A structural crack monitoring gasket for aircraft bolt-jointed structures with temperature compensation

Tao Chen, Jinqiang Du and Yuting He

Air Force Engineering University, Xi’an 710038, People’s Republic of China

E-mail: 762738050@qq.com (Tao Chen)

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Abstract
In order to meet the need of the quantitative monitoring of cracks in critical connection structures of aircraft, aiming at improving the durability of sensors and the reliability of signals, a structural crack monitoring (SCM) gasket, which can be used for the quantitative monitoring of cracks in bolted joints, is developed. The gasket is formed by a gasket substrate and a flexible eddy current sensor integrated to withstand the load, with the capability of temperature compensation. First of all, a new temperature-compensated rosette eddy current array (TC-RECA) sensor is designed and used to study the failure mode of the sensor. According to the failure mode of the sensor, a gasket substrate with load-bearing capacity is developed. Subsequently, the influence of permeability, conductivity and lift-off on the trans-impedance of the sensor is studied. The influence of permeability on the trans-impedance is characterized by conductivity. Based on this, a temperature compensation method for ferromagnetic materials is developed. Then, a temperature influence experiment and a structural crack quantitative monitoring experiment are carried out using a front beam connection structure of an aircraft wing. The temperature effect experimental results show that even if the ambient temperature changes from 60°C to −40°C, the characteristic signal ΔC does not change significantly, indicating that the gasket has a temperature compensation capability. The experimental results of the crack monitoring of the front beam connection structure show that the gasket can bear the load and has the capability to quantitatively monitor cracks, and can be used for the quantitative monitoring of cracks in the critical connection structure of aircraft structures.

Keywords: structural crack monitoring gasket, temperature compensation, quantitative monitoring crack

(Some figures may appear in colour only in the online journal)

1. Introduction

Structural health monitoring (SHM) technology can not only ensure flight safety and reduce aircraft maintenance costs, but can also serve as a technical support for the life extension of aircraft structures. Due to the dispersion of structural fatigue life, existing damage detection methods cannot accurately detect the damage of each key part in a timely manner, resulting in the partial conservativeness of the existing life assessment and life extension methods for aircraft structures, and leading to a waste of aircraft life resources. The SHM technology can detect the structural damage of critical parts in time and realize condition-based maintenance. This will completely change the traditional aircraft maintenance mode, and greatly extend the service life of aircrafts.

An aircraft is made by joining together many components. Bolt connection is the most important connection
method of aircraft structures, which is widely used in the wing, fuselage, rudder and other key connection components. These locations are also the most prone to cracks, and once a crack exceeds a critical length, it will lead to serious accidents [1, 2]. These critical parts are important references when evaluating and extending the life of aircrafts. These critical parts are designed by damage tolerance criteria, which hold that the structure has initial defects and the structure is safe before the crack length reaches a critical length. Therefore, in the use of such structures, engineers are more concerned about the length of cracks rather than whether there are cracks in the structure. Therefore, one of the most important works in the field of aircraft SHM is to carry out research on the quantitative monitoring of cracks in bolted joints.

The harsh service environment of an aircraft structure, including load, temperature, vibration, humidity and so on, has a significant impact on the durability and reliability of sensors, which may result in their failure [3]. For bolted structures, the critical length of the crack is so small in some areas (such as joints made of high-strength steel) that the structure beneath the gasket needs to be monitored. Currently, despite the development of various technologies for SHM, including technology such as optical fiber [4–7], CVM sensors [8, 9], acoustic emission [10, 11], guided wave [12], and other sensor technologies [13, 14], these sensors cannot be used in critical bolted structures due to the unacceptable load of the bolts. Because the flexible eddy current array sensor possesses the characteristics of non-contact monitoring and flexibility, it can be used for the damage monitoring of metallic structures, including various curved surface structures. Rakow and Chang [15] developed a kind of SHM fastener for monitoring the crack of a bolted joint structure by integrating the flexible eddy current sensor and fastener, and carried out preliminary research on the durability of the sensor. JENTEK Sensors [16–20] developed a series of meandering winding magnetometer eddy current sensors, which have been applied for the damage inspection of metal structures [18, 19], and has carried out much research in the quantitative monitoring of structural cracks [20]. But these studies have only completed the function verification of the crack monitoring ability, and have not studied the impact of the service environment on the monitoring process.

