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Theory of Economic Life Prediction and Reliability Assessment of Aircraft Structures

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Abstract

The theory of economic life prediction and reliability assessment of aircraft structures has a significant effect on safety of aircraft structures. It is based on the two-stage theory of fatigue process and can guarantee the safety and reliability of structures. According to the fatigue damage process, the fatigue scatter factors of crack initiation stage and crack propagation stage are given respectively. At the same time, mathematical models of fatigue life prediction are presented by utilizing the fatigue scatter factors and full scale test results of aircraft structures. Furthermore, the economic life model is put forward. The model is of significant scientific value for products to provide longer economic life, higher reliability and lower cost. The theory of economic life prediction and reliability assessment of aircraft structures has been successfully applied to determining and extending the structural life for thousands of airplanes.

Keywords: life prediction; model of economic life; fatigue scatter factor; full scale test; reliability

1. Introduction

Failure accidents caused by fatigue occasionally occurred on aircraft structures in the past[1]. The fatigue of structures has been studied a lot[1-3]. The theory of economic life prediction and reliability assessment of aircraft structures has a significant effect on safety of aircraft structures[4].

With the development of design and technology, aircraft structures of longer economic life, higher reliability and lower cost have been produced by other countries[5]. However, little literature can be found with regard to theory of economic life prediction and reliability assessment of aircraft structures. The safe life and inspection periods are the key question of the theory. In Refs.[5]-[8], the safe life of aircraft structures was determined by probabilistic fracture mechanics, which is complex and cannot be easily used in engineering practice. Meanwhile, the inspection periods were given by studying the relation of crack growth and crack size. In this method, the safety of aircraft structures was not taken into full consideration.

The safe life can be determined by fatigue scatter factor and full scale fatigue test. The fatigue scatter factor plays a vital role in life prediction of aircraft structures. But in the past, the fatigue scatter factor was general and the difference of different stages was not considered[1]. In this paper, according to the two-stage theory of the fatigue damage process, the fatigue scatter factors of crack initiation stage and crack propagation stage are given respectively. The whole life are divided into crack initiation life and crack propagation life. At the same time, the mathematical models of fatigue life prediction are presented by utilizing the fatigue scatter factors and full scale test

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results of aircraft structures. Furthermore, a new method, called economic life model, is put forward by establishing the relation of crack initiation life and crack propagation life. The economic life model incorporates the design of safe life with the damage tolerance design organically. The model is of significant scientific value in providing longer economic life, higher reliability, and lower cost products.

2. Fatigue Life and Reliability

The fatigue life of aircraft structures is determined by the state of dangerous position[9]. Aircraft structures endure cyclic load during every fight. Crack will initiate and propagate in some dangerous areas after many flights. In the end, the aircraft structures will rupture.

The fatigue life and reliability of aircraft structure are relative. The reliability of aircraft structures is defined as the probability that the aircraft structures perform their intended function under specified conditions[10-11], at the same time the economy and maintenance are taken into account. The failure of aircraft structures caused by fatigue and rupture is minimized. Quantitatively, the reliability can be expressed as

$$R=1-F \tag{1}$$

where R is the probability of survival (also called reliability) , and F the probability of failure.

If R equals 99.9%, and the safe life of some types of aircraft is 3 000 flight hours, then 999 of 1 000 airplanes are safe and will not be destroyed by fatigue after 3 000 flight hours.

Flight hours, flight takeoff-landing number and calendar life can represent fatigue life of aircraft structures. If any of the above three reaches its expected value, the aircraft will be no longer put into service. In this paper, flight hours and flight takeoff-landing number are investigated.

3. Mathematical Model of Life Prediction by Applying Fatigue Scatter Factor of Whole Life

Usually, the fatigue of fighter plane is caused by maneuver load, and it follows lognormal distribution. Meanwhile, the fatigue of transport plane is caused by gust load, and it follows two-parameter Weibull distribution. Different reliability and confidence levels are needed for different life distributions. When the fatigue life follows lognormal distribution, at least 99.9% reliability and 90% confidence level are required. When the fatigue life follows two-parameter Weibull distribution, at least 95% reliability and 95% confidence level are needed.

If the fatigue life, denoted by N, follows lognormal distribution, it can be explained that the logarithm of fatigue life, denoted by x , follows normal distribution, i.e.

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}\mathrm{e}^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{2}$$

where μ and σ are the mean value and standard deviation of population, respectively.

If the fatigue life follows two-parameter Weibull distribution, the probability density function (PDF) can be expressed as

$$f(N)=\frac{\alpha}{\beta}\left(\frac{N}{\beta}\right)^{\alpha-1}\exp\left[-\left(\frac{N}{\beta}\right)^{\alpha}\right] \tag{3}$$

where α is the Weibull slope (shape parameter) and β the characteristic life (with 36.8% reliability).

3.1. Mathematical model of life prediction with normal distribution

If crack initiation life and crack propagation life follow lognormal distribution, the whole life is the sum of the lives of the two stages. According to the two-stage theory of fatigue process, the method of fatigue scatter factor of the whole life is established[1]:

$$L_{\mathrm{f}}=\frac{[N_{50}]_{\mathrm{t}}}{N_p} \tag{4}$$

where L_{f} is the scatter factor of fatigue, $[N_{50}]_{\mathrm{t}}$ the median test life, and N_p the safe life when the reliability is p.

The median test life is the estimator of the fatigue life with 50% reliability. When the logarithm of fatigue life follows normal distribution, the logarithm of the median test life is the mean value of sample, i.e., $\lg\,[N_{50}]_{\mathrm{t}}=\bar{x}$. To obtain the mean value of population by the mean value of sample, confidence interval method is adopted. The fatigue life can be calculated by replacing the mean value of population with the lower limit of confidence interval.

When the logarithm of fatigue life follows normal distribution, we can obtain

$$\frac{\bar{x}-\mu}{\frac{\sigma}{\sqrt{n}}}\sim N(0,1) \tag{5}$$

where $\bar{x}$ is the mean value of sample, and n the numble of sample.

When the confidence level γ is given, Eq.(6) holds:

$$P\left(\frac{\bar{x}-\mu}{\frac{\sigma}{\sqrt{n}}}\le u_\gamma\right)=\gamma \tag{6}$$

which can be rewritten as

$$P\left(\mu\ge\bar{x}-u_\gamma\frac{\sigma}{\sqrt{n}}\right)=\gamma \tag{7}$$

where u_γ is the standard normal variable with confidence level γ.

The fatigue life with reliability p and confidence level γ can be calculated by replacing μ with

$\bar{x}-u_\gamma \dfrac{\sigma}{\sqrt{n}}$.

When the logarithm of fatigue life follows normal distribution, we can obtain

$$x_p = \mu + u_p\sigma \tag{8}$$

where x_p and u_p are the logarithm of fatigue life and the standard normal variable with reliability p, respectly.

By replacing μ with $\bar{x}-u_\gamma \dfrac{\sigma}{\sqrt{n}}$, Eq.(8) can be rewritten into

$$x_p = \bar{x} - u_\gamma \frac{\sigma}{\sqrt{n}} + u_p\sigma \tag{9}$$

In the stage of crack initiation, Eq.(4) shows that the safe life can be obtained by utilizing the median test life and fatigue scatter factor.

When the standard deviation of population $\sigma=\sigma_0$ is known, the following equations can be obtained according to Eq.(9) and Eq.(4):

$$\lg N_p = \lg [N_{50}]_{\mathrm{t}} - u_\gamma \frac{\sigma_0}{\sqrt{n}} + u_p\sigma_0$$

$$\lg L_{\mathrm{f}} = \lg \frac{[N_{50}]_{\mathrm{t}}}{N_p} = \lg [N_{50}]_{\mathrm{t}} - \lg N_p = \left(\frac{u_\gamma}{\sqrt{n}} - u_p\right)\sigma_0$$

then Eq.(10) holds:

$$L_{\mathrm{f}} = 10^{\left(\frac{u_\gamma}{\sqrt{n}} - u_p\right)\sigma_0} \tag{10}$$

When u_p, u_γ, n and σ_0 are all known, the fatigue scatter factor can be calculated.

According to Eq.(4) and Eq.(10), the safe life can be obtained:

$$N_p = \frac{[N_{50}]_{\mathrm{t}}}{10^{\left(\frac{u_\gamma}{\sqrt{n}} - u_p\right)\sigma_0}} \tag{11}$$

In China, the standard deviation of logarithm of crack initiation life for different metal structures is adopted as

$$\sigma_0 = 0.16\text{-}0.20$$

When σ_0 equals 0.17, the scatter factor of the crack initiation stage is shown in Table 1.

To study further, the coefficient of fatigue reliability $S_{\mathrm{L}R}$ and the coefficient of confidence level S_{LC} are adopted, which are defined as

$$L_{\mathrm{f}} = S_{\mathrm{L}R} S_{\mathrm{LC}} \tag{12}$$

$$S_{\mathrm{L}R} = 10^{-u_p\sigma_0} \tag{13}$$

$$S_{\mathrm{LC}} = 10^{\frac{u_\gamma}{\sqrt{n}}\sigma_0} \tag{14}$$

Similarly, in the stage of crack propagation, Eqs.(15)-(16) hold:

$$L_{\mathrm{f}}^* = 10^{\left(\frac{u_\gamma}{\sqrt{n}} - u_p\right)\sigma_0^*} \tag{15}$$

$$N_p^* = \frac{[N_{50}^*]_{\mathrm{t}}}{L_{\mathrm{f}}^*} = \frac{[N_{50}^*]_{\mathrm{t}}}{10^{\left(\frac{u_\gamma}{\sqrt{n}} - u_p\right)\sigma_0^*}} \tag{16}$$

where L_{f}^* and $[N_{50}^*]_{\mathrm{t}}$ are the fatigue scatter factor and the median test life of the crack propagation stage, and σ_0^* is the standard deviation of logarithm of crack propagation life.

The standard deviation of logarithm of crack propagation life for different metal structures is adopted as

$$\sigma_0^* = 0.07\text{-}0.10$$

When σ_0^* equals 0.09, the scatter factor of the crack propagation stage is also shown in Table 1.

Table 1 Fatigue scatter factors with 90% confidence level and 99. 9% reliability

Number of sample	Fatigue scatter factor	
	Crack initiation stage	Crack propagation stage
1	5.54	2.47
2	4.78	2.29
3	4.48	2.21
4	4.31	2.17

3.2. *Mathematical model of life prediction of two-parameter Weibull distribution*

If crack initiation life and crack propagation life follow two-parameter Weibull distribution, the fatigue life factor is defined as

$$L_{\mathrm{f}} = \frac{\beta}{N_p} \tag{17}$$

When the fatigue life follows Weibull distribution, its cumulative distribution function (CDF) is given by

$$F(N) = 1 - \exp\left[-\left(\frac{N}{\beta}\right)^\alpha\right] \tag{18}$$

The CDF of fatigue life with reliability p can be obtained by

$$F(N_p) = 1 - \exp\left[-\left(\frac{N_p}{\beta}\right)^\alpha\right] = 1 - p \tag{19}$$

According to Eq.(19), we can obtain

$$N_p = \beta(-\ln p)^{\frac{1}{\alpha}} = \beta\left(\ln\frac{1}{p}\right)^{\frac{1}{\alpha}} \tag{20}$$

The coefficient of fatigue reliability is defined as

$$S_R = \frac{\beta}{N_p} \tag{21}$$

By utilizing Eq.(20) and Eq.(21), we can obtain

$$S_R = \left(\ln \frac{1}{p} \right)^{-\frac{1}{\alpha}} \tag{22}$$

The fatigue life N_i (i=1, 2, $\cdots$, n) is obtained by small sample test, and the estimator of characteristic life $\hat{\beta}$ can be obtained by applying the maximum likelihood method:

$$\hat{\beta} = \left(\frac{1}{n} \sum_{i=1}^{n} N_i^{\alpha} \right)^{\frac{1}{\alpha}} \tag{23}$$

The shape parameter α can be obtained by experience and test.

In fact, the characteristic life cannot be obtained by finite test data but it can be calculated by the lower confidence limit of estimator of characteristic life.

$$P\left\{ \beta \geq \frac{\hat{\beta}}{S_C} \right\} = C \tag{24}$$

where C and S_C are the confidence level and the coefficient of confidence level with two-parameter Weibull distribution.

The characteristic life can be given as

$$\beta = \frac{\hat{\beta}}{S_C} \tag{25}$$

When the shape parameter is known, we can obtain

$$\int_0^{S_C} \frac{\alpha n^n}{\Gamma(n)} y^{\alpha n - 1} \mathrm{e}^{-n y^{\alpha}} \mathrm{d}y = C \tag{26}$$

where $\Gamma(n)$ is Gamma function, and y the variable, then S_C can be known by solving Eq.(26).

According to Eqs.(20)-(21) and Eq.(25), the safe life can be expressed as

$$N_p = \frac{\beta}{S_R} = \frac{\hat{\beta}}{S_R S_C} = \frac{\hat{\beta}}{L_\mathrm{f}} \tag{27}$$

It can be known that

$$L_\mathrm{f} = S_R S_C \tag{28}$$

Similarly, in the stage of crack propagation, we can obtain

$$N_p^* = \frac{\beta^*}{S_R} = \frac{\hat{\beta}^*}{S_R S_C} \tag{29}$$

$$L_\mathrm{f}^* = S_R S_C \tag{30}$$

When the reliability equals 95% and the confidence level reaches 95%, the fatigue scatter factor is shown in Table 2. For two-parameter Weibull distribution, the fatigue scatter factors of crack initiation stage and crack propagation stage are same.

Table 2 Fatigue scatter factor with 95% confidence level and 95% reliability

Number of sample	1	2	3	4
Fatigue scatter factor	2.75	2.58	2.50	2.46

4. Mathematical Models of Reliability of Fatigue Life

The coefficient of fatigue reliability $S_{\mathrm{L}R}(S_R)$ reflects the dispersion of fatigue life, and the structure reliability coefficient, FRF, reflects the characteristic of structure. With the development of durability and damage tolerance technology, the structure reliability coefficient is used to predict aircraft structure fatigue life. When the check of structure is very difficult and the cost of maintenance is high, the value of structure reliability coefficient should be increased.

Consider the reliability and confidence level, the expected design life of aircraft structure $N_{\mathrm{E},C/R}$ is defined as

$$N_{\mathrm{E},C/R} = \frac{N_{C/R}}{\mathrm{FRF}} \tag{31}$$

where $N_{C/R}$ is the basic reliability life.

If the fatigue life accords with two-parameter Weibull distribution, the safe factor is defined as

$$F_\mathrm{W} = S_C S_R S_\mathrm{t} \mathrm{FRF} \tag{32}$$

where S_t is the coefficient of test sample size. For full scale fatigue test, S_t equals 1.

The expected design life of aircraft structure by adopting the estimator of characteristic life is defined as

$$N_{\mathrm{E},C/R} = \frac{\hat{\beta}}{F_\mathrm{W}} = \frac{\hat{\beta}}{S_C S_R S_\mathrm{t} \mathrm{FRF}} \tag{33}$$

According to Eq.(31) and Eq.(33), the basic reliability life can be given by

$$N_{C/R} = N_{\mathrm{E},C/R} \mathrm{FRF} = \frac{\hat{\beta}}{S_C S_R S_\mathrm{t}} \tag{34}$$

When both the reliability and the confidence level equal 95%, Eq.(33) can be rewritten as

$$N_{\mathrm{E},95/95} = \frac{\hat{\beta}}{S_{95} S_{95} S_\mathrm{t} \mathrm{FRF}} \tag{35}$$

where the FRF equals 1-2 for the structure designed by the damage tolerance technology; FRF equals 2-4 for the structure designed by the safe life technology.

The relations of different lives of aircraft structures with different coefficient are shown in Fig.1.

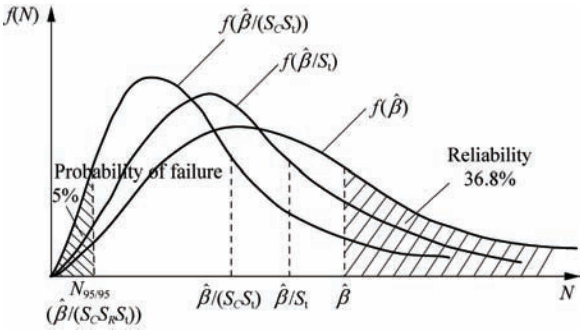

Fig.1 Relation of different lives of aircraft structures.

5. Model of Eeconomic Life

Safe life method, damage tolerance method and durability method are adopted to design aircraft structures. The economic life of aircraft structures is the key question of durability design. The model of economic life is put forward to determine the economic life and inspection period of aircraft structures.

For the design of safe life, the equation can be written as[1]

$$N_p = \frac{[N_{50}]_{\mathrm{t}}}{L_{\mathrm{f}}} \tag{36}$$

For the design of damage tolerance, researchers admit that the aircraft structures could have flaw at first but the residual strength of aircraft structures should meet the requirement to keep the structures safe.

If any one of the system composed of m structures fails and the system cannot work properly, it is called series system. In the stage of crack initiation, the reliability p_i is the function of crack initiation life N_{pi}, i.e.

$$p_i = f_i(N_{pi}) \tag{37}$$

and the function can be given by utilizing scatter factor of crack initiation life:

$$N_{pi} = \frac{[N_{50}]_{\mathrm{t}i}}{10^{\left(\frac{u_\gamma}{\sqrt{n}} - u_{pi}\right)\sigma_0}} \tag{38}$$

Similarly, in the stage of crack propagation, the reliability p_i^* is the function of crack propagation life N_{pi}^*, i.e.

$$p_i^* = g_i(N_{pi}^*) \tag{39}$$

and the function can be given by utilizing scatter factor of crack propagation life:

$$N_{pi}^* = \frac{\left[N_{50}^*\right]_{\mathrm{t}i}}{10^{\left(\frac{u_\gamma}{\sqrt{n}} - u_{pi}\right)\sigma_0^*}} \tag{40}$$

The probability of failure of crack initiation for any structure is $1 - p_i$. The probability of failure of crack propagation for any structure is $1 - p_i^*$. When the two cases happen at the same time, the structure will fail. The probability of failure of the structure can be expressed as

$$f_i = (1 - p_i)(1 - p_i^*) \tag{41}$$

The reliability of the structure is

$$R_i = 1 - f_i = 1 - (1 - p_i)(1 - p_i^*) \tag{42}$$

Therefore, the reliability of the system can be obtained:

$$R = \prod_{i=1}^{m} [1 - (1 - p_i)(1 - p_i^*)] \tag{43}$$

The probability of failure of the system can be expressed as

$$F = 1 - \prod_{i=1}^{m} [1 - (1 - p_i)(1 - p_i^*)] \tag{44}$$

Then the reliability of the system can be obtained:

$$R = \prod_{i=1}^{m} [f_i(N_{pi}) + g_i(N_{pi}^*) - f_i(N_{pi})g_i(N_{pi}^*)] \tag{45}$$

When the reliability of the system is given, the relation of crack initiation life and crack propagation life can be found according to Eq.(43), Eq.(37) and Eq.(39), as shown in Fig.2.

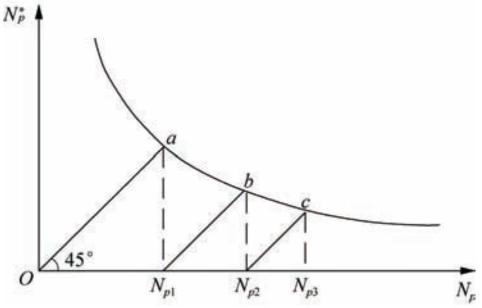

Fig. 2 Relation of N_p and N_p^*.

Eq.(43) is the model of economic life. It incorporates the design of safe life with damage tolerance design organically. The safe life of crack initiation is used as the structural service life with the expectation that cracks would not initiate during the service life. The safe life of crack propagation is used as the inspection period, with the objective that even if cracks may initiate during the inspection period and/or there is undetected cracks, the structures can work safely and the cracks will not develop into complete fracture. The safety and potential of the structure can be guaranteed by arranging the inspection period properly.

It needs to point out that if the aircraft structures are repaired during the first inspection period, the relations between crack initiation life and crack propagation life must be established by the characteristic of structures that are repaired. Usually, the latter inspection period is shorter than that of the former. For example, as shown in Fig.2 the interval between N_{p2} and N_{p1} is shorter than that between N_{p1} and the original point O. When the interval of inspection becomes short and the cost of maintenance is very high, the aircraft structure will not be in service.

6. Full Scale Test of Aircraft Structures

According to Eq.(38) and Eq.(40), the safe life can be calculated. Both equations are based on the full scale test of aircraft structures. The full scale test includes load spectrum test, design of reliability test and verification of reliability.

Fig.3 is the full scale test of a type of airplane. Before the test, the aircraft has finished *X* flights. When the full scale test finishes *XX* flights, crack initiation life of the structure is accepted. When the test finishes *XXX* flights, the crack propagation stage is over.

