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Research on the fatigue life testing for composite wings

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Abstract
This paper carries research on fatigue life testing of the full-composite wings for aerospace flight. First, the fatigue load spectrum is compiled by a segmental method. Secondly, a fatigue loading system which can provide multi-directional loads on the surface of the composite wing is designed. Then, some non-destructive testing methods are introduced. Finally, a fatigue life testing for a composite wing of an aerospace vehicle is made. The results show that this test method can complete the composite wing fatigue test accurately and efficiently. It provides help for the fatigue life evaluation study of composite wings.

1. Introduction

The lift of an aircraft is usually provided by the wings. The aerospace vehicle is different. The lift of an aerospace vehicle is not provided by the wings. The wings only play a role of balance and buffer. The mission profile of an aerospace vehicle is composed of several different stages. In some stages, the spacecraft is launching vertically, and the wings are mainly subjected to inertial load. The course load is larger and the vertical load is smaller. In other stages, the wings are subjected to the combination of aerodynamic load and inertial load. The loads are multi-direction loads, among which the vertical load is the main load. And the loads in different stages are totally different. It can be seen that the load conditions in any stage of the flight are very different.
In the fatigue life testing for a wing, the loading system needs to simulate the multi-direction aerodynamic loads and inertial loads that subject to the surface of the wing. The fatigue load spectrum is difficult to make out because of the complicated load conditions. And the traditional methods of imposing distributed loads are not suitable for composite wings. According to many studies, loads on the surface of a wing can be imposed by the pressure lever system and the load pads [1~3]. The tests of rubber pads and bounding agents were completed by NASA DFRC research center with MTS testing machine [4]. And Zhuo Yi from China also researched and tested the strength of different pads and bounding agents [5]. But these tests only researched unidirectional load. There is no research and test on multi-direction loads. Therefore, in this paper, the research on FLS is completed; a fatigue loading system is designed to solve these problems; the non-destructive testing methods are introduced. Finally, a fatigue life testing for a composite wing of an aerospace vehicle is made.

2. Fatigue Load Spectrum

Mission analysis method is used to compile the fatigue load spectrum of aircraft. The preparation of the load spectrum of the mission segment type is mainly based on the measured results. The average occurrence frequency of every stage load of each mission segment is obtained by a certain counting method. And then the reference load spectrum with arithmetic mean characteristics can be prepared by multiplying it with the proportion of the "weight matrix". The steps are as follows:

- Achieving the gravity overload spectrum and corresponding flight parameter.
- Counting and statistical processing according to each mission segment of a flight.
- Differentiating loading conditions.
- Calculating loads.
- Compiling task spectrum.
- Compiling mission profile spectrum.

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2.1 Counting and statistical processing method

The important part of compiling the spectrum is to deal with the measured data with statistical theory. For random load, statistical analysis method mainly has two kinds: one is cycle counting method, another is power spectrum method. Cycle counting method is dividing the continuous load - time process into a series of values, and then counting the frequency, probability density function, probability distribution function, etc. Power spectrum method is to decompose continuously changing random loads into infinite simple variations with various frequencies by means of Fourier transform, so as to obtain power spectrum density function. For fatigue strength designing, cycle counting method is widely used.

There are many kinds of counting methods used to compile load spectrum, which can be roughly divided into three basic types: peak type, wear class type and variation type. The peak-type counting method is mainly used to count load peak value, including simple peak-to-peak counting method, cross-mean peak-to-peak counting method, limited-stage peak-to-peak counting method and limited-range peak-to-peak counting method. The wear class counting method mainly includes simple wear class counting method and fatigue method. Variation counting method is mainly used to count the load variation and additional parameters, generally to count two parameters at the same time. It includes variable to count method, variable -mean counting method, variable range logarithmic method, the rain flow method, variable logarithmic to mean counting method and the NLR method, etc. We compare them with authenticity, uniqueness and simplicity. For authenticity, the variable logarithmic to mean counting method is the best, and the three simple counting methods (peak, pass and variable-range) are the worst. In terms of uniqueness, the results of other counting methods are basically unique except for simple wear type, fatigue gauge method and simple variable range method. In terms of simplicity, variable logarithmic to mean counting method is the most complex, and the cross-mean peak counting method and the other three simple counting methods are simplest. In summary, the rain flow counting method has the advantages of authenticity, uniqueness, and simplicity. Therefore, the rain flow counting method is widely used to compile the fatigue load spectrum [6].