Furthermore, signals are easily disturbed by environmental factors [21], often leading to false indications. False alarms lead to an increase in the maintenance cost. In particular, for the difficult-to-access locations, false alarms not only increase the maintenance cost, but also add to the downtime of equipment which is unacceptable for users. For example, to disassemble some inner components of an aircraft may take a dozen days or even months, and missed alarms will cause the the damage information to be missed, threatening safety. At present, impacts of the service environment on structural damage monitoring has become the key to the application of SHM technology for aircraft structures. It is possible for a plane to fly from the ice-cold North Pole to the hot equator in one flight, while with a climb in flight, it is possible for the ambient temperature to change from 60 °C to −40 °C. Traditional damage detection does not need to consider impacts of dramatic changes in ambient temperature on detection, and SHM techniques need continuous signal acquisition, and the change of ambient temperature is a huge challenge for the reliability of monitoring. Various approaches have been developed to avoid the influence of ambient temperature, such as the optimal baseline selection method [22], the baseline signal stretch method [23, 24], the reference free approach [25], model-based approaches [26, 27] and the physics-based method [28]. These temperature compensation methods need data sets of in situ sensor measurements, which limit the practical application for any possible combination of structural and environmental changes, especially for bolt connected structures.

A previous study [29] has found that a variation of ambient temperature will change the electrical conductivity of aluminum alloys, which has a greater impact on the signals of the eddy current sensor. Therefore, a flexible eddy current sensor is designed and used for non-ferromagnetic materials. However, this research only studied non-ferromagnetic materials such as aluminum alloys, and did not study ferromagnetic materials which are widely used for critical connection structures. In traditional eddy current testing, both the permeability and conductivity of ferromagnetic materials will be affected by the ambient temperature, and the permeability and conductivity change of the tested materials will have an impact on the signals of eddy current sensors. In order to eliminate the negative influence of permeability change on detection, the structure under testing is usually magnetized to saturation by DC magnetization, so the permeability becomes smaller and the influence of the change of permeability is reduced. However, for aircraft structures, it is impossible to mount these instruments on aircrafts. Therefore, this method is not suitable for the SHM of aircraft structures.

To improve the durability of the sensor and the reliability of the signal, this paper develops a crack monitoring gasket that can be used for the quantitative monitoring crack of the
bolt connection structure. Firstly, a new TC-RECA sensor is developed and used to investigate the failure modes for the crack detection of bolt connection structures. Then, the SCM gasket is developed and the temperature compensation method for ferromagnetic material monitoring is proposed for the first time. Then, verification experiments are carried out using a connection structure manufactured according to the actual aircraft structure.

2. SCM gasket

2.1. Sensitivity-boosted TC-RECA sensor

The sensor consists of two drive windings, four sense channels and one reference channel, as shown in figure 1. The difference between the sensor in the previous work [29] and the new sensor is that the former has only one excitation winding, while the new sensor has two separate drive windings which work alternately. When the new sensor is working, the inner drive winding is first excited and signals of channel 2, channel 4 and the reference channel are collected; then, the outer drive winding is excited and signals of channel 1 and channel 5 are collected. With this method, the new sensor has a higher sensitivity than the former one. It should be noted that two drive windings lie on the opposite side of the substrate layer so that the lead wire of each drive winding is not connected, and the lift-off is the distance between the sensor and the structure under testing, as shown in figure 2.

This paper defines the trans-impedance of the sensor as:

\[ Z_R = \frac{V}{I} = A_R e^{i\theta} \]  

where \( Z_R \) is the trans-impedance of the sensor, \( V \) is the voltage of the sensing channel, \( I \) is the exciting current, \( A_R \) is the magnitude of the trans-impedance and \( \theta \) is the phase of the trans-impedance.

