

结构可靠性定寿模型 及其在航空动力结构中的应用*

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【摘要】 本文以安全寿命定寿,以损伤容限保障安全,发展了结构可靠性定寿模型,给出了确定结构首翻期和检修周期公式;还给出了该模型应用于航空发动机动力构件疲劳定寿的实例。

主题词: 疲劳 断裂 寿命 模型

分类号: O 346. 2

1 前 言

60 年代以前,飞机疲劳关键构件都是按照安全寿命原理设计,但安全寿命设计方法仅适用于可统计预测的破坏,不能定量描述可能存在的裂纹。60 年代初,破损安全设计原理开始在飞机设计中得到发展,并有一定的应用。70 年代初,损伤容限迅速发展,它作为安全寿命的补充,在飞机生产中得到应用。

虽然安全寿命设计方法是建立在裂纹形成时间基础上,而损伤容限方法是以裂纹扩展至破坏的时间为基础,二者都是“寿命”方法,损伤容限方法可看成含裂纹体的安全寿命方法。它与安全寿命方法所不同之处是损伤容限设计要借助于检测手段。由此可见,因疲劳过程的二阶段论而发展起来的安全寿命设计和损伤容限设计互为补充互为发展。安全寿命设计与损伤容限设计有机结合起来^[1,2],评定结构疲劳使用寿命与检修周期,促进了疲劳可靠性设计的发展。

结构“安全裂纹形成寿命”与“安全裂纹扩展寿命”不仅可使用概率疲劳/断裂 Miner 理论求出,还可采用分散系数法和局部应力应变法计算。分散系数法将少量结构疲劳试验结果所得的中值寿命除以分散系数,即给出具有任一可靠度的“安全寿命”。它主要适用于少量结构全尺寸疲劳试验结果情况下的寿命评估。

2 安全寿命估算

飞机使用寿命主要根据全尺寸结构的疲劳试验确定。但飞机结构价值昂贵,对此种破坏性试验,只能提供一两个试验件。因此,依据极少量试验结果,以高可靠度给出总体的使用寿命乃是十分棘手的问题。目前国内外广泛采用的是“分散系数”的方法。

分散系数 L_f 定义为:使用寿命=中值试验寿命/ L_f 。其计算公式^[3]: $L_f = 10^{(W_y \sqrt{\frac{n - U_p}{n}}) \sigma_y}$ 据

此将中值试验寿命除以 L_f , 即可给出具有可靠度 p 、置信度 γ 的使用寿命。

通过大量金属材料和结构的试验统计分析, 裂纹形成寿命和裂纹扩展寿命二者分散程度差异甚大, 作为度量分散性的标准差也有所不同, 应分别使用。在标准差的取值方面还应注意: 实际结构标准差大于小试样的; 高强度材料标准差大于低强度材料的; 脆性材料标准差大于延性材料的; 高周疲劳标准差大于低周疲劳的; 无应力集中试样标准差大于有应力集中的。

对于稳态循环载荷, 依据结构 $P-S_a-S_m-N$ 曲面, 采用二维概率疲劳 M_{iner} 公式, 可估算结构的安全裂纹形成寿命^[4]。

$$T \cdot \int_{S_m}^{S_m)_{max}} \int_{S_a}^{S_a)_{max}} \frac{n_T f(S_a, S_m)}{N_p(S_a, S_m)} dS_a dS_m = 1$$

式中 $f(S_a, S_m)$ 为二元随机变量 (S_a, S_m) 的概念密度函数, $N_p(S_a, S_m)$ 为应力水平 (S_a, S_m) 单独作用下可靠度为 p 的破坏循环数。同理, 依据结构 $P-K_m-da/dN-\Delta K$ 曲面, 采用二维概率断裂 M_{iner} 公式, 可估算结构的安全裂纹扩展寿命^[4]。在连续型随机载荷谱作用下, 二维断裂概率 M_{iner} 公式为

$$T^* \cdot \int_{S_m}^{S_m)_{max}} \int_{S_a}^{S_a)_{max}} \frac{n_T f(S_a, S_m)}{N_p^*(S_a, S_m)} dS_a dS_m = 1$$