The rain flow counting method represents the average amplitude of all levels of cycles by matrix form, and then treats it with the statistical inference. It needs to turn the cycle statistical result into the load history to get the fatigue load spectrum.

2.2 Load spectrum calculation

Before calculating load spectrum, it needs to determine the load condition. It needs to combine the performance parameters of the mission section, the response parameters of the structural load environment and other relevant parameters, so as to form different load conditions. The load conditions serve as the input of load calculation and stress analysis.

The determination of load conditions can be generally divided into three categories: transient combination of flight parameters, single combination of flight parameters and statistical combination of flight parameters. .

A. Transient combination of flight parameters

The transient combination of flight parameters is to combine the peak value of centre of gravity overload and the corresponding flight parameters in every transient. It means each overload and the corresponding parameters form a load condition.

B. Single combination of flight parameters.

A single combination of flight parameters is to combine one flight parameter with all the overloads. The flight parameter is usually the most serious condition.

C. Statistical distribution combination of flight parameters.

The statistical distribution combination of flight parameters refers to converting the frequency distribution of barycentre overload and the frequency distribution of other flight parameters in a mission segment into probability distributions. And then the parameters are combined according to their probability of occurrence.

In the above three methods of determining the load conditions, the transient combination of flight parameters can truly reflects the conditions of the aircraft. But the calculation of the load is too complex and too expensive. So it is rarely used in fact. Although the single combination of flight parameters is simplest and it has been used in previous aircraft, it is rarely used now. Because the load conditions are the least realistic and the results are conservative. It is better to use the statistical distribution combination of flight parameters. It can not only retain the important load condition, but also reduce the workload of load calculation. In addition, the statistical distribution curves are easy to compare with similar data given in other sampling monitoring or design stages, and can be modified to improve the design of new machines.

In this fatigue test, first the barycenter overload coefficient should be made according to of the ballistic data. If the first method is adopted, the load conditions under each overload coefficient shall be determined. And then the load value shall be calculated to combine the fatigue load spectrum. If the second method is adopted, only the most

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serious condition shall be determined. If the third method is adopted, it is necessary to determine the barycentre overload spectrum according to the frequency distribution. And the load conditions under each peak and valley shall be determined. According to the flight condition of the wing, the method of segmental processing is adopted. According to the different loads of different stages, the fatigue load spectrum is compiled by different methods.
In the active segment, the wing is mainly subjected to inertial load. The wing load and the centre of gravity overload change linearly, so the second method can be directly adopted. In the calculation of the load spectrum of the active segment, the load of the wing under the condition of 1g is calculated according to the loading condition in the most severe condition. And each overload value of the barycentre load spectrum is multiplied by the load value of 1g as the load spectrum.
In the passive segment, the wing is not only subjected to the inertial load, but also the aerodynamic load. So this experiment adopts a combination of the second and the third method. The passive segment is divided into several sections. The load of the wing under the condition of 1g is calculated according to the loading condition in the most severe condition in each section. And each overload value of the barycenter load spectrum is multiplied by the load value of 1g as the load spectrum of each section.

3. Fatigue Loading System

According to the load condition of the wing and the requirements of fatigue test, the fatigue loading system should have the following functions:

- Simulating aerodynamic load with distributed loads.
- The loading system can apply double lateral load and vertical load.
- The vertical load is applied by the pressure load according to the structural characteristics of the wing.
- Try to simulate the real load environment of the wing and reduce the additional stiffness.
- Good fatigue performance.
- Minimize loading space.

Traditional loading methods of distributed loads such as canvas pulls, stance card board loading method don't have all the functions. The canvas can only provide one directional pulling load. And it can cause some problems like the layered, matrix cracking and interface deboning, if the wing is composite materials. The stance card board loading method will cause additional stiffness on the wing structure. These traditional loading methods make the capacity of the whole structure of the wing severely affected. Nowadays the pad loading method adopt did not load the lateral load at home and abroad. Therefore, it needs to improve the pad loading method. It needs to increase the lateral multipoint fatigue loading system to make it suitable for fatigue life testing. And it needs to design a set of variable proportional pressure lever that can provide vertical pressure load, so as to adapt to more proportional loading conditions.
In order to satisfy the above requirements, the loading system (Figure 1) needs to include loading pad that can realize lateral load loading, the pressure lever system that can provide variable proportional pressures, and lateral pull lever structure, etc.

