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密布多孔构件的低周疲劳寿命予测和试验研究

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一、多孔构件应力场有限元分析

为了计算多孔的涡轮叶片和燃烧室等构件的应力应变，我们编制和开发了壳体弹塑性有限元分析程序。用退化方法从三维单元推导出的曲壳单元。这种单元直接离散连续介质力学的三维方程，避免了由一般壳理论带来的复杂。曲面等参元具有独立的转角自由度和平移自由度，三维应力应变就退化为壳体情形。本文编制的这种退化壳单元程序还可进行各向异性材料的应力应变分析[1]。涡轮叶片因开有很多孔而使结构强度大大降低，由于孔间的相互影响，应力场相当复杂。我们用下列三种简化模型作计算分析。三种平板尺寸为 100×20×5mm，分别沿横向开有三个孔，七个孔及双排七个孔。孔的直径为 1mm，沿 20mm 板宽均匀分布。三种构件均受单向拉伸载荷，用有限元计算的应力集中系数沿截面分布，如图 1 所示。可以看

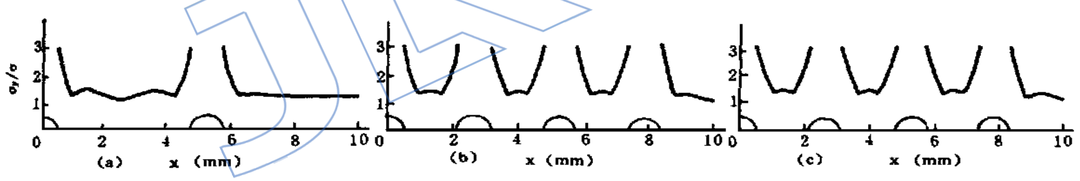

图 1　试件开孔的应力集中系数沿截面分布

出，最大应力集中系数都在 3 左右 (2. 95、3. 08、3. 03)。七孔与三孔构件相比，虽然孔的密度增加了一倍，而应力集中系数只是略有增加。说明在这样的开孔密度 (七孔构件孔径/中心距= 0. 381) 下，小孔之间的相互干涉还不很明显。当孔径/中心距 ($\emptyset$/p) 到达 0. 5 以上时，应力集中系数则明显增加。双排孔与单排孔的计算结果相比，应力集中系数略有减小趋势，说明沿着受力方向加密圆孔，应力集中得到缓和。

二、疲劳寿命试验研究

本文对多孔构件进行了疲劳试验。研究了孔的排列方式对构件疲劳寿命的影响。采用的试验设备是自行研制的小型疲劳试验机。试件材料是采用经过调质处理的45# 钢。主要性能为 $E= 12148$，$E' = 182.2$，$\sigma_s= 62.5$，$H' = 185$ (单位为 kg/mm^2)，$\mu= 0.3$。试件为前述的多

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孔构件，共分三组。第一组是沿板宽均布三个小孔的单排孔。第二组是七孔均布的单排孔。第三组是七个均布的双排孔。孔径和孔间距与计算模型相同, 对每组试件施加有四个载荷值, 从 3. 5N 到 5. 0N 之间变化。在试验中先对无孔试件作了疲劳试验，对开孔试件的裂纹起始寿命和断裂寿命分别作了记录，载荷寿命曲线，如图 2 所示。

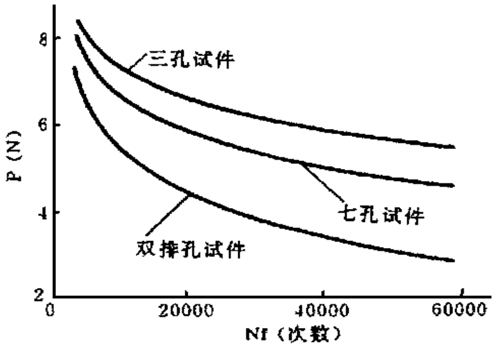

图 2　试验的载荷寿命曲线

本文用局部应力应变法对三组多孔试件作疲劳寿命予测。根据 45# 钢的应力疲劳寿命曲线转变成图 3 所示的应变寿命曲线。用计算机拟合出近似方程并绘出总应变寿命曲线。根据不同的平均应力 σ_m (kgf/mm^2) 拟合方程:

