coils S1 and S2 are shown in Fig.10. First, the linear varying trend of the induced voltage with the crack angle in

Figs.8 and 9 can also be found when the crack has a different radial direction. Then, when the crack propagates radially at positions C1—C4, the induced voltage of Coils S1 increases with the increase of the radial length of the crack, but the speed of change slows down. At position C5, although the induced voltage of S1 is significantly higher than the reference, it can no longer distinguish the radial growth of the crack. The change of Coil S2 is just the opposite. At positions C4 to C5, the induced voltage change of Coil S2 increases with the radial length of the crack more obviously, while at positions C1 to C3, it cannot be used to judge the radial growth of cracks.

In summary, after identifying the crack angle, Coils S1 and S2 can be selected to track the radial growth of the crack.

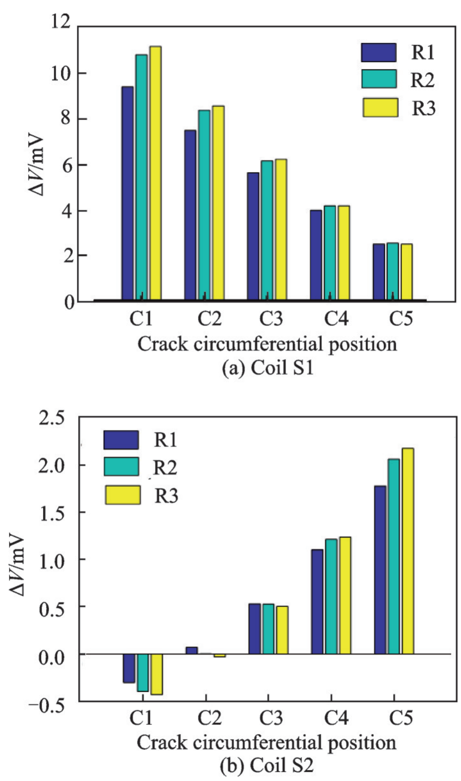

Fig.10 Induced voltage of coils versus the crack growth in the radial direction at different angles

2.5 The ability of identifying the crack depth

Two circumferential positions in Fig.8, C1 and C5, are selected to study the ability of the parallelogram coil array to detect crack depth. The radial length of the crack is set as 1 mm, and the crack extends from the upper boundary of the jointed structure to the lower boundary with a step of 3 mm. The crack propagates through one layer (3 mm) at each time, up to a total of 9 mm.

Figs.11(a) and (b) show the induced voltage changes of each coil when the crack propagates axially at the circumferential positions C1 and C5, respectively. At C5, it can be seen that when the crack penetrates the first axial layer, only the induced voltages of Coils S1 and S2 rise significantly. When the tip of the crack reaches the second layer, the induced voltages of Coils S3 and S4 also begin to increase significantly. When the crack penetrates the third layer, the induced voltages of Coils S5 and S6 change significantly. At C5, only the induced voltage changes of Coils S1, S2 and S3 have a sig-

