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鸟撞击的载荷因素对叶片响应的影响

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【摘要】　本文以矩形悬臂板模拟真实叶片, 以冲击载荷模拟鸟撞击载荷, 采用有限元法计算悬臂板在冲击载荷下的非线性瞬态响应。通过计算多个算例进行分组比较, 分析了鸟撞载荷的冲量传递, 加载持续时间, 加载位置, 载荷的空间分布等不同载荷因素对叶片响应的影响。为鸟撞击载荷过程的合理简化提供了依据。

一、前　　言

在对航空发动机的风扇或压气机叶片进行鸟撞击损伤预估时, 首先要建立鸟撞击的载荷模型。鸟对叶片撞击的相对速度一般在 200m/s 左右, 撞击时产生的巨大压力远远超过鸟体的承受能力, 致使鸟体发生了流变。因此鸟撞击过程被描述成一个非恒定的流体动力学过程。由初始撞击, 松驰, 恒定流动及流动终止四个阶段组成[1]。按照这样一个复杂的加载过程来计算叶片的瞬态响应无疑是困难的, 显然应当对其进行简化, 略去一些次要因素, 仅保留一些主要因素。为此, 需要分析鸟撞击的各种载荷因素对叶片响应的影响。

本文以矩形悬臂板模拟真实叶片, 以冲击载荷模拟鸟撞击载荷, 采用有限元法计算悬臂板在冲击载荷下的非线性瞬态响应。通过计算多个算例进行分组比较, 分析了鸟撞击载荷的冲量传递, 加载持续时间, 加载位置, 以及载荷的空间分布形式等不同载荷因素对叶片响应的影响, 本文得出的结论可供建立鸟撞击载荷模型时参考。

二、计算模型与载荷

用长 24.46cm, 宽 7.62cm, 厚 3.81mm, 在 Y= 0 一端固定的矩形悬臂板模拟具有中等尺寸的风扇叶片。网格剖分方案见图 1。采用三维 8 节点超参壳元, 共分为 36 个单元, 135 个节点。叶片的材料为 410 不锈钢 (美 AISI)[2], 材料屈服后接理想塑性考虑。应当指出的是, 在高速撞击下材料的性能参数将发生变化。因目前无法获得材料在高应变率下的动态特性及破坏准则, 故在计算中未计及高应变率的影响, 按弹塑性、大变形瞬态响应问题处理。

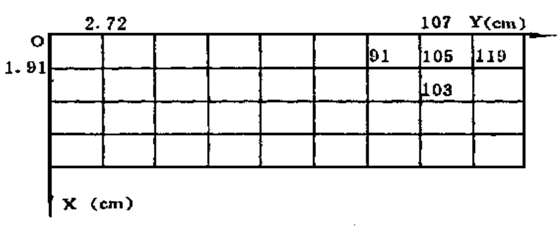

图 1　网格剖分方案

在进行叶片的瞬态响应计算时, 冲击载荷通过力—时间函数施加。力—时间函数的两个

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主要载荷数据为载荷幅值 P 及加载持续时间 T。T 由鸟切片（经叶栅切割后撞击叶片的鸟体[3]）长度及撞击时的相对速度决定。当 T 确定后，P 的大小则受到鸟切片对叶片的冲量传递 H 所制约。H 值可据发动机、叶片及鸟切片的具体参数计算得出。在本计算中 H 及 T 一般分别取为 3. 5586Ns 及 0. 4ms[4]。为突出各种载荷因素的作用，计算时只虑了正撞击情况。

三、计 算 结 果

除特殊说明外，计算的时间域一般为 0～0. 6ms。

1. 冲量传递　为分析不同数值的冲量传递对叶片响应的影响，在悬臂板的78%展向50%弦向，即节点 103 处施加一个集中载荷。其力—时间函数见图 2（a），其中 EX102 的H 值为 EX101 的两倍，即分别为 3. 5586Ns 及 1. 7793Ns。当 T 值均为 0. 4ms 时，对应的 P 值分别为 8896. 4N 及 4448. 2N。