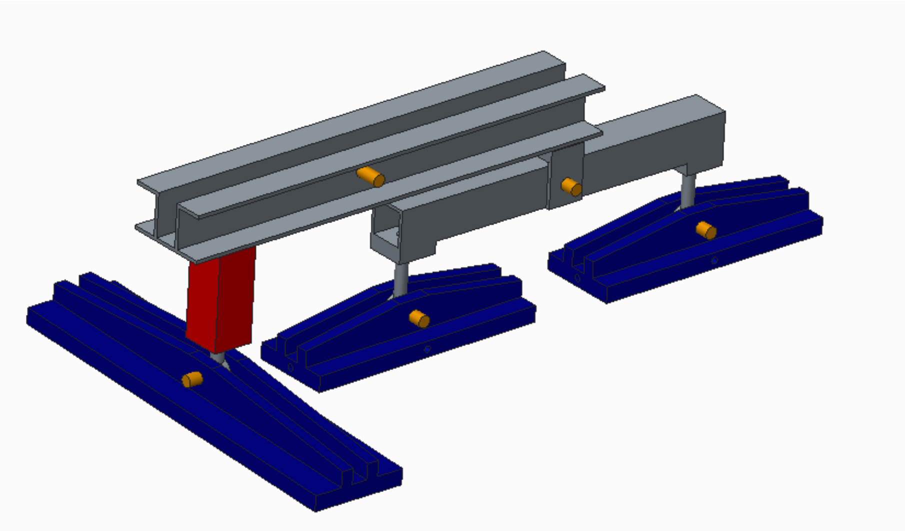

Figure 1: The loading system.

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3.1 Design of loading pad.

The loading pad is usually pasted in the compression area of the test piece, which is composed of metal pressing block and cushion pad. The metal pressing block is used to connect the multi-directions loading system and the cushion is used to transfer the load.

The metal pressing block can be made of steel or aluminium according to the actual situation. The structure (Figure 2) is composed of bottom plate and bilateral plates.

A Y-direction vertical loading point is set between the bilateral plates. The bilateral plates are connected with the loading rod by a loading pin. When the wing has a large deformation, the degree freedom of rotation can be released. The diameter of loading hole for the pin is decided by the vertical loading. The bilateral loading holes are set on the side of the bottom plate. The loading hole is connected with the pull rod, which is used to apply the double-direction bilateral load. In the fatigue test, it is necessary to add the thread locking structure at the loading point to avoid the thread of the pull rod being spun out due to the cyclic loading. In order to ensure the strength of the pull rod, the diameter of loading hole shall be determined by the lateral force, and the corresponding pull rod shall be adopted. The thickness of the bottom plate shall not be less than 2 times of the diameter of loading hole.

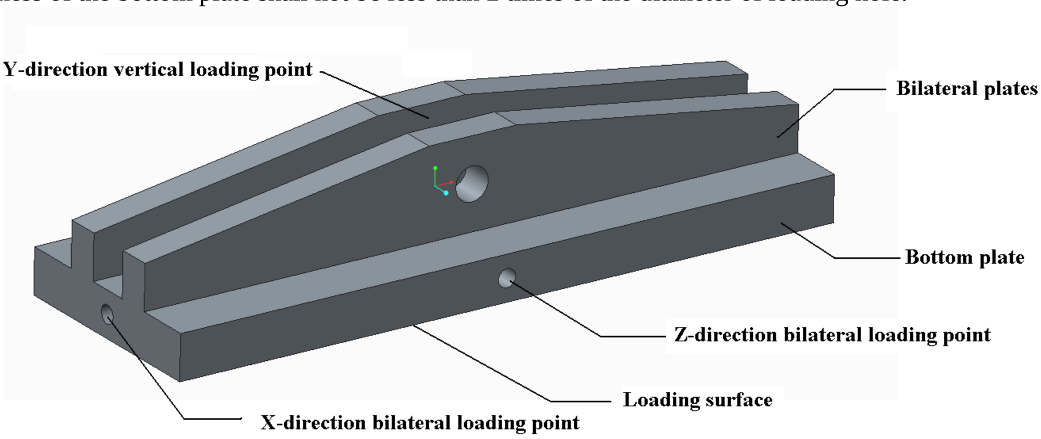

Figure 2: Metal loading blocks.