The new sensor is designed using a 3D finite element model in a COMSOL AC/DC module, as shown in figure 3. In this model, the drive windings are simulated with two circle lines, and the sense elements are simulated with two areas. The former sensor is firstly calculated and the distributions of the eddy currents are shown in figure 4 when the crack propagates. As shown in figure 4, when the crack tip propagates to channel 2, part of the eddy currents excited by the inner drive winding flow towards the currents excited by the outer drive winding and form a loop, resulting in the perturbation effect of the crack on the eddy currents becoming weaker. When the crack propagates to channel 1, only a small part of the eddy currents excited by the outer drive winding flow around the crack tip because most of the eddy currents flow to currents excited by the inner drive winding. When the two windings are separately excited, the distributions of the eddy currents are shown in figure 5 when the crack propagates. As shown in figure 5, when the crack tip propagates to channel 2 and channel 1, the eddy currents flow around the crack tip much more, resulting in a stronger perturbation effect of the crack.

In this section, the variation rate of the trans-impedance magnitude is defined as follows:

\[ S_C = \frac{\Delta A_R}{A_{R0}} = \frac{|A_R - A_{R0}|}{A_{R0}} \]  

where \( S_C \) is the variation rate of the trans-impedance magnitude, \( A_{R0} \) is the initial trans-impedance magnitude; the sensitivity of the sensor to the crack is characterized by the maximum value of the \( S_C \).

As shown in figure 6, the maximum \( S_C \) of each channel of the new sensor is separately 1.91, 3.59 times of that of the former sensor, which means the sensitivity of each channel increases separately by about 91% and 259%.

When a crack initiates and extends below the measurement channel, the distribution of the eddy current field will be changed, resulting in variations of the signals of the corresponding measurement channel. Accordingly, it can be
Figure 3. 3D FE model of the sensor.

Figure 4. The eddy current distribution using the former sensor.

Figure 5. The eddy current distribution using the new sensor.

Figure 6. The $S_C$ variations of the two sensors with the crack growth.
The installation schematic of the sensor.

Figure 7. The installation schematic of the sensor.

determined whether there is a crack in the structure, and then the length of the crack can be obtained according to the geometric size of the sensor windings. The measurement channels are arranged on both sides of the hole so as to monitor the bilateral crack which appears around the hole, which is more reasonable for structural damage tolerance analysis. The purpose of adding a reference channel is to compensate for the effect of temperature changes on the signals of the sensor. For metal materials, the change of ambient temperature causes a uniform change of the permeability and conductivity of materials at the same location. The interference of temperature with signals can be eliminated by extracting the characteristic signals that can characterize the variations of permeability and conductivity of materials at the same location. When the sensor is installed, sense channels are mounted on the areas where cracks may initiate and grow, while the reference channel is mounted at the location where the crack is not very likely to occur, as shown in figure 7.

When the sensor is applied in a bolted structure, there are mainly two typical cases, as shown in figure 8. For the case in figure 8(a), the sensor mounted on the outer side of the common gasket does not bear the load and is suitable for a structure with a long critical crack length. This application method does not have too strict requirements on the load-bearing performance of the sensor. Many structures manufactured by high strength steel have a smaller critical crack length, which means the structure may be fractured before the crack propagates out of the gasket region. For these structures, the sensor must be mounted under the gasket, as in the case of figure 8(b). The pressure and friction force generated during the tightening process of bolts and the fatigue load applied on structures form the main load condition of the sensors, which requires strict durability of the sensor. Therefore, it is necessary to study the failure mode of the sensor in case (b) and take corresponding measures to improve the durability of the sensor.

2.2. Research on failure modes of the sensor

As shown in figure 8(b), the sensor is directly mounted below the gasket and a tightening torque is applied on the bolt by a torque wrench. The specimen integrated with a sensor is installed on the fatigue testing system to carry out a fatigue test, and the signals of the sensor are monitored. The test is stopped when the sensor fails. A comparative experiment is carried out under three tightening torques of 5 N·m, 15 N·m and 30 N·m. The sensor fails at 65 856, 15 856 and 4675 cycles, respectively, under three kinds of tightening torque. The failure situations are shown in figures 9–11.

As shown in figure 9, cracks appeared in the specimen with an applied tightening torque of 5 N·m when the sensor failed, and the path of the crack growth is consistent with the trend of the sensor cracks in the figure. Near the crack source area of the specimen, the crack of the sensor is larger and deeper, and near the crack tip area of the specimen, the crack of the sensor is smaller and shallower. When the crack grows, the opening of the crack causes a large deformation in the corresponding region of the sensor. With an increase in the crack opening angle, the deformation gradually becomes larger until the sensor fails.