式中 $N_p^*(S_a, S_m)$ 为应力水平 (S_a, S_m) 单独作用下可靠度为 p 的裂纹扩展破坏循环数。

3 结构疲劳寿命可靠性模型

考虑一有 m 个关键构件组成的结构。如果其中某一构件破坏将导致整体结构失效, 则此种结构可视作由 m 个部件组成的串联模型。各部件的安全裂纹形成寿命 N_{pi} 与其可靠度 p_i 的关系 $p_i = f_1(N_{pi})$, 可利用分散系数或根据二维概率疲劳 M_{iner} 法则估算得到。各部件的安全裂纹扩展寿命 N_{pi}^* 与其可靠度 p_i^* 的关系 $p_i^* = f_2(N_{pi}^*)$, 也可利用分散系数或根据二维概率断裂 M_{iner} 法则估算得到。任一部件裂纹形成寿命的破坏率 $(1-p_i)$, 表示出现工程裂纹的概率。裂纹扩展寿命的破坏率 $(1-p_i^*)$, 表示由工程裂纹扩展到临界裂纹或完全断裂的概率。当此二事件都发生时, 则该部件即认为破坏。其破坏率为 $f_i = (1-p_i)(1-p_i^*)$ 。

该部件的可靠度为

$$r_i = f_1(N_i) + f_2(N_i^*) - f_1(N_i)f_2(N_i^*) \quad (1)$$

对一串联模型, 整体结构的可靠度 R 应等于各部件可靠度的乘积。根据部件的重要性和可检程度, 可靠度一般取 99%, 99.9%, 99.99% 等。当给定可靠度 r 时, 由式(1)可建立安全裂纹形成寿命 N_p 和安全裂纹扩展寿命 N_p^* 的关系(如图 1 所示):

$$N^* = f_2^{-1}\{[r - f_1(N)]/[1 - f_1(N)]\} \quad (2)$$

如以安全寿命设计定寿, 以损伤容限设计保障安全, 则 N_p 表示使用寿命; N_p^* 表示检修周期。在曲线上任意一点 a , $N_p < N_p^*$, 表示服役时间未达到检修周期, 无需检修。最经济的首次翻修期 $[N_p]_1$ 应满足 $N_p = N_p^*$ 的条件(如图 1 中 A 点所示), 此时, 由下式可求得首翻期 $[N_p]_1$:

$$f_1([N_p]_1)f_2([N_p]_1) - f_1([N_p]_1) - f_2([N_p]_1) + r = 0 \quad (3)$$

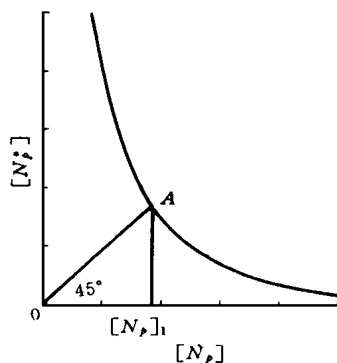


图 1 N_p 和 N_p^* 的关系

如检修后未发现裂纹, 则 $[N_p]_2$ 为第二次检修期。 $[N_p]_2$ 由下式得到

$$f_1([N_p]_2 - [N_p]_1)f_2([N_p]_2 - [N_p]_1) - f_1([N_p]_1 - [N_p]_{12}) - f_2([N_p]_2 - [N_p]_1) + r = 0 \quad (3)$$

依此类推, 可见使用寿命相当于不断缩短的检修周期的累加。如果某次检修时发现裂纹, 则根据修复后部件重新建立 $N_p - N_p^*$ 曲线, 直至预测的检修周期过短, 其经济效益不足以补偿维修费用时为止。检修周期过短会造成浪费, 过长则导致危险。

4 应 用

某直升机发动机传力系统关键构件由耳片接头、螺栓、大梁组成。接头材料: 40CrNiMoA (II类锻件)。螺栓材料: 40CrNiMoA。大梁材料: LD2CS (II类锻件)。对其关键危险件的裂纹形成 (p, N) 数据和裂纹扩展 (p^*, N^*) 数据进行统计处理, 分别得到裂纹形成 $p - N$ 曲线和裂纹扩展 $p^* - N^*$ 曲线如下:

$$p = 0.99921383 - 1.04611 \times 10^{-9}(N - 319)^2$$

$$p^* = 1.0071012 - 5.53052 \times 10^{-10}(N^* + 3659)^2$$

当给定 $r = 0.9999$ 时, 由式(2)得图2曲线:

$$N^* = \frac{1.9091 \times 10^{14} + 1.34307 \times 10^7(N - 319)}{7.8617 \times 10^5 + 1.0460(N - 319)^2} - 3659$$

那么, 首翻期 $[N_p]_1$ 由下式解出:

$$\begin{aligned} & ([N_p]_1 - 2034.5)^4 + 1.48170 \times 10^4([N_p]_1 - 2034.5)^3 \\ & + 1.01460 \times 10^8([N_p]_1 - 2034.5)^2 \\ & - 3.40695 \times 10^{13}([N_p]_1 - 2034.5) - 1.03707 \times 10^{14} = 0 \end{aligned}$$

