Research of Acoustic Emission Health Monitoring Test of Plane Welding Joint

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Abstract. The welding joint is the key area of Aircraft bearing structure, which is not only subjected to alternating fatigue force, but also to the impact force during takeoff and landing. In this paper, the formation model of fatigue crack is studied, and the health monitoring of aircraft welds based on optical fiber acoustic emission technology is proposed in combination with the principle of acoustic emission detection. The sensor arrangement scheme and test conclusion are given through the actual acoustic emission test of simulated damage of welding joint, which provides the basis for the health monitoring of welding joint of aircraft in service.

1. Overview

Welding joint is an important connection area of aircraft bearing structure, which bears the effects of fatigue force, impact force and stress under high-frequency vibration. The welding joint is often the stress concentration area, easy to produce fatigue source, and then develop into fatigue crack, crack propagated until fracture, which seriously affected the flight safety. At present, the commonly used detection methods are permeability detection, magnetic particle detection and so on. During the detection, the weld surface needs to be depainted to destroy the anti-corrosion coating on the surface, and these detection method are static detection, which can’t realize real-time damage detection.

Figure 1. Aircraft landing gear brace weld
When parts are subjected to deformation or external effects, due to rapid release of elastic energy, transient stress waves can be excited. This phenomenon is acoustic emission (AE). In general, the change of internal stress in solid materials can generate acoustic emission signals. There are many factors that cause the change of internal stress in the airplane weld, such as dislocations, crack initiation and propagation, fracture, deformation under applied load and so on [1]. Surface vibration can be caused by elastic waves emitted from these event sources, which propagate through the weld and eventually reach the surface of the weld. The vibration can be received with acoustic emission sensor, and be converted to electrical signal by fiber optic sensor. Then the signal can be amplified, recorded and processed. By analyzing and infer the acoustic emission mechanism produced by welds based on the observed acoustic emission signals, the material can be determined whether complete and reliable.

Figure 2. Schematic diagram of magnetic particle inspection weld

In this paper, acoustic emission technology is applied to in-service monitoring of welding seam of aircraft, and optical fiber transmission technology is combined to realize long-term real-time monitoring of health condition of welding seam under working condition. This will help to achieve intelligent and automated monitoring of aircraft structures, the occurrence and expansion of damage can be detected in time, the safety status of the bearing structure can be reported to the pilot in time, which can effectively reduce the incidence of accidents.

2. Theoretical research on acoustic emission monitoring technology

The formation and propagation of fatigue crack will produce acoustic emission signal, it is a major acoustic emission source. The strong plastic deformation of welding joint will cause the formation and development of crack, when crack forms, the stress concentration in the local area of the weld is unloaded and the acoustic emission signal is generated. There are three stages of the material fracture process: crack nucleation, crack propagation and final fracture. Strong acoustic emission source can be generated in all three stages [2].

One of the most famous models of crack formation is the dislocation plug theory applicable to brittle fracture. The theory can be applied to welding seams of aircraft. As dislocations encountered obstacles at one end of the slip zone, such as grain boundaries, impurities, and hard points, stress concentration will emerge. The orthogonal stress $\sigma_c$ at plugging point is:

$$\sigma_c = \sigma \sqrt{\frac{L}{c}} f(\theta) \quad (c \ll L)$$

Where
- $L$ —— Crack length
- $c$ —— The distance from force field accumulation to the plugging point
According to Griffith theory, crack occurs when $$\sigma_c = \sqrt{\frac{4\gamma E}{\pi c(1 - \nu)^2}}$$. 

Where

- \(E\) —— Young's modulus
- \(\nu\) —— Poisson's ratio
- \(\gamma\) —— Surface energy

So, for isotropic solids, take \(\theta = 70^\circ\) and take \(E = 2G(1 + \nu)\) into account, the shear stress \(\sigma_s\) required to form the crack slip surface is:

\[\sigma_s = \sqrt{\frac{3\pi\gamma G}{8(1 - \nu)L}}\]

When the shear stress \(\sigma_s\) reaches the value of the above formula, crack occurs, where \(G\) the shear modulus is. The relationship between the number of dislocations \(n\) on the slip surface and the shear stress \(\sigma_s\) is

\[L = \frac{Gb\pi}{\beta(1 - \nu)\sigma_s}\]