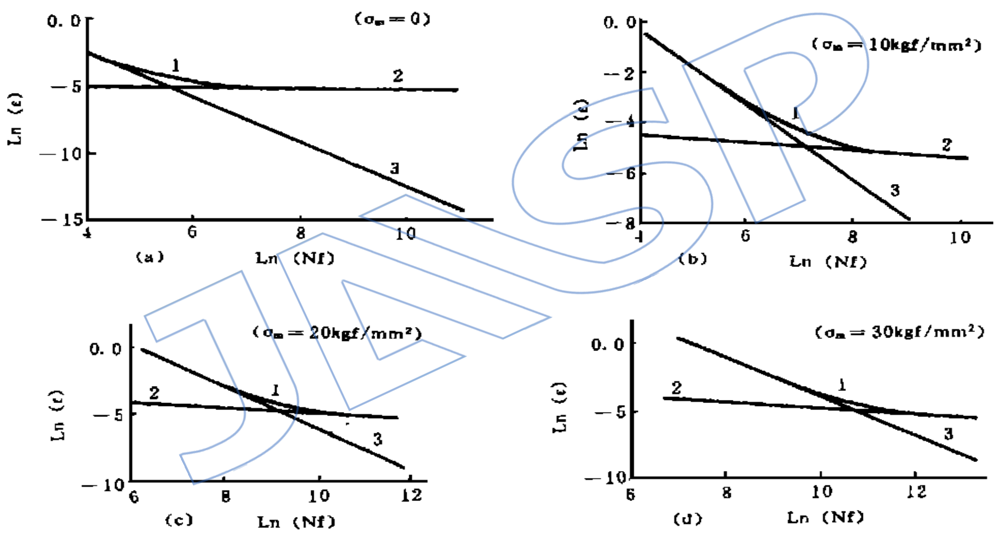

图 3　45# 钢的等效应变寿命曲线 (1 为 $Ln(\epsilon) \sim Ln(Nf)$, 2 为 $Ln(\epsilon_e) \sim ln(Nf)$, 3 为 $Ln(\epsilon_p) \sim Ln(Nf)$)

σ_m = 0 时　$l_n\epsilon_p = -16572 l_n N_f + 4192$

$l_n\epsilon_e = -0.0235 l_n N_f + 5.034$

σ_m = 10 时　$l_n\epsilon_p = -14860 l_n N_f + 5.744$

$l_n\epsilon_e = -0.1290 l_n N_f - 3.967$

σ_m = 20 时　$l_n\epsilon_p = -16099 l_n N_f + 10.15$

$l_n\epsilon_e = -0.5682_n N_f + 0.6265$

σ_m = 30 时　$l_n\epsilon_p = -1432 l_n N_f + 10.611$

$l_n\epsilon_e = -0.751 l_n N_f + 2.735$

对三组多孔构件分别进行弹塑性计算，得到载荷应变标定曲线，如图 4 所示。

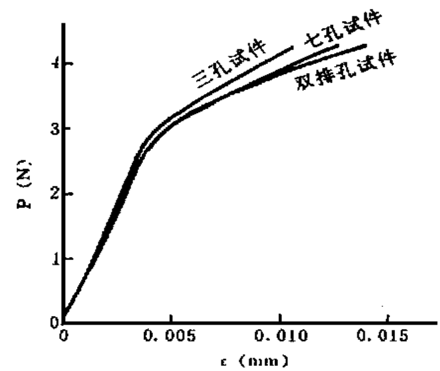

图 4　三组试件的载荷应变标定曲线

用局部应力应变法对每个试件进行疲劳寿命计算，其大致步骤是，从载荷历程中最大峰值开始，将载荷应变标定曲线按等载荷分成一系列单元；在相应的 p-ϵ 标定曲线上找到对应的应变增量；确定应力及其增量；由有效系数法进行循环记数；计算各封闭环的应力幅，应变幅和平均应力；根据闭合环的应变幅和平均应力在图 3 中查得寿命值 N_f；计算总损伤和疲劳寿命（循环数）。予测寿命值如表 1 所示。由表看出，第一组试件和第二组试件的予测值和试验值符合较好。而第三组试件两者相差较大，这是由于双排孔加工质量较差，使得试验的疲劳寿命过于偏低。尽管如此，但经过计算和试验分析，仍然可得出这样的结论，即沿着受力方向加密开孔时，应力集中虽有所缓和，但疲劳寿命仍有所降低。而沿着受力垂直方向加密开孔时，构件疲劳寿命降低显著。

表 1　疲劳寿命的预测值与试验值

类　　型	三　孔　试　件				七　孔　试　件				双　排　开　孔			
序　　号	1	2	3	4	5	6	7	8	9	10	11	12
载荷（N）	4.0	4.41	4.47	3.77	3.6	4.0	4.4	4.6	3.78	4.0	4.3	4.6
试验寿命（循环数）	28301	9888	8700	58800	28758	20770	9817	5600	9352	6164	5310	1980
预测寿命（循环数）	43884	30064	24399	92407	59821	38986	23485	13644	53119	37566	20706	9909