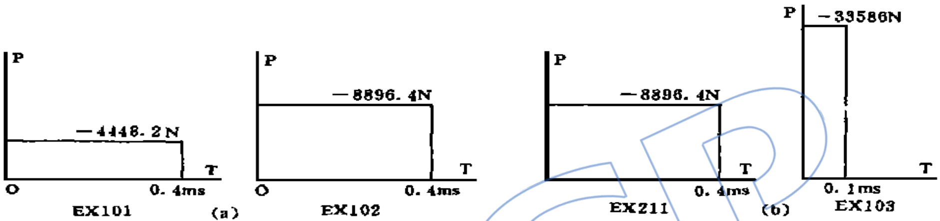

图 2　力- 时间函数

计算的时间域取到 1. 20ms。图 3 示出了 EX101、EX102 在 0. 36ms 及 1. 20ms 时刻下，在 50% 弦向处的展向挠度分布。由图中可知在各个时刻下，EX102 各点的挠度约为 EX101 相应点挠度的两倍。因载荷加在 50% 弦向处，叶片没有发生绕展向纵轴的偏转。由绘制的加载点处的挠度—时间变化，亦可看出在各个时刻下加载点处局部挠度间的两倍关系。

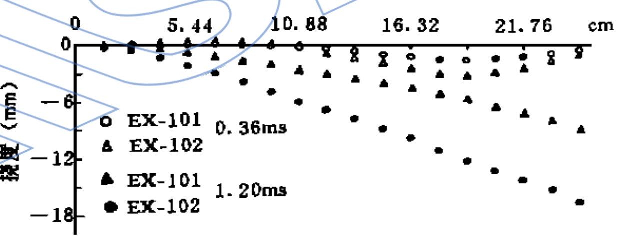

图 3　不同冲量传递下的展向挠度分布（50% 弦向处）

2. 加载持续时间　在观察叶片对不同加载持续时间的响应时，计算了两个算例。在 78%展向 25% 弦向，即节点 105 处施加一个集中载荷。采用这种沿弦向的偏心载荷，目的是更接近真实发动机在鸟撞击下的情况。两次计算的H 值均为 3. 5586Ns，但 T 值分别为 0. 4ms 及 0. 1ms，对应的 P 值分别为 8896. 4N 及 35586N。见图 2(b) 所示的力—时间函数。

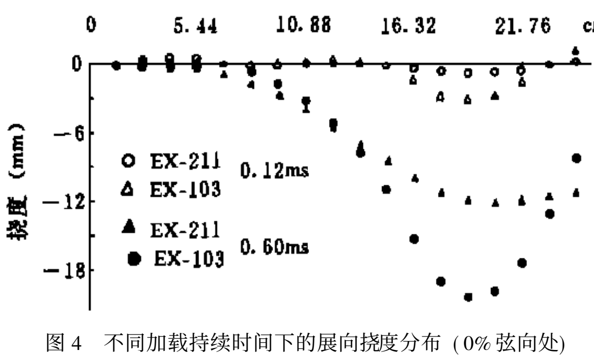

图 4　不同加载持续时间下的展向挠度分布（0% 弦向处）

由图 4 可以看出，在加载点附近区域，EX103 的挠度值始终远大于 EX211 的，由于载荷沿弦向的偏心施加，使叶片产生了绕展向纵轴的偏转。从应力计算结果可知，在 0. 12ms 时刻下，EX103 在加载点附近的相当大区域均已屈服。以后，塑性区

域不断扩大，致使叶片端部及根部均进入塑性状态。而EX211只是在加载期间，加载点附近区域的个别高斯点发生屈服。

3. 加载位置　为比较不同加载位置对叶片响应的影响，现将加载位置分为表1所示的两组。第一组为固定展向位置改变弦向位置，用以比较弦向加载位置变化对叶片响应的影响。第二组则反之，用以比较展向加载位置变化对叶片响应的影响。所加的为一集中载荷，其力—时间函数与图2(b)中的EX211算例相同。

表1　加载位置(见图2)说明

	展向位置	弦向位置	节点编号	算例编号
第一组	78%	0%	107	EX311
	78%	25%	105	EX211
	78%	50%	103	EX312
第二组	67%	25%	91	EX313
	78%	25%	105	EX211
	89%	25%	119	EX314