The cushion pad is usually rubber. Its one side is pasted on the loading area of test piece; the other side is pasted with metal loading block. It makes the loading force well-distributed to the surface of structure. According to research, the tests of rubber pads and bounding agents were completed by NASA DFRC research center with MTS testing machine. The comparison and analysis of tension and compression performance are given. The chosen pad was a firm 1.5-inch-thick neoprene rubber, of 30 to 50 durometer hardness on the Shore OO scale. It got good fatigue performance. And through the tensile failure test, ZhuoYi test evaluation of various kinds of rubber pad and adhesive glue tensile performance and fatigue performance. He chooses the neoprene and chloride rubber as the basic component of cushion pad. They verify the feasibility of using rubber as cushion pad for vertical tension and compression fatigue test. In this paper, neoprene was selected as the cushion pad to carry out the lateral force bearing capacity test of the load pad. The compression/shear and pure decoction tests were designed to assess the bearing capacity of the load pad, and the per unit area bearing capacity of the loading pad was calculated.

The size of the loading pad used in the verification test is 320mmx80mm. and the shear load line is offset by 20mm on the surface of the bottom plate. The bottom plate is the same material with the composite wing. In the compression/shear load verification test, the ratio of compression/shear load is 1:2; the maximum lateral load is 4 times of the maximum test load. The result is the load pad can load normally. In the shear load verification test, during the loading from 3.8 times to 4 times of the maximum load in the test, the metal surface and the rubber pad were deboned. It can be seen from the test results that the load bearing capacity of the loading pad is stronger when the pressure and shear load act together than when the pure shear load acts. Assuming that the loading area is linearly related to the bearing capacity, the bearing capacity per unit area of the loading site can be calculated according to the test results. And the maximum bending moment load that the unit surface loading pad can bear under the action of pure shear can be calculated according to the following formula. Where F is the maximum test load, 1 is the distance between the test loading point and the surface of the test piece, and k is the ratio of the bending section coefficient of the test pad and the unit area loading pad.

$$M_{\max} = \frac{F \times l}{k} \quad \textbf{(1)}$$

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According to the above test and calculation results, the relationship between the area of the loading pad and the bending moment generated by the shear force is obtained. The size of the loading pad can be determined according to the actually applied shear bending moment load. Generally, the safety coefficient of the applied load is n=1.5-1.8. The bearing capacity per unit area of the test piece should be considered to select the appropriate size of the loading pad at the same time.

3.2 Design of Pressure Lever System

The aerodynamic load borne by the wing is the surface load. During the test, the wing is usually divided into several loading stations according to the stress environment and structure. It is common to combine multiple load points into one or several load points by means of leverage when loading distributed loads. It can reduce the installation space, improve the efficiency and enhance the loading coordination ability. The lever systems include pressure lever system and pull lever system. It usually uses pressure lever system for composite structure.
The current application of pressure lever usually cannot be more than two levels. Every lever is hinged at one end and clamped at the other end to transfer the pressure load. The pressure lever system should transfer proportional force stably and have enough strength and stiffness. In this paper, according to the y-direction load of each stage of the wing, a set of variable proportion pressure lever system (Figure 3) is designed. The structure of the pressure lever system is similar to the whiffle tree which is used on the Swiss F/A-18 full scale fatigue test and improve it. It includes the first lever, single point loading rod, connecting structure, fixed connecting piece and the second lever. This lever system is a two-stage lever that can combine three loading points into one loading point. According to the actual situation, the single point loading rod can be replaced by the first lever of two-point loading. And it can combine four loading points into one loading at most. The first lever and the second lever with sufficient strength can be designed according to the bending moment of the lever. The hollow square pipe structure or the welded structure of channel steel can be adopted. The single point loading rod is the hollow square pipe structure with sufficient strength. The connecting structure between the two levels is hinged at one end and clamped at the other end. In order to satisfy the requirements of different working load, the pressure lever system added the fixed connecting piece and the connecting hole of the second lever is the groove type hole. The pressure lever system can realize the variable ratio pressure by changing the position of the fixed connecting piece.