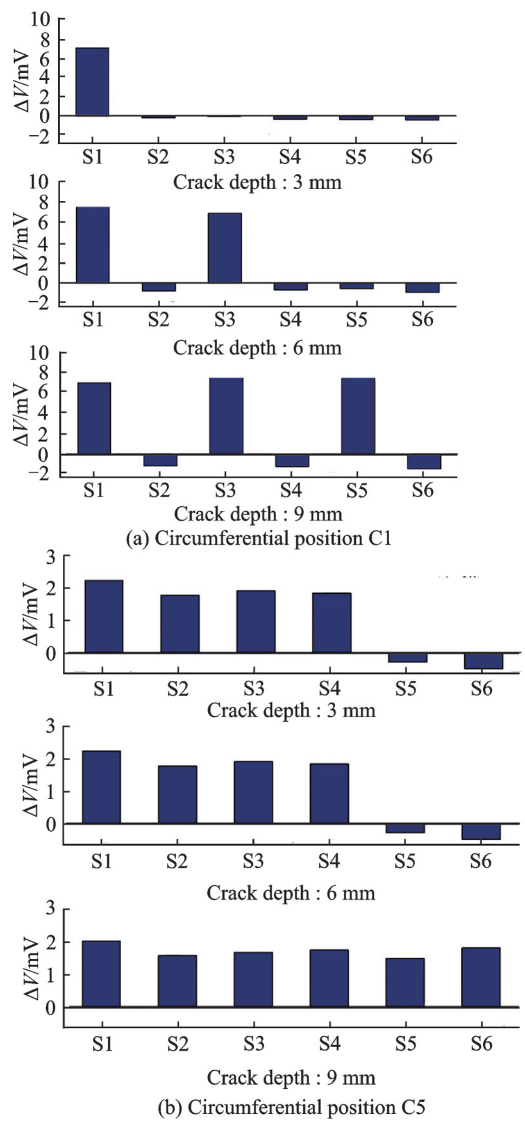

Fig.11 Simulation results of crack axial position monitoring

nificant change, but it is enough to identify the crack depth. It can be seen that the parallelogram coil array can be used to determine the crack depth, and it is not restricted by the circumferential position of the crack.

3 Experimental Verification

Experiments are conducted to verify the ability of the parallelogram eddy current array coil to monitor crack parameters.

In Fig.12(a), the eddy current sensing film is made using multi-layer flexible circuit board technology. The thickness of the sensing film is 0.2 mm, and the coil region has the dimension of 40.7 mm×15 mm (length×heigth). The exciting coil covers the whole coil area, and the receiving coil is composed of 9 coils, named from S1 to S9. In Fig.12(b), the test sample is made up of three aluminum blocks with the dimension of 75 mm×75 mm×5 mm. A bolt hole with a diameter of 13.5 mm is set at the center of the aluminum block. The film is wound and surface bonded to a steel bolt, which is used to connect the three aluminum blocks.

As shown in Fig.12(c), a signal generator, Tektronix AFG 1022, is utilized to connect the exciting coil in the sensing film and generate a sinusoidal signal with the frequency of 1 MHz. An NI Oscilloscope PXIe-522 is used to acquire the eddy current signal of the receiving coils.

3.1 The ability to identify the crack angle

In the experiment, the centers of Coils S1, S2 and S3 are set as 0°, 120°, and 240°, respectively. The crack, with the dimension of 0.2 mm×3 mm×1 mm (width×axial length×radial length), is machined by a wire-cutting process and only covered the depth of Coils S1—S3. After one crack is set in the aluminum block, the different crack angle could be realized by rotating the aluminum block, while the bolt and sensing coils are fixed. By rotating the aluminum block, the crack angle changes from 0° to 240° at 15° intervals. Fig.13 shows the changes of the induced voltage of Coils S1—S3 with the crack angle. As can be seen from Fig.13, from 0° to 120°, the induced voltage change of S1 shows a downward trend, while the change of S2 shows an upward trend, and the change of S3 is close to 0. From 120° to 240°, the induced voltage change of S1 is basically less than 0, and the change of S2 shows a downward trend, while the change of S3 shows an upward trend. The change trend of the induced voltage of each receiving coil is consistent with the simulation, indicating that the coils can effectively distinguish the crack angle. However, from 210° to 240°, the induced voltage change rate