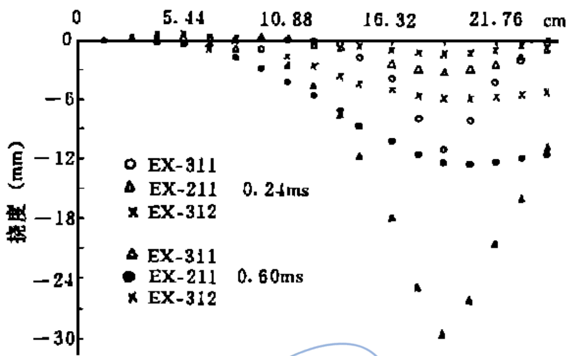

图5　不同弦向加载位置的展向挠度分布（0%弦向处）

(1) 改变弦向加载位置　由图5可知在各个时刻下，作用在50%弦向处的载荷(EX312)使

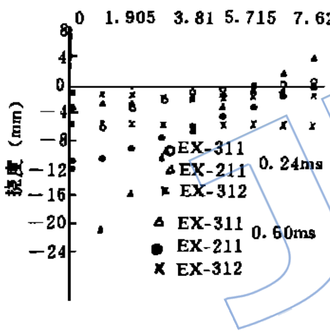

图6　不同弦向加载位置与不同空间分布形式的弦向挠度分布（78%展向处）

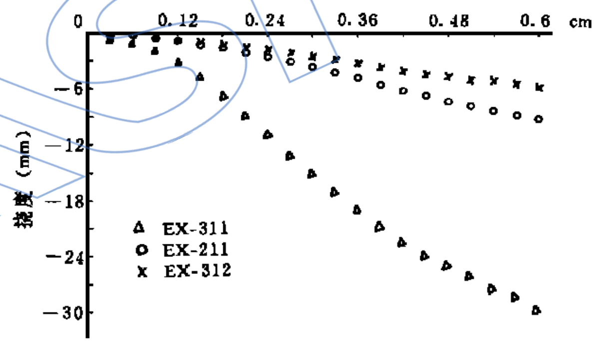

图7　加载点处的挠度时间变化

叶片产生的挠度最小；而偏心载荷使叶片产生较大的挠度。偏心程度越高，叶片的挠度越大。随着时间的增加，EX311在加载点附近的挠度增长很快，使得整体挠度曲线在该处显得很“尖”，这是局部进入塑性所致。由图6示出的上述三例在78%展向处的弦向挠度分布可明显看出，载荷的偏心程度越高，叶片绕展向纵轴的偏转越严重。图7示出了三个加载点处的挠度—时间变化，其中EX311的局部挠度值远大于其余二者。

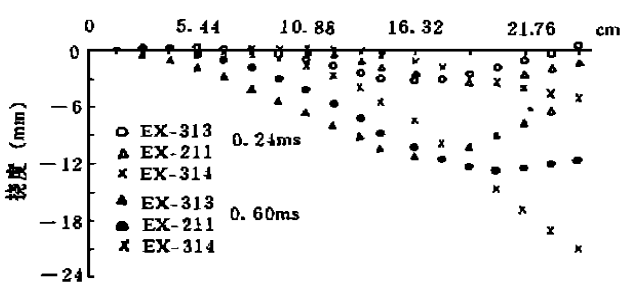

图8　不同展向加载位置的展向挠度分布（0%弦向处）

(2) 改变展向加载位置　由图8可看出，EX313及EX211在响应早期均为加载点处的挠度最大，以后自由端处的挠度增加较快，使挠度曲线呈下降趋势。而EX314由于加载位置靠

近自由端，除 0.12ms 时刻外，其余时刻均为自由端处挠度最大，整体挠度呈明显下降。

4. 载荷的空间分布形式　在沿展向长 5.44cm，沿弦向宽 3.81cm 的矩形面积上施加一个分布载荷。面积中心位于 78% 展向 25% 弦向处，即载荷分布在以节点 105 为中心的四个单元上。载荷的力—时间函数同图 2 (b) 中的 EX211，载荷的空间分布形式如图 9 所示。由图 10 中看出在不同时刻下，EX401 及 EX402 各点的挠度基本相同；而 EX403 的较前两者大。这是由于在 EX403 所示的直角三角形空间分布形式下，其合力作用线向前缘方向移动，使载荷的偏心程度加大，因此叶片挠度加大。