Where \(b\) —— Burgers Vector. From the energy point of view, the relationship between the average crack length \(l\) and the number of dislocations \(n\) is

\[l = 0.5bn^2\]

It can be seen that the crack length generated by 100 dislocations is about 0.1 \(\mu\)m, which means that the acoustic emission caused by cracks with a length of 0.1 \(\mu\)m is about 100 times larger than the acoustic emission generated by a single dislocation slip. Before a micro crack grows into a macro crack, there exists slow crack propagation stage. The energy required for crack growth is about 100 to 1000 times greater than the energy required for crack formation by theoretical calculations. Crack propagation is carried out intermittently. The crack propagates forward one step, releasing the accumulated energy, and the tip area of the crack is unloaded. In this way, the acoustic emission from crack propagation is likely to be much greater than the acoustic emission from crack formation. When the crack propagates to a near-critical state, it begins to grow unstable and fracture rapidly.

3. Fiber acoustic emission testing of plane weld

3.1. Arrangement of grating sensors

According to the above analysis, grating sensors can be arranged at the welding joint, which is used to capture the signal of crack growth at welding joint. How to effectively arrange the sensor must grasp three principles: The first is to reduce the number of sensors as much as possible. The second is to ensure the accuracy of signal acquisition and parameter identification based on the optimization methods such as neural network and genetic algorithm; third, the sensor is installed in the welding joint bearing parts, and to be fixed firmly, not affected by other aircraft parts [3].

Experiment was conducted on the welding joint of landing gear strut of a certain type of aircraft, in which 9 optical fiber sensors were used as shown in Fig.3. The function of 7#, 8#, 9# is SDPR triangular surface positioning, which can realize the health monitoring of the defects. The function of 2#, 3#, 4#, 5#, 6# is line positioning monitoring, it can realize the line location monitoring of defects and the whole welding joint area. For observation convenience and research needs. In figure 3, the welding seam is in an axially expanded state along the outer surface of the strut. Fiber optic adhesive glue is used to closely attach the sensor to the surface of the brace weld. Although this arrangement method cannot accurately detect the damage information inside the structure, it has no effect on the strength and stiffness of the outer cylinder structure [4], which is suitable for aircraft in service health monitoring.
3.2. Study on crack signal propagation

The instrument in the experiment has 24 channels. The acquisition parameters are set as follows: host gain is set to 20 dB, threshold is set to 40 dB. The peak definition time of the acoustic emission signal is 1000 microseconds, the definition time of the impact is 2000 microseconds, and the impact blocking time is 20,000 microseconds. The loading device is a hydraulic pulsation fatigue tester, which simulates the impact of the landing gear on the ground during landing, the loading speed is 4t/s, and the load is stable for 5 min after 10.

Acoustic emission signal source is simulated by HB lead core break, and the position of No. 1 sensor is the point where the pencil breaks. Four measurements were taken at each site and the average value was taken. The longitudinal attenuation measurement locations are 3 cm, 5 cm, 10 cm, 15 cm, 20 cm, 30 cm, and 40 cm away from the sensor, as shown in Figure 4. Theoretically, as the distance between the measurement site and the sensor increases, the attenuation of each parameter of the acoustic emission signal also increases. The measurement results are shown in Table 1. From Table 1, it can be concluded that in the area within 10 cm near the acoustic emission sensor, the energy of the acoustic emission signal is rapidly attenuated. When the distance from the sound source to the sensor is 15-40 cm, the energy decay is very slow and almost unchanged. These results prove that the propagation mechanism of acoustic emission waves in the weld is more complicated, which is related to the special formation of the weld. It can be seen from Table 1 that as the distance from the sound source to the sensor increases, the energy emitted by the sound emission basically shows a trend of attenuation, which is consistent with the theoretical analysis results.

