

考虑二次流效应的叶片颤振预估方法*

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【摘要】 采用流线曲率法和 Adkins-Smith 二次涡模型相结合的方法得到周向非均匀的定常流场, 再与变叶片间相角的变形激盘法相结合发展了考虑二次流效应的三维叶片颤振预估方法, 并用此方法对 BF-1-2 转子的气弹稳定性进行了分析。结果表明, 考虑二次流效应计算的颤振边界与实验一致。不同二次流与叶片颤振的相关性中尖部漏流涡对叶片气弹稳定性的影响较大。

主题词: 二次流 叶片 气动力弹性 稳定性 预测

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1 二次涡的计算

为了考虑二次流效应的影响^[1], 定常流计算必须打破周向平均假设。本文采用流线曲率法和 Adkins-Smith 二次涡模型相结合的方法得到周向非均匀的定常流场^[2], 再与变叶片间相角的变形激盘法相结合首次发展了考虑二次流效应的三维叶片颤振预估方法。文献[3]发展的可考虑变叶片间相角的三维变形激盘法假设定常流沿周向是均匀的, 计算中所有定常分量沿周向的偏导数都为零, 沿周向的计算站间距定义为叶片的间距, 从而大大减小计算量。沿周向叶片间也应设计算站以考虑二次流造成的流场周向不均匀的影响。激盘运动方程中叶片站的振动频率、相位、振幅就是叶片的频率、相位和振幅。文献[4]的二维平面振荡叶栅的流场显示实验表明叶片振动对流场是个小扰动, 对流场结构无太大的影响, 叶片间的烟线随叶片的振动而振荡、频率相同、相位滞后。假设叶片间的点的振频为叶片的振频, 叶片间各点相位在叶片间线性分布。

利用 Adkins-Smith 模型对主流进行修正, 并假设叶片排扇形出口为矩形, 将各个二次涡分布在此矩形上, 在矩形域内求解二次流场, 再按位置关系将二次流场分布在对应的扇形上。主流二次涡采用下式进行计算

$$\zeta_a = \left\{ \left[\frac{1}{\rho_1} \frac{dP_1^*}{dn_1} - \frac{d(UC\theta)_1}{dn_1} + \left[U_1 C_{\theta 1} - \frac{U_1^2}{2} \right] \frac{ds}{C_p dn_1} \right] \frac{\Gamma_A}{W_\infty^2} - \frac{A}{2C_p} \frac{ds}{dn_1} + \frac{d\Gamma}{dn_1} \right\} \frac{dn_1}{dn_2} \quad (1)$$

在端壁有相对运动的条件下计算得到的主流二次涡比实际的小, 需引入端壁二次涡修正

$$\zeta_a = \frac{k_1 C_1}{\delta_1} \left\{ W_1 \cos(\alpha_1 - \beta_1) \frac{\Gamma_A}{W_\infty^2} + \frac{2\pi}{N} \left[r_2 \frac{W_1}{W_2} \cos(\alpha_1 - \beta_1) \sin \beta_2 - r_2 \sin \alpha_1 \right] \right\} \frac{dn_1}{dn_2} \quad (2)$$

漏流涡采用 Lakshminarayana 和 Horlick 模型^[5], 其环量为: $\Gamma_{sv} = (1 - k_\tau) \Gamma_{2D}$ 。式中 Γ_{2D} 是主流环量, k_τ 是由径向间隙 τ 与叶片弦长 b 之比确定的经验系数。设漏流涡沿周向均匀分布 ($0 \leq \theta \leq 2\pi N$), 沿径向呈半个 $\sin$ 曲线分布

$$\zeta = \begin{cases} \zeta_{\max} \sin\{\pi [r - (r_{\tau} - \delta_{\tau})] / \delta_{\tau}\} & , (r_{\tau} - \delta_{\tau} \leq r \leq r_{\tau}) \\ 0, (r < r_{\tau} - \delta_{\tau}) \end{cases} \quad (3)$$

其中, $\delta_{\tau} = 6.5\tau$, $\zeta_{\max} = N\Gamma_{sv} / [2\delta_{\tau}(2r_{\tau} - \delta_{\tau})]$ 。叶片边界层及尾迹的径向迁移速度 W_{rs} 由下式确定

$$\frac{W_{rs}}{W_{z2}} = - \frac{z_2^2 - z_1^2}{2r_2} \cdot \frac{1 - k_w}{k_w} \left[(1 + k_w) \text{tg}^2 \beta_{z2} + 2 \frac{\omega^2}{W_{z2}} \text{tg} \beta_{z2} \right] \quad (4)$$

经验系数 $k_w = W_{zs} / W_z = 0.5$ 。上述涡的分布求得后,再求解波松方程 $(\partial^2 \Psi / \partial^2) + (1/r)(\partial \Psi / \partial r) = \zeta \cos \beta$, 便可得二次流速度为:

$$W_{sr} = \partial \Psi / \partial r; \quad W_{s\theta} = - \partial \Psi / \partial \theta \quad (5)$$

2 叶片的气动阻尼

利用流线曲率管流法对转子周向平均的 S_2 流面流场进行求解,并在栅后切平面中按 Adkins-Smith 模型求解波松方程,得到多种二次涡量对主流的扰动,叠加得到周向不均匀的定常流场,再通过求解 Euler 方程的小扰动振幅方程得到非定常分量,详细的计算方法参见文献 [6]。非定常流场求解后便可求出图 1 所示的控制体的各点的气动力。

$$\begin{cases} \tilde{F}