The specimen with an applied tightening torque of 15 N·m is inspected after the sensor fails, which shows there is no crack in the specimen. Then, the sensor is observed by a microscope, and the crack shown in figure 10 is found on the excitation coil of the sensor. The main reason for the failure is that the gasket will rotate under the larger frictional force between the gasket and the sensor when the tightening torque is applied on the bolt, causing the sensor to bear shear stress; when the fatigue stress is applied on the specimen, the fatigue load transferring to the sensor is large, causing the failure of the sensor coil due to a failure crack.

As shown in figure 11(a), after the failure of the sensor with a tightening torque of 30 N·m, there are serious distortions in the multiple locations of the sensor, which are mainly due to the extrusion and shearing effects applied on the sensor when the gasket rotates. In addition, as shown in figure 11(b), the sensor coil is fractured and there is an obvious trace of extrusion deformation near the crack. When the specimen is subjected to a fatigue load, there is a great static friction between the sensor and the specimen, which also causes the sensor to be subjected to fatigue load. Under the joint action of large shear stress and fatigue load, the sensor is destroyed in a very short time.

Therefore, the main failure modes of the sensor can be concluded as follows: under the tightening torque, the sensor bears the pressing force and shear force, which produces a certain deformation on the sensor. When the fatigue load is applied on the specimen, the sensor also bears fatigue stress; thus, installation stress, deformation and fatigue load lead to the damage and failure of the sensor. The main damage forms of the sensor include the deformation of sensor coils, the fatigue fracture of coils and the tear of the sensor.

2.3. Design of the SCM gasket

The research in the previous section shows that during the tightening process of the bolts, compression force and shear force are applied to the sensors, and the shear force is closely related to the static friction between the sensor, the specimen
and the gasket. When fatigue loading is performed on the specimen, the sensor will also be affected by the fatigue load from the specimen. The load transferred from the specimen to the sensor depends on the magnitude of the static friction between the sensor and the specimen. Therefore, it is an effective way to improve the durability of the sensors by adopting certain measures to reduce the static friction between the sensor and specimen and the sensor and the gasket. In this paper, the SCM gasket for the quantitative monitoring of cracks in connecting structures is proposed by using the advantages of the non-contact monitoring of the flexible eddy current sensor. As shown in figure 12, the gasket is made by encapsulating the TC-RECA sensor inside the gasket substrate and can be directly attached to bolt hole locations to monitor structural cracks.

The purpose of developing the SCM gasket is to reduce the load borne by the sensor and to improve the durability of the sensor. At the same time, the metal part of the gasket must be retained as much as possible so that the bearing capacity of the gasket is sufficient. For this reason, a finite element model, as shown in figure 13, is established to analyze the stress distribution of the structural gasket. In this paper, the stress distribution of an ordinary gasket under a tightening torque of 30 N·m is analyzed, as shown in figure 14. It can be seen from the graph that the most serious stress area of the gasket under preload force is mainly concentrated in the yellow ring area shown in the diagram. This area bears most of the pressure. When the gasket is designed, the stress distribution of the new gasket should be close to this.

Therefore, the gasket substrate is designed as shown in figure 15. There is a groove for installing the sensor, meaning the sensor does not bear a large load, and it greatly reduces the pressing stress and shear stress acting on the sensor. In the meantime, to make the gasket maintain enough of the load-bearing capacity, a circular boss with a width of 1.5 mm near the hole is maintained. As shown in figure 16, the stress concentration area of the SCM gasket has not changed greatly compared with the ordinary gasket. In addition, when the sensor is integrated with the gasket, the sensor is not subjected to stress, which can effectively avoid sensor failure and improve the durability of the sensor. Therefore, the SCM gasket designed with this method can meet the load-bearing requirement of the structure. The final form of the SCM gasket is shown in figure 17. The sensor is encapsulated with a sealant, and the SCM gasket can be directly used at the bolt hole locations.