三、多孔构件带有热循环下的低周疲劳试验

在上述试验基础上，对三孔试件还进行了热循环下的低周疲劳试验研究。温度循环与低周载荷循环均为梯形波。载荷循环周期每分钟 2～3 次。由于试件加温（20℃～350℃）是缓慢上升的，所以升温曲线略滞后于载荷曲线。加载幅值如前。以试件断裂时的载荷温度循环数（LC+ TC）记为疲劳寿命 N_{f1}，列在表 2 上，并与前述恒温（室温）下低周疲劳寿命（LC）进行比较。根据试验数据，绘制出△P-N_{f1} 曲线，如图 5 所示。由于温度循环是与低周机械载荷同步加于试件的，所以这种温度循环与低周机械载荷共同构成低周疲劳损伤。在低周机械载荷之上叠加温度循环时，多孔构件的疲劳寿命大为降低，这说明温度循环会造成大幅度的疲劳损伤。对于 45# 钢 3 孔试件来说，叠加 20℃～350℃的温度循环会使疲劳寿命下降一个数量级。

表 2　疲劳寿命 Nf_1

△P（T）		3.77	4.00	4.41	4.71
σ_1（MPa）		369	392	432	462
Nf_1	LC	58800	28301	19880	8700
	LC+ TC	2234		1380	1170

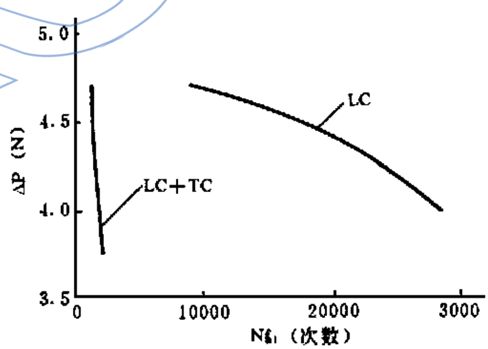

图 5　Δp-Nf_1 曲线

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[2]　徐风旌，“多孔试件在热循环下复合疲劳的损伤特性研究”，北京航空航天大学硕士论文，1991. 4. 30。
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under the same m-ratio and LCF stress, as test temperature rises from room temperature to 150℃, the complex fatigue life N_{fL} drops by 66% under $m = 10\%$ and $\sigma_{max} = 945$ MPa. If the temperature comes up continuously to 300℃, its fatigue life approaches to zero. In addition, a model of the accumulative damage for complex cyclic fatigue is formulated as follows: $1/N_{fL} = 1/N_L + n/N_h$.

A REAL-TIME RAIN-FLOW METHOD OF CYCLE COUNTING AND ITS PROGRAM DESIGN FOR AEROENGINE SERVICE LOADS

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ABSTRACT The paper presents briefly a real-time rain-flow method of cycle counting and its program design for the service loads of aeroengines. The concept of real-time counting and its value to engineering application are also discussed. A detailed program flow chart is given which can be used in software programming of small size airborne data processing equipment.

EXPERIMENTAL RESEARCH ON BLADE CONTAINMENT

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ABSTRACT This paper describes the blade containment tests for six sets of single model blade on a vertical breaking-down tester with excess revolution. The experimental results indicate that the blade body fragment flying off impacts against the model aeroengine case time and again. The incident angle of the blade fragment against the case in the initial impact is smaller than in the later impacts, the case damage of the first impact is smaller than that of the final impact, and the impacts of the blade fragment against the case make the blade fragment crimple. In principle the experimental results of the blade fragment containment and non-containment are consistent with the containment curve of single compressor blade (for use only in case of the blade body) in the Spey MK202 Stressing Standards (EGD-3) and are on the safe side. It is the preliminary conclusion that the containment curve of single compressor blade (for use only in case of the blade body) in EGD-3 can be used to predict the containment of the similar blade.

THE LOW-CYCLE-FATIGUE LIFE PREDICTION OF A MEMBER WITH HOLES

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ABSTRACT The stress and strain field and the low-cycle-fatigue life of a structure member with holes are calculated theoretically and investigated experimentally. The calculated results show that it is reliable to calculate the stress and strain field of a member with holes by using the shell-structural elasto-plastic finite element program, which has been designed and developed by the author. The satisfactory results are obtained from LCF life prediction of a member with holes by the advanced local stress and strain method. The calculation and tests show that the stress concentration of the tensile plane member is intensified and the fatigue life reduces drastically when its holes are densified in the direction perpendicular to that of tensile; the stress concentration is mitigated slightly but the fatigue life is also shortened when they are densified in the tensile direction.