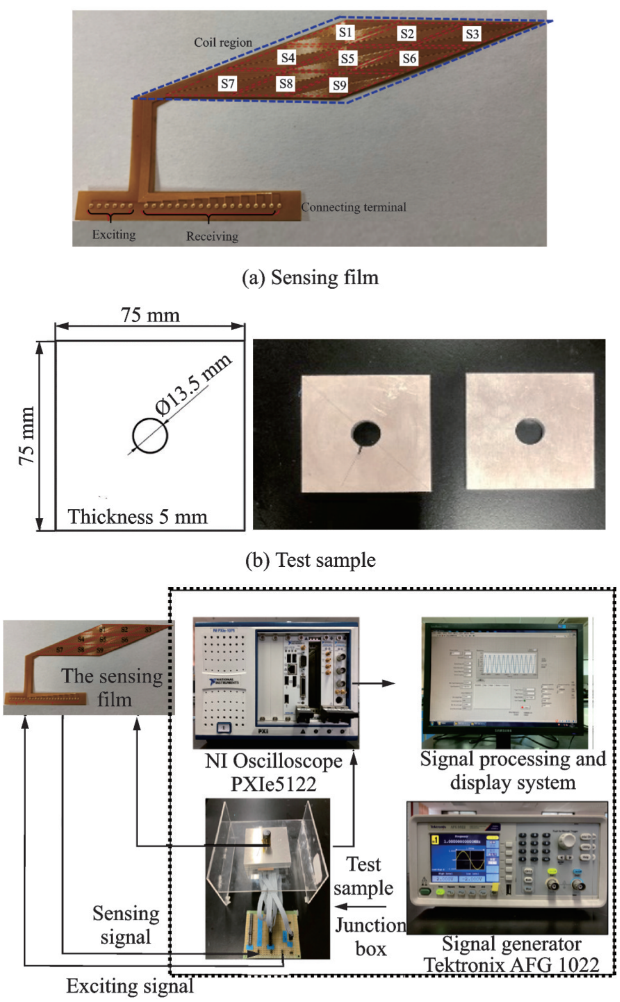

Fig.12 Sensing film and experimental system

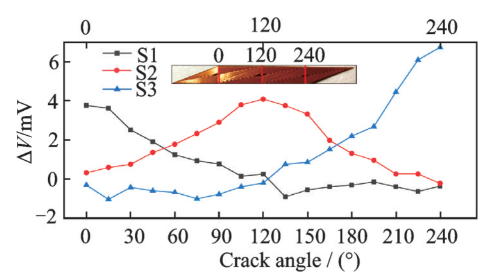

Fig.13 Induced voltage change versus crack angle

of S3 increases, which may have been caused by uneven lift-off in the different angles in the experiment.

Fig.14 shows the difference between the induced voltage changes of Coils S1 and S2 from 0° to 120°, and the difference between the change of S2 and S3 from 120° to 240°. The R-squared values of their linear fitting curves are 0.989 44 and 0.986 96, respectively. This denotes that the difference of the induced voltage changes of the cross coils may be used to identify cracks effectively.

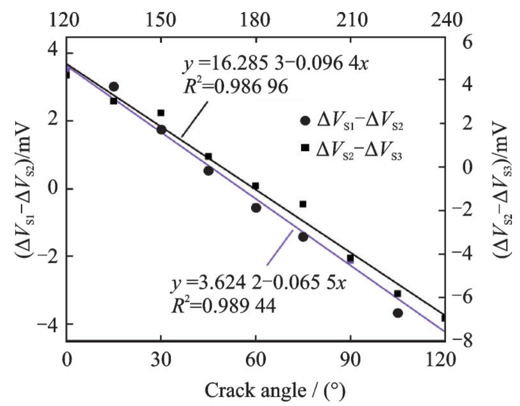

Fig.14 Fitting diagram of crack angle identification curves

3.2 The ability to track the crack length

In order to explore the ability of the parallelogram coil array to monitor crack growth in the radial direction, two crack angles, 0° (the center of S1) and 60° (the middle between S1 and S2) are considered. The crack with the dimension of 0.2 mm×3 mm (width×axial length) covers the depth of S1, and the length of the crack propagates from 1 mm to 4 mm in steps of 1 mm. Fig.15 shows the induced voltage changes, from which the following conclusions can be drawn.

(1) When the crack expands radially at 0°, the induced voltage of Coil S1 has a significant increase, but those of the other coils do not change. This is consistent with the simulation results.

(2) When the crack expands radially at 60°, the induced voltages of S1 decreases by about 1 mV. At the same time, the induced voltage of S2 increases sharply by about 4 mV.

(3) The change amount of induced voltage of S1 at 60° is less than that of at 0°, consistent with the results of detecting the crack angle.