3. Effects of permeability variations on the trans-impedance response of the sensor

The following equation is often used to describe factors that can affect the impedance $Z$ of the sensor:

$$Z = f(x, \sigma, \mu, \omega)$$

where $x$ is lift-off, and $\omega$ is the frequency of the exciting current which is a constant value in this paper. However, the permeability and conductivity of the material are always considered as a constant value in traditional eddy current testing. There are theoretical studies on the effect of electrical conductivity or permeability variation on the trans-impedance
Figure 11. The damage morphology of the sensor under a tightening torque of 30 N \cdot m. (a) Serious distortions in the coils of the sensor. (b) The fractured coil of the sensor.

Figure 12. The basic composition of the SCM gasket.

Figure 13. The finite element model for stress analyses.

Figure 14. The stress distribution of the ordinary gasket under a tightening torque of 30 N \cdot m.

Figure 15. The geometry of the SCM gasket substrate.

Figure 16. The stress distribution of the SCM gasket under a tightening torque of 30 N \cdot m.
of the sensor. However, no literature can be found studying the effects of the common change of conductivity and permeability on the trans-impedance of the sensor.

For non-ferromagnetic materials, a variation of the ambient temperature will lead to a change in conductivity and lift-off. In previous work [29], the grid database representing the effects of conductivity and lift-off on the trans-impedance response is obtained and a new characteristic signal is proposed to eliminate the effects of temperature variations. This method is feasible for non-ferromagnetic materials, but for ferromagnetic materials, temperature variations not only result in a change of lift-off and conductivity, but also cause a change in the magnetic permeability. Therefore, the effects of conductivity, permeability and lift-off on the trans-impedance response of the sensor are investigated.

In order to study the effect of permeability, conductivity and lift-off on trans-impedance response, a finite element equivalent model is set up in a COMSOL AC/DC module, as shown in figure 18. In this model, ten conductivity (σ) values, ten relative permeability (μ) values and ten lift-off values are given. Then, ten groups of grid diagrams relating the trans-impedance response to conductivity and lift-off under certain permeability for ferromagnetic steels are calculated. Both conductivity and permeability increase with a rate of 20% each time. That is, $\sigma_i = (1 + 0.2)\sigma_{i-1}$, $\mu_j = (1 + 0.2)\mu_{j-1}$, ($i, j = 1, 2, 3,...,10$).

In order to investigate the impact of permeability on trans-impedance response, ten sets of conductivity and lift-off grid diagrams in figure 19 are all depicted in figure 20. When relative permeability $\mu_j$ increases with a rate of 20% each time, every equivalent conductivity curve representing conductivity $\sigma_i$ moves to the next equivalent conductivity curve representing conductivity $\sigma_{i-1}$. For example, when permeability $\mu$ increases with a rate of 20% from 7.7523 to 9.3027, the equal conductivity curve representing conductivity $\sigma_{10} = 51.6$ MS m$^{-1}$ moves to the equal conductivity curve representing conductivity $\sigma_9 = 43$ MS m$^{-1}$. It means that an increase in conductivity and a decrease in
relative permeability with the same rate have the same effect on the trans-impedance response of the sensor.

Therefore, permeability variations can be converted to conductivity variations. As illustrated in figure 21, ten conductivity and lift-off grid diagrams under ten permeability values can be converted to only one set of conductivity and lift-off grid diagrams under relative permeability $\mu = 7.7523$ by simply adding 9 smaller conductivity values ($\sigma = 8.33, 6.94, 5.79, 4.82, 4.02, 3.35, 2.79, 2.33, 1.94 \text{ MS m}^{-1}$). Therefore, permeability, conductivity and lift-off variations
can be represented by one set of conductivity and lift-off grid diagrams under certain permeability, which can reduce the 3D problem to a 2D one.