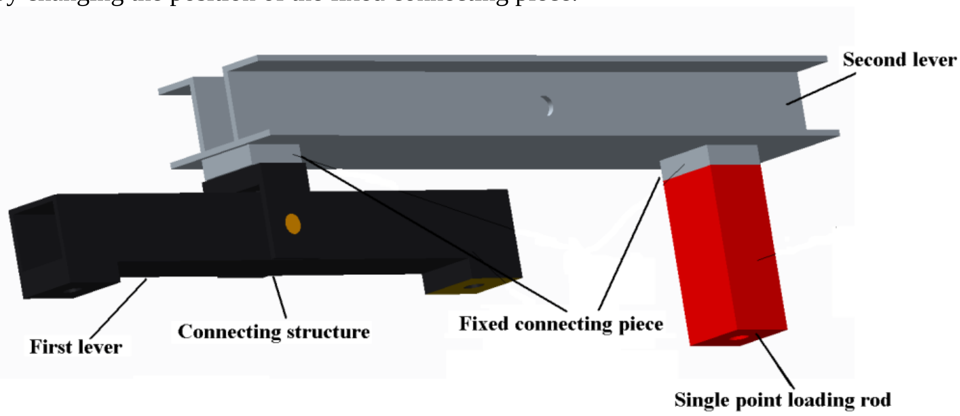

Figure 3: Pressure lever structure

By using the finite element analysis software, the static strength of the pressure lever system is analyzed, and the force transfer characteristics of the pressure lever are verified. According to the size and loading position of the load, a 3d model of the lever system is established. The proportion of the first lever is 1:1. The proportion of the second lever is 1:1.6. The computational grid division of the lever system (Figure.4) is established. The maximum resultant test load is 12kN. The stress of the pressure lever system (Figure.5) is calculated. The maximum stress is 159.8Mpa. It can be seen that the maximum stress of the lever system is small and has enough strength to withstand the test pressure load. The transfer load of each loading pad (Figure.6) is calculated. The comparison between theoretical load and calculated transfer load is shown in table 1. The errors at each point are 1.74%, 1.74% and 1.04%. The errors are small and the transmission characteristics of the pressure lever system are well.

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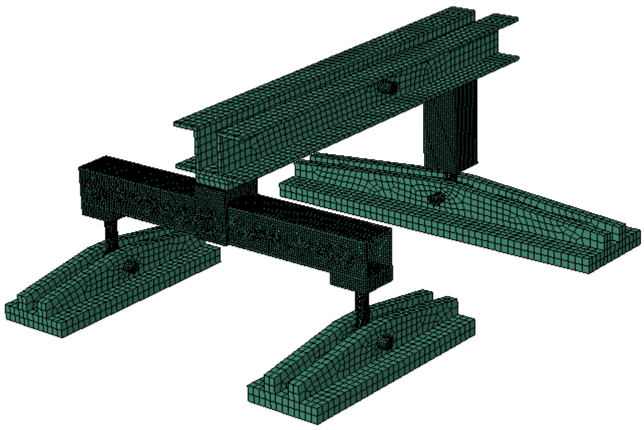