Table 1. AE signal attenuation measurement parameters

| Items          | Distance(cm) | values |
|---------------|-------------|--------|
| Distance(cm)  | 3           | 5      | 10 | 15 | 20 | 30 | 40 |
| Amplitude(dB) | 88          | 86     | 80 | 79 | 75 | 68 | 59 |
| Energy        | 375         | 360    | 265 | 150 | 120 | 125 | 112 |
| Count         | 455         | 412    | 380 | 356 | 295 | 264 | 180 |
| Peak count    | 4           | 8      | 18 | 22 | 12 | 6  | 3 |
| Rise count(μs)| 10          | 18     | 22 | 30 | 40 | 52 | 69 |
| Duration(μs) | 300         | 280    | 220 | 160 | 100 | 220 | 240 |

Figure 3. Diagram of sensor layout

Figure 4. Diagram of simulated sound emission source attenuation measurement site
3.3. Test result and analysis of time difference characteristic parameter
Acoustic emission source location adopts the characteristic law of time difference characteristic parameter, from the test, it can be seen that the characteristic parameters of time difference basically satisfy the normal distribution law in the process of surface crack propagation. Since the uncertainty of acoustic emission source is very small, it can be considered that the location source of acoustic emission signal is at the tip of fatigue crack, the source region of acoustic emission is small and unique. According to the test results, the characteristics of acoustic emission signals generated in the whole process of welding joint from intact to fracture were analyzed using the deformation and fracture rules of welding joint materials.

Elastic stage: In the elastic deformation stage, the deformation of the weld is completely elastic, and the weld will not show irreversible deformation, that is, the deformation will completely disappear after the load is removed, which is the effective range of the weld work. At this stage, there is almost no energy release inside the weld, so no acoustic emission signal is generated at this stage.

Yield stage: As the stress continues to increase, when the elastic limit is exceeded, the weld is plastically deformed, and the deformation will not disappear after the load is removed. At this stage, the internal crystal structure of the weld changes, causing a crystal slip phenomenon and releasing a large amount of energy, so a large number of acoustic emission signals are generated at this stage, and the signal energy is very high.

When the upper yield point is reached, the activity and intensity of the acoustic emission signal are extremely high, and the amplitude and energy will also reach a maximum value. During the process from the upper yield point to the lower yield point, the acoustic emission activity, amplitude and energy will decrease rapidly; beyond the lower yield point, the activity and intensity of the signal as well as the amplitude and energy will increase again.

Strengthening stage: During the strengthening stage, the internal crystal structure of the material is readjusted due to plastic deformation, and the ability of the weld to resist deformation is gradually enhanced. With the increase of stress, plastic deformation will also intensify. At this time, the plastic deformation will be permanently retained after unloading. At this stage, a large number of acoustic emission signals are still generated, and the signal's activity, amplitude and energy will gradually decrease, but high-intensity signals are still generated.

Cracking stage: At this stage, large-scale sliding dislocations are generated, the weld cracks, releasing a large amount of strain energy, and generating a large number of acoustic emission signals. Acoustic emission characteristics at this stage are mainly manifested in that the cracking process produces concentrated acoustic emission signals with large amplitude and other parameters. The cracking process eventually develope into fractures, and acoustic emission signals no longer appear.

Aircraft welds are generally in the normal elastic stage, and no acoustic emission signals are generally generated at this stage. Once in the yielding stage, a large number of acoustic emission signals are generated, indicating that damage to the weld has begun. At this time, the acoustic emission equipment can receive a strong acoustic signal. The pilot needs to take emergency measures to avoid danger and minimize losses.

4. Conclusion and outlook
It can be seen from the acoustic emission monitoring test of welding joint of the aircraft that if there is a fatigue source causing the crack in the welding joint, a large number of acoustic emission signals will be generated by the acoustic emission source during the working process, these signals can be collected and identified in time, indicating that the welding joint monitoring of aircraft can be realized by acoustic emission technology. In order to improve the in-service health monitoring technology of aircraft welding joint, the author believes that the following problems remain to be studied:

(1) By analyzing various damage mechanisms of aircraft welding joint, through a large number of health monitoring tests and the collection of typical acoustic emission signals on site, the characteristics of acoustic emission signals under different stress and different arrangement states are analyzed, and the acoustic emission signal library of welding joint damage is established, which can more accurately
determine the damage situation of welding joints.

(2) Because the aircraft produces a lot of noise during its operation, it is possible to drown out the acoustic emission signals that we really need. Therefore, how to effectively identify the real acoustic emission signals from the background noise becomes the key problem of in-service monitoring. In the future, classical spectrum analysis, modern spectrum analysis, wavelet analysis, artificial neural network pattern recognition and other theories can be focused on, as well as the effective recognition of assisted acoustic emission signals.

(3) Continue to optimize the sensor arrangement, which can not only accurately and comprehensively measure the change of signals inside the welding joint, but also not affect the normal operation of other aircraft structures.

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