For ferromagnetic materials, crack, temperature and stress can change the conductivity, permeability and lift-off. According to the conclusion in the last paragraph, these variations can be simply represented in the conductivity and lift-off grid diagram by using the trans-impedance response of the sensor. The trans-impedance response can be influenced by the relative conductivity and lift-off. So it is not feasible to use the trans-impedance response as the characteristic signal. The conductivity of each channel can be obtained by using the trans-impedance response with the same method illustrated in the previous research work [29]. Similar to non-ferromagnetic materials, using the characteristic signal $\Delta C$ can eliminate the influence of ambient temperature on the signal:

$$\Delta C = \left( \frac{C_m - C_r}{C_r} \right)$$  \hspace{1cm} (4)

where $C_r$ is the conductivity of the reference channel, and $C_m$ is the conductivity of the measure channel. Actually, the characteristic signal $\Delta C$ represents the variation of the measure channel relative to the reference channel. When a crack propagates to a measure channel, the $C_m$ measured by the channel will decrease, while the $C_r$ will not be affected. Therefore, the characteristic signal $\Delta C$ will increase, indicating that the crack tip has reached the measure channel. When the ambient temperature changes, both the permeability and conductivity of the material will change. It is assumed that all the permeability or conductivity of the region around the same hole changes with the same amount. Then $C_m$ and $C_r$ measured by each channel also varies with the same amount and the characteristic signal $\Delta C$ will not be affected by temperature variations.

4. Experiments and results

4.1. The connection structure of the aircraft wing

As shown in figure 22, the connection structure of the aircraft wing used in the experiment is manufactured according to the actual aircraft structure, which is divided into two parts: the upper joint and the lower joint. The dangerous parts of the structure are the two lugs of the lower joint, and the material of the lugs is 30CrMnSiA high strength steel, which is a ferromagnetic material. As an important reference for the life assessment of an aging aircraft, it is necessary to carry out a fatigue crack monitoring experiment and obtain the crack propagation data of the structure. However, the dangerous
part of the structure is on the side of the bolt hole, which is a typical difficult-to-access location, and it is difficult to detect cracks and monitor the length of cracks by other monitoring technologies.

4.2. The experimental study on the impact of temperature variations

To verify whether the gasket developed in this paper has the function of temperature compensation, an experimental investigation on the impact of temperature variations on the characteristic signal is carried out. As shown in figure 23, the experimental system consists of a measurement instrument, the structure integrated with the SCM gasket and an environment test chamber. As depicted in figure 24, the SCM gasket is mounted at the bolt hole location of the lower joint, and a tightening torque of 30 N·m is applied on the bolt. In the experiment, the environment temperature increases from 10°C to 60°C first, and then decreases from 60°C to −40°C. During the experiment, the signals of the SCM gasket are collected.

During the experiment, the change of conductivity measured by each channel is shown in figure 25. As shown in the figure, the measured conductivity decreases with an increase in temperature, and increases with a decrease in temperature. When the temperature is reduced from 60°C to
−40 °C, the conductivity changes by about 40%. This causes serious interference to the monitoring signal. If an effective temperature compensation method is not taken, it will inevitably produce incorrect instructions. A decrease of temperature will lead to an increase in the signal, which is similar to signal variations when the crack propagates. At this time, the system will offer false alarms. If the crack is propagating, crack growth and a decrease of temperature may cause the signals to remain unchanged. At this time, the system cannot recognize the crack, leading to missed alarms.

As illustrated in figure 26, the characteristic signals of all the measure channels almost stay at the same level when the environmental temperature increases to 100 °C. It is obvious that the signal $\Delta C$ will not be affected by varying temperature.

4.3. The relation between the signal $\Delta C$ and the length of the crack

For the capability of the quantitative monitoring crack, it is necessary to carry out the test of crack monitoring and establish the relation between the signal $\Delta C$ and the length of the crack. As shown in figure 27, the experimental system includes the measurement instrument, the MTS 810 material testing system, the specimen integrated with the sensor and a microscope. The sensor is mounted on the hole of the specimen to carry out the crack monitoring experiment under constant amplitude spectra. The specimen is shown in figure 28, and two initial cracks are present. The signals of the sensor are collected during the test, and the propagation of the crack is observed and recorded by a microscope, as shown in figure 29.

After 42 781 cycles, the specimen is fractured and the test is stopped at this time. The result of the test is shown in figure 30. Crack initiation and propagation first emerge in the specimen on the right of the hole. When the crack tip is extended to the excitation winding 1, the signal $\Delta C$ of channel 2 reaches the inflection point A, and the crack length
is 2 mm. Then the signal $\Delta C$ increases gradually with the propagation of the crack. With the cyclic loading, when the crack tip propagates to the back sense coil of channel 2, the signal $\Delta C$ reaches the turning point A1, and the crack length on the left side is 3 mm. When the crack tip reaches the outer drive winding, the signal $\Delta C$ of channel 1 comes to the turning point B, and the crack length is 3.6 mm. When the crack tip propagates to the rear coil of channel 1, the signal $\Delta C$ comes to the turning point B1, and the crack length is 3.3 mm at this time. As shown in figure 30(b), there is a similar pattern for the results on the left side. Therefore, according to the distance between the windings of the sensor, the corresponding inflection points correspond to the corresponding crack length values. Inversely, the location and length of the cracks can be judged according to characteristic signals.