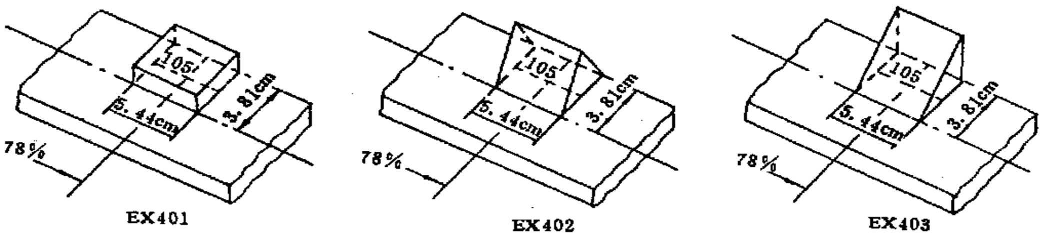

图 9　载荷的空间分布形式

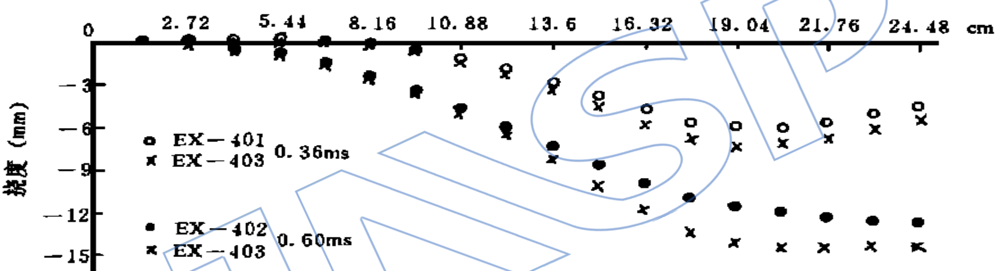

图 10　不同空间分布形式下的展向挠度分布 (0% 弦向处)

结论　(1) 冲量传递及加载持续时间对叶片响应的影响很大，在相同的加载持续时间下，叶片的局部及整体挠度均正比于载荷的冲量传递。反之，在冲量传递一定的情况下，加载持续时间也直接影响着叶片的变形及应力状态。当加载持续时间很短时，相当高的载荷幅值使得叶片立刻进入塑性状态。因此，在建立鸟撞击载荷模型时，首先要准确地确定这两个量。然后再考虑载荷模型的其它因素。(2) 加载位置对叶片响应的影响较大。偏心载荷不仅使叶片产生较大的局部及整体挠度，且产生了绕展向纵轴的偏转。偏心程度越高，挠度及偏转越大。靠近自由端处的加载使得自由端处 (而不是加载点处) 的挠度始终最大，形成叶片绕根部的转动。载荷的空间分布形式对叶片响应的影响不大。

参 考 文 献

[1] Wilbeck J. S., "Bird Impact Loading", Shock & Vibration Bulletin, Part 2, 1978, pp115～120.

[2] 安继儒等，"中外常用材料手册"，陕西标准化情报研究所，1984. 4。

[3] Storace A. F., "Foreign Object Impact Design Criteria", AD A112701.

[4] Bauer D. P., Bertke R. S., "Response Sensitivity of Typical Aircraft Jet Engine Fan Blade-like Structures to Bird Impact", AD A 119974.

been predicted loose load of real jointed structure in an aeroengine by means of the model test and investigated the factors which have influence on bearing capacity.

NUMERICAL MODELLING FOR GAS DUCT IN TUBOANNULAR COMBUSTOR

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ABSTRACT A numerical approach to modelling of hot-gas duct in tuboannular combustor is suggested. The modelling scheme is based on five controlling rules: top and bottom curves on central profile, radii of top and bottom arcs of cross sections, and area of cross sections. A three-dimensional hot-gas duct is regarded as a stacking of finite two-dimensional cross sections constrained by the rules. A brief analysis of computed rules is presented as well. As an example the hot-gas duct of SPEY engine is computed by using this method. Comparison between the computed cross sections and real ones obtained from SPEY technical drawings shows that the method is effective and practicable.