Figure 4: The computational grid division of the lever system

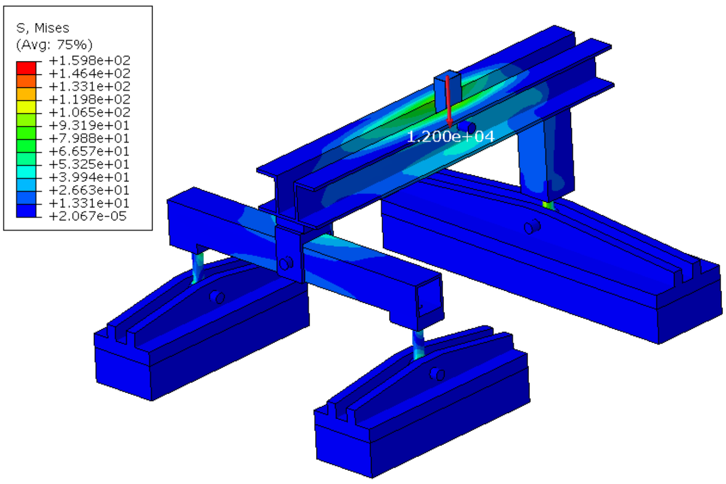

Figure 5: The stress of the pressure lever system

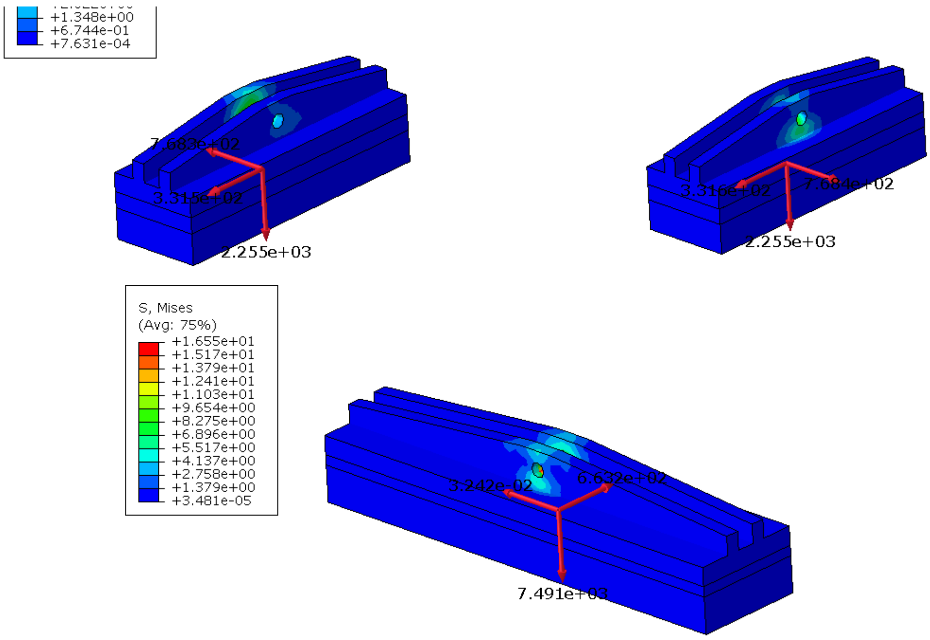

Figure 6: The transfer load of each loading pad

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Table 1: The comparison between theoretical load and calculated transfer load

Number of pad	Theoretical load（kN）	Calculated load（kN）	Error(%)
1	2.295	2.255	1.74
2	2.295	2.255	1.74
3	7.414	7.491	1.04

4. Non – destructive inspection

In order to obtain the damage condition of the wing, non-destructive inspection technology is needed. Commonly used non-destructive inspection technique is TOFD (Time of Flight Diffraction Technique), AE（Acoustic Emission）and AU（Acoustic-ultrasonic）.

4.1 Time of Flight Diffraction Technique

TOFD is a technique based on diffraction signal, namely time difference of ultrasonic diffraction method. A method of detecting defects by diffraction energy from the "end Angle" and "end point" of the internal structure of the specimen to be tested (mainly referring to the defect).
When the ultrasonic wave pass through a long crack defect, diffraction occurs in the gap and reflection occurs on the crack surface. TOFD locates and quantifies the defect through the diffraction wave generated by the two ends or the corner of the crack. The schematic diagram is shown below.