4.4. Experimental research on the quantitative monitoring of cracks

In order to verify whether the SCM gasket can be used directly for the quantitative monitoring of cracks in a bolted connection structure, an experiment of a quantitative monitoring crack in the front beam connection structure is carried out. The test system consists of the measurement instrument, the structure integrated with two SCM gaskets and an MTS 510 fatigue testing system, as shown in figure 31. During the test, two SCM gaskets are respectively installed on each side of the bolt hole of the lower joint, and a tightening torque of 30 N·m is applied to the bolt. Then the front beam connection structure is clamped on the fatigue testing system by clamping devices, and a flight-by-flight random load spectrum that can simulate the loading process of the aircraft structure is applied on the structure.

In the process of testing, the characteristic signals of each channel are monitored. In the whole process, only the SCM gasket on the outer side of the structure has monitored the characteristic signal of the crack. Figure 32 shows changes of the characteristic signals of channel 2 and channel 1 from 91 398 cycles to the fracture of the structure. When the cycle number $N$ is 102 400, the signal $\Delta C$ of channel 2 arrives at the C1 point; at this point, the crack tip propagates to the front coil of channel 2, and the crack length is 2 mm. When the cycle number is 124 398, the signal $\Delta C$ of channel 2 arrives at the C2 point and the crack tip propagates to the back coil of channel 2 at this time, and the crack length is 3 mm. When the
cycle number is 132 350, the signal $\Delta C$ of channel 1 arrives at the C3 point; at this time the crack propagates to the front coil of channel 1, and the crack length is 3.6 mm. When the cycle number is 141 400, the signal $\Delta C$ of channel 1 reaches the C4 point and the crack tip reaches the back coil of channel 1, and the crack length is 4.6 mm at this time. When the test is carried out to 149 557 cycles, the joint is fractured and the experiment is stopped. After the joint is disassembled, only a single side crack is found on the right side of the outer lug, which breaks instantly when the crack propagates to 5.8 mm, as shown in figure 33. At this point, the relation between the crack length $a$ and the cycle number $N$ can be given in figure 34. Therefore, the SCM gasket has the bearing capacity, and can achieve the quantitative monitoring of cracks on bolt connected structures.

5. Conclusions

To improve the durability and reliability of sensors for SHM, an SCM gasket formed by a gasket substrate and a flexible eddy current sensor is developed, which has the capability to quantitatively monitor cracks of bolted structures under varying temperatures.

The sensitivity of the TC-RECA sensor is boosted by using two separate drive windings that work alternately. Then, the main damage forms of the sensor are studied, including the deformation of the sensor coils, the fatigue fracture of the coils and the tear of the sensor. Therefore, a gasket substrate with a load-bearing capacity is obtained through FE simulation. In addition, the effects of permeability, conductivity and lift-off on the trans-impedance are obtained, which shows that the increase of conductivity and decrease of relative permeability with the same rate have the same effect on the trans-impedance response of the sensor. The effects of permeability can be converted to the effects of conductivity and the 3D problem can be reduced to a 2D one, which can be used to eliminate the effects of temperature variations.

The temperature experiment is carried out to verify the capability of temperature compensation. Even if the ambient temperature changes from 60°C to −40°C, the signal $\Delta C$ does not change significantly, which indicates that the gasket has a temperature compensation capability. Finally, the experimental results of the quantitative monitoring of cracks show that the gasket can bear the load and has the capability to quantitatively monitor cracks, which can be directly used for the quantitative monitoring of cracks in key connection structures.

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Declaration of conflicting interests

The authors declare that there is no conflict of interest.

ORCID iDs

Tao Chen https://orcid.org/0000-0002-0238-2052

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