STUDY ON RELIABILITY DESIGN OF TURBINE BLADE

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ABSTRACT A reliability design method is presented for fatigue strength of turbine blades. The method considers static stresses, dynamic stresses and the blade endurance strength as random variables. The scatter effects of the centrifugal tensile stress, the centrifugal bending stress and the gas bending stress are taken into consideration when the distribution parameters of static stresses are determined. The scatter effects of the static natural frequency, the dynamic natural frequency, the stimulus and the amplification factor are considered as the distribution parameters of dynamic stresses are determined. The distribution parameters of the blade endurance strength are determined under the condition that the scatter effects of the corrosion correction factor, the surface quality correction factor, the stress concentration correction factor, the dimension correction factor and the material fatigue limit are taken into account. The distribution parameters of the fatigue stress and the fatigue strength for turbine blades are obtained by the plotting method from the blade endurance strength graphs. The reliability of turbine blades can be estimated in the designing stage by use of interference models for fatigue stress distribution and fatigue strength distribution, which provides a scientific basis for designers to analyze and improve reliability of the turbine blades.

EFFECT OF SOME LOAD FACTORS OF BIRD IMPACT ON BLADE RESPONSE

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ABSTRACT The effect of some load factors of bird impact on blade response is analysed in this paper. These factors include momentum transfer, load-duration, loading location, and spatial distribution of loads. The finite element method is used to compute the nonlinear transient response of the blade by means of simulating a real blade with a rectangular cantilever plate and simulating bird impact loads with shock loads. By computing and comparing the response of the cantilever plate to various load factors, the following

conclusions can be obtained: The local and total deflection of the blade are directly proportional to momentum transfer to the blade. The load-duration affects directly the deformation and stress states of the blade too. So the two parameters must be accurately predicted when a load model is developed. It is also very important to correctly predict the load location on the blade because the eccentric loads cause the greater deflection and twisting. The spatial distribution forms for distributed loads seem to have a little effect on blade response. The work which is conducted in this paper can provide the basis for the development of the bird impact load model.

STRATEGIES FOR OPTIMAL DESIGN OF GAS TURBINE DISKS

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(*Dalian University of Technology*)
Liu Xiangsheng and Chen Junyue
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ABSTRACT A number of strategies for optimal design of the gas turbine disks are proposed, which include separation of tenons design from disk design, rational simplification of structural model, check on local constraints, optimal design based on elastic analysis and further check based on elastoplastic analysis, multi-level optimization by grouping design variables. According to the strategies a computer program TDSOS is developed for practical use. By applying the strategies and the program TDSOS, shape optimization of gas turbine disk with light mass and low stress level can be obtained and the contradiction among high performance index, reliability and long life expectation is better solved.

A NEW FORM OF NUSSELT'S DIMENSIONLESS EQUATION

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ABSTRACT It is expounded theoretically that C and m of the dimensionless equation $Nu = CRe\,Pr^m$, which is in common use, should not be constant. This simple dimensionless equation is unable to reflect accurately the heat transfer when Prandle number equals 0.001～7500. The authors made use of integral equations to solve the laminar flow heat transfer problem of various field flow fields around a plate of Prandtl number 0.001 to 7500. Another form of dimensionless equation is recommended which can describe the functional relationship among Nusselt number, Raynolds number and Prandtl number more accurately.

STUDY ON SECONDARY ATOMIZATION OF LIQUID FUEL AT THE LIP OF THE FLAMEHOLDER

Yang Maolin, Huang Yong, Gu Shanjiang, Zhang Yingnian
(*Beijing University of Aeronautics and Astronautics*)

ABSTRACT An experimental investigation of secondary atomization of liquid fuel at the lip of the flameholder has been completed by means of Malvern Particle-Sizer. This secondary atomization has several features: Fine droplets occur in the high speed air flow side, while gross droplets occur in the recirculation zone side; the velocity of air flow (V_a) has a predominant influence on the mean drop size (MMD) of the spray, the effect may