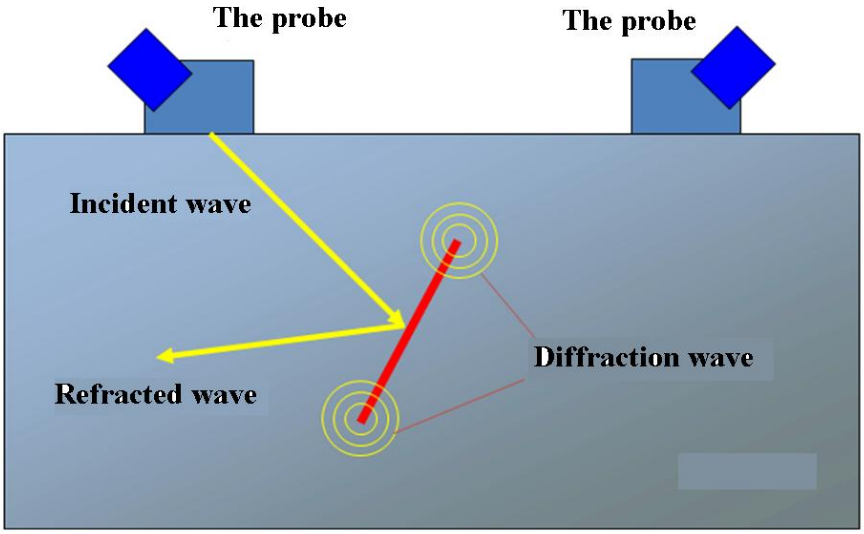

Figure 7: The theory of TOFD

The TOFD method can be used for material inspection, defect location and quantification. It has been approved by ASTM E2373-04, ASMI VIII Code 2235, CEN ENV 583-6 (2000), BS 7706 (1993) and other standards. It is very effective to determine the authenticity and accuracy of defects. .
The advantages of TOFD technology are as follows:

- TOFD has a good reliability. TOFD is based on diffraction signal .The diffraction signal is not affected by the sound beam, and the defects in any direction can be effectively found, so the technology has a high defect detection rate.
- TOFD has a high quantitative accuracy of technology. The accuracy is much higher than that of the conventional ultrasonic testing. It is generally believed that the TOFD quantitative error is less than 1mm for linear or area defects. And height measurements of cracks and unfused defects are usually within a few tenths of a millimetre. .

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- TOFD detection is simple and fast. The most commonly used non-parallel arm inspection only requires one person to operate. The probe only needs to move along both sides of the welding seam. No saw-tooth scanning is required.
- TOFD detection system is equipped with automatic or automatic inspection device. It can determine the relative position of the defect and the probe. The signal can be converted into TOFD image through processing.
- TOFD technology can also be used for monitoring defect propagation. It is one of the effective and accurate methods to measure crack growth. .
- TOFD can accurately locate the depth position of defects and quantify the height of defects.

4.2 Acoustic Emission and Acoustic-ultrasonic

AE and AU can detect defects of structure before possible catastrophic failure. Because the cutoff can produce detectable acoustic emission before structural integrity and structural failure are compromised.
AE uses an elastic stress produced by the rapid release of energy from a source of damage .These waves can be detected by piezoelectric crystal sensors mounted on the material’s surface and converted into piezoelectric signals. The sensors respond waves that are removing audible noise below 100 kHz by front and rear filters. The active damage of the structure can be monitored by acoustic emission even if the noise level is very high. The damage sources include fracture, plastic deformation, impact, friction, corrosion and so on. AE is enough sensitive to detect newly formed cracks on surface which is hundreds of square microns or smaller.
AU is the ultrasonic method used in the frequency range with the characteristics of acoustic emission. This technology can detect and describe the difference between single and multi-layer metal, ceramic and composite plate. It can also detect corrosion and distribution differences of microstructure, mental thickness and thick composite material. AU detects damage with pulse generators and receiving sensors at resonant frequencies in the low ultrasonic range, combined with prediction of wave propagation dynamics. Ultrasonic waves are reflected back by surfaces and interfaces. The modes change during reflection and propagation due to scattering and absorption attenuation. The results mainly depend on the frequency, direction, initial mode of the wave and the position and orientation of the surface damage. When structure damage occurs, the signal change indicates the type of damage. The damage can be estimated by analyzing the given damage type and the average change of the signal.

5. Fatigue test for a composite wing

The above mentioned technology is applied to carry out the fatigue test of a full-composite wing. The joints of the main girder of the wing and the front and rear pin positions were respectively connected with their transition tooling. The transition tooling was fixed on the bearing wall.
The wing was divided into four stations. The fatigue load spectrum and test load spectrum were compiled for the whole mission profile. Each station adopted 1 or 2 loading pads for loading. The loading pad and the pressure lever system were designed according to the method mentioned in chapter 3. The load in the Y direction is in the form of compression load, which is composed into two loading points through the pressure lever system. The loading modes in the X direction and Z direction are shown in Figure.8. The loads in both directions were applied by the lateral loading points of each loading pad. Each lateral loading point leads to the loading pull rod. The loading points in the same direction were reasonably composed through the pull lever system according to the size and the position of loads. In general, the ratio of levers cannot exceed 4:1, and the principle of proximity is adopted. Eventually the loads in the same direction were combined into a single load point through a pull lever system.
Acoustic emission technology was used to monitor the wing damage in real time during the whole process of the test. The strain gauge, optical fiber test technology and displacement test technology are used to complete the data acquisition. Finally, the strain distribution and deformation in the whole fatigue testing process were obtained, and the acoustic emission non-destructive testing data were obtained.
The fatigue test completed 250 flights. The wing didn’t have catastrophic damage during the process of test. The loading system worked well. The loading pads had no debonding and cracking. The strain and displacement curves had no mutation. They were consistent with the trend of fatigue load spectrum. The partial load spectrum and the displacement data curve is shown in figure 9and 10. The experimental results show that the wing can satisfy the design requirements, and the loading technology can complete the fatigue test for a composite wing accurately and efficiently.

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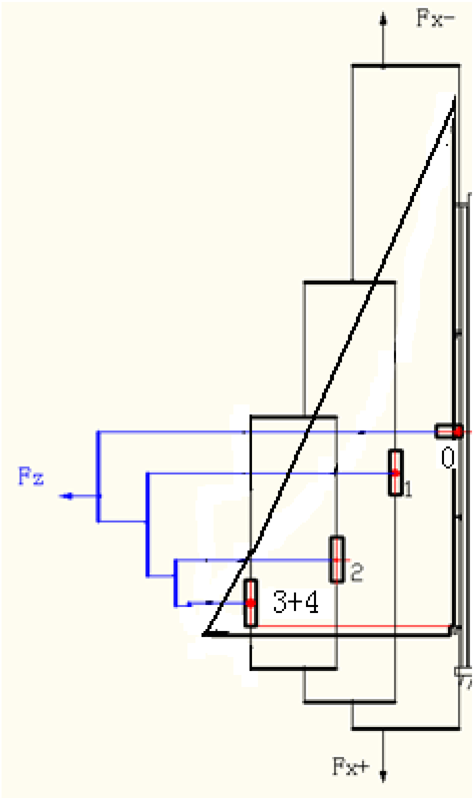

Figure 8: Composition of lateral loading

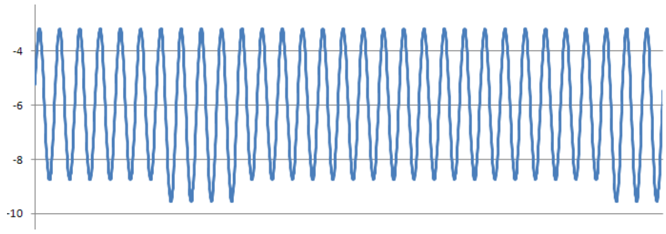

Figure 9: Partial load spectrum

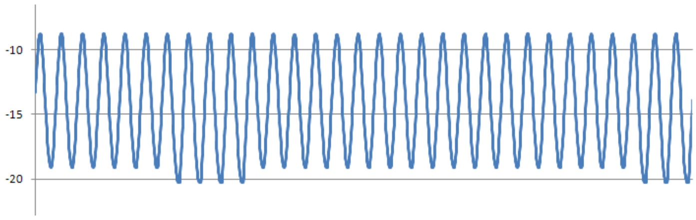

Figure 10: Partial displacement data curve

6. Conclusion

In this paper, the fatigue life testing technology for composite wings is researched. A segmental method is proposed to deal with the complexity of load environment in the preparation of fatigue load spectrum, According to the load characteristics of different stages, different methods are used to compile the fatigue load spectrum. A loading system which can apply multidirectional distributed fatigue load on the structure surface is presented. The loading pad technical is researched. The loading pad that can apply bilateral load and vertical load was designed, and experimental verification and calculation analysis were carried out. The pressure lever technology is researched. The variable proportional pressure lever system was designed and analyzed by using the finite element analysis software. According to the fatigue load spectrum, the fatigue test of a full-composite wing was completed by using loading technology and real time non-destructive testing technology. The experimental results show that this test method can

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complete the composite wing fatigue test accurately and efficiently. It provides help for the fatigue life evaluation study of composite wings.

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