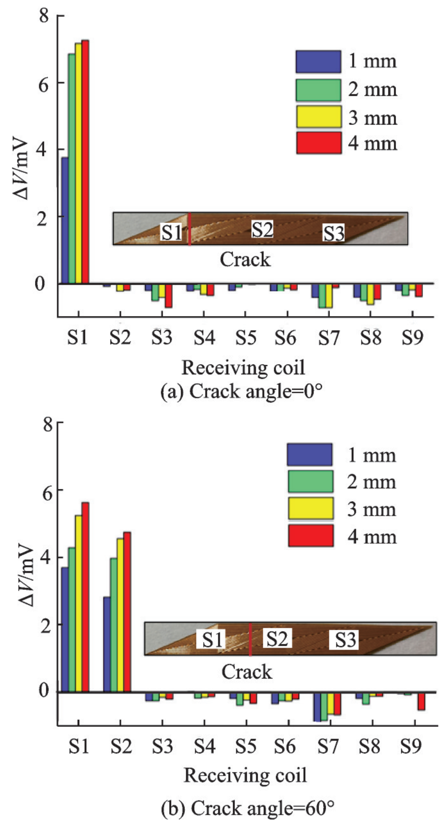

Fig.15 Induced voltage change versus the crack length at two crack angles

The above results prove that the parallelogram coil may track the crack length effectively.

3.3 The ability to identify the crack depth

An experiment is conducted to verify the capability of the proposed sensing film to identify crack depth. The crack is set at 60°, i.e., the middle between S1 and S2. The crack has the dimension of 0.2 mm×1 mm (width×radial length), and the crack depth is set as 5 mm, 10 mm and 15 mm, that is, it passes through S1, S2, S5, S6, S9 and S7 in order from top to bottom along the axial direction. Fig.16 gives the induced voltage change of all coils. It can be seen that when the crack depth is 5 mm, only the induced voltage of Coils S1 and S2 at the first layer increases significantly. When the crack propagates to the second layer, the induced voltages of Coils S5 and S6 also increase. When the crack propagates to the third layer, the induced voltage of Coils S7 and S9 rises significantly. The above results are consistent with the simulation results. It is thus proven that the parallelogram coil ar-

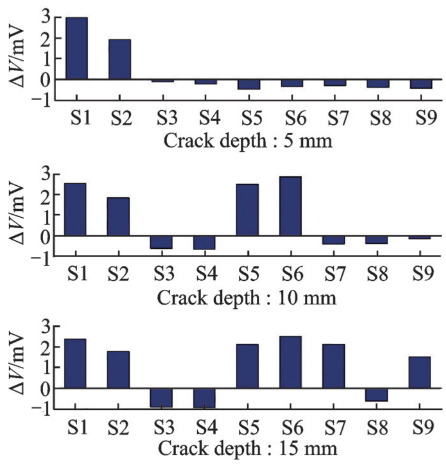

Fig.16 Induced voltage change versus the crack depth

ray can be used to identify the crack depth.

4 Conclusions

A parallelogram coil array-based eddy current sensing film has been developed to characterize cracks in bolted joints. Finite element simulations and experiments have been both conducted to verify the capabilities of the developed sensing film. The main conclusions are drawn as follows.

(1) Compared with the existing coils arrays, the parallelogram coil array has smaller number of layers, although it can also quantify crack parameters with the similar resolution.

(2) The configuration of the parallelogram coil array, especially the exciting coil, has been designed and analyzed in detail to obtain an optimized type for quantifying the crack parameters with a better ability.

(3) Through the simulation and experiments, it has been proven that the parallelogram coil array may effectively detect the angle, depth and length of the hole-edge crack of bolted joints.

In addition, the following important studies need to be thoroughly studied in the future: (1) The effect of film thickness on the mechanical properties of bolt installation; (2) the sensitivity of the sensing film to identify crack parameters.

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基于平行四边形涡流阵列传感薄膜的螺栓连接结构裂纹定量监测技术研究

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摘要:螺栓孔边裂纹监测是飞机结构健康监测的重要内容之一。本文提出了一种基于平行四边形线圈阵列的新型涡流传感薄膜,与现有方法相比,可以在更少的传感层和线圈数量定量监测螺栓孔边的裂纹参数。本文设计并优化了平行四边形线圈阵列的构型,采用3×3平行四边形线圈阵列定量监测螺栓孔边裂纹参数,可以有效提升裂纹定量监测能力。有限元仿真和实验验证了本文所提出的平行四边形线圈阵列不仅可以准确、定量地识别螺栓孔边裂纹的角度,还可以跟踪裂纹沿螺栓孔径向的长度和沿轴向的深度。

关键词:螺栓连接结构;柔性涡流传感薄膜;平行四边形线圈阵列;结构健康监测