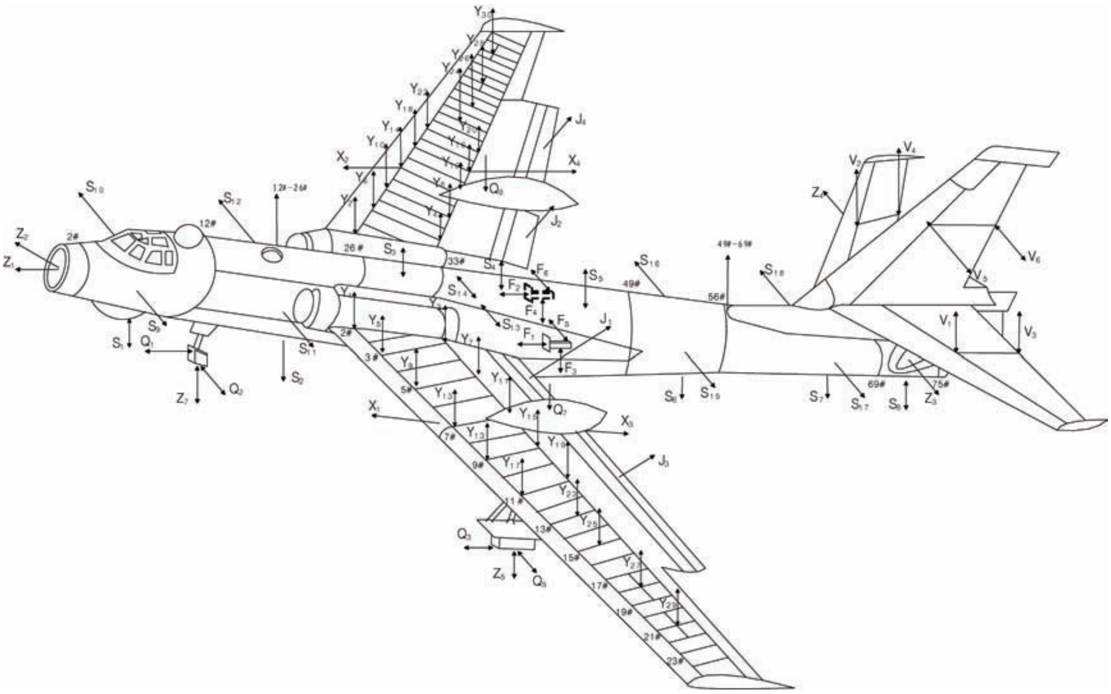

Fig.3 Full scale test of aircraft structures.

According to the results of the full scale test of aircraft structures, the economic life and the inspection period are given by applying the damage tolerance principle and economic life model. The results are given as follows:

(1) The service life of the second pole of the structure supporting engine is 4 486 flight hours[12-13]. The structures are designed by adopting safe life method. It needs to be replaced after 3 000-4 000 flight takeoff-landing.

(2) The service life of the second frame of the wing is 6 464 flight hours[12-13]. It is designed by applying damage tolerance method. When the crack length is less than 8 mm, the structure can be used after the short crack size is polished.

(3) The service life of the skin of the second rib of wing is 6 618 flight hours[12-13]. It is designed by applying damage tolerance method. The first inspection period is 3 309 flight hours.

(4) The service life of the aircraft structures is 6 000 flight hours, 6 000 flight takeoff-landing. If any of the two standards are met, the aircraft will not be in service.

7. Life Management of Aircraft Structures

The median fatigue life can be calculated by adopting damage cumulative model and applying the load spectrum database and material fatigue/fracture database[4,14-15]. The safe life with confidence level and reliability can be calculated. The economic life can be given by the safe life and inspection period. If the ecomomic life cannot meet the need, design against fatigue and optimization design of structures should be applied to meet the customers' demand[15].

In fact, the fatigue life predicted by utilizing safe life prediction method is the safe life of the weakest aircraft in the airplane group, which is very conservative.

Aircraft life management can be implemented by database technology, including computer visualization technology, cumulative damage rule, stand-alone life monitoring and structural online health monitoring technology and so on[16-17].

Aircraft life management aims to apply the potential of every aircraft and ensure the safety and reliability. By utilizing full scale reliability test, damage cumulative model, flight data and load, the residual safe life of every aircraft can be given. By arranging inspection period properly, maximum potential of every aircraft can be used.

8. Conclusions

The whole life can be obtained by full scale test results of aircraft structures and the fatigue scatter factors of crack initiation stage and crack propagation stage.

The economic life and inspection period of aircraft structure can be determined by economic life model.

The theory of economic life prediction and reliability assessment of aircraft structures has been successfully applied to determining and extending the structural life for thousands of airplanes and it can ensure safety and reliability of aircraft structures.

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