经数值计算得首翻期 $[N_p]_1 = 2678$ 飞行小时。

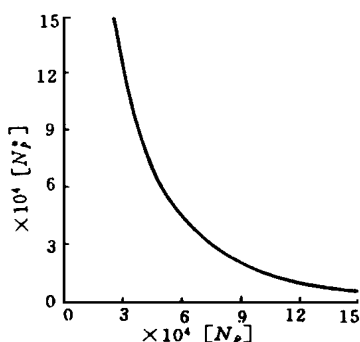


图2 $[N_p] \sim [N_p^*]$ 曲线

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AEROENGINE LIFE MONITORING AND REAL - TIME DATA PROCESSING

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ABSTRACT Aeroengine load and life monitoring technology play very important role in monitoring and assessing operating conditions, life consumption and remaining life of aeroengine. Aeroengine load can improve the safety and reliability of an engine in high performance operation, and reduce its direct operation cost. The on-board life monitoring system requires the real-time analysis method of flight data processing and life consumption evaluation. Three point method, shortest sail-route method and rain-flow method are used to conduct real-time data condensing processing, including peak valley values inspection, un-effective magnitude value detecting and LCF counting for each flight. The information obtained by the on-board life monitoring system is very useful for life track on the data base of the engine parts.

Key Words Aircraft engines Afterburners Transient process Control problems

PROBABILISTIC FINITE ELEMENT STRESS ANALYSIS FOR CYCLIC SYMMETRIC CONTACT STRUCTURE

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ABSTRACT The cyclic symmetric contact relation of corresponding node pairs on cyclic symmetric contact surfaces is given and its derivative expression with respect to random variables is deduced. A probabilistic finite element stress analysis technique is developed for the basic segment of the cyclic symmetric contact structure including random material property and load. A structure strength reliability analysis formula is also established with the first-order second moment method proposed by Hasofer and Lind. Finally the structure strength reliability analysis for a centrifugal impeller of an engine is carried out by using the method presented. The results show the effectiveness and practicability of the present method not only for the cyclic symmetric contact structure, but also for other non-cyclic symmetric contact structures.

Key Words Symmetrical bodies Probabilistic methods Finite element analysis Structural reliability

A STRUCTURE LIFE EVALUATION MODEL AND ITS APPLICATION TO DYNAMIC COMPONENTS OF AIRCRAFT POWERPLANT

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ABSTRACT The life of a structure is evaluated with its safe-life design, and its safety is ensured with the damage tolerant design, so the safe-life design and the damage

tolerant design are combined and a structure life evaluation model is developed. The formulas to determine the service life and the inspection periods of a structure with the high reliability are presented. Then the model is applied to evaluating the inspection periods for aircraft powerplant dynamic components, and an example is given.

Key Words Fatigue Fracture Lifetimes Model

DETERMINATION OF AXIAL PRELOADS OF ROTORS WITH CURVIC COUPLINGS

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ABSTRACT Rotors with curvic couplings, which are separately prestressed from the front part and the rear part, are often applied to modern turboprop and turboshaft engines. It is very important but difficult to determine the values of preloads for a rotor. The prerequisite of the axial relaxed/pressed forces caused by variety of rotor loads in operation is available, the criteria to determine the axial preloads of rotors are proposed in this paper, which takes into account synthetically the factors, such as tightness margin, strength margin, assembling relationship and etc. Hence the optimization model of the axial preloads is established, and the corresponding solution is presented. The computer program is developed according to the presented criteria and method. Finally, an example is given.

Key Words Rotors Axial preloads Optimization

AN OPTIMUM METHOD OF JOURNAL BEARING STABILITY

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ABSTRACT The expression of journal instantaneous whirl energy is formulated, based on solution for shaft center whirl orbit of a short bearing under the nonlinear oil film force. An optimization model of journal bearing parameters with optimum stability is established with the aim of minimizing time integration of whirl energy. The model has been solved with the optimal control method. In the last, a numerical example illustrates the determination of the optimal parameters of a given bearing.

Key Words Plain bearings Stability Optimal control

A NEW APPROACH TO COMBINED FATIGUE EXPERIMENT OF TURBINE DISK MORTISES AT ELEVATED TEMPERATURE

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ABSTRACT Crack and fracture fault emerged in the mortises of a given aero-engine second-stage turbine disk for a long time and seriously endangered the aircraft's regular flight. The fractography analysis indicated that the faults were caused by combined fatigue at elevated temperature. So we were engaged in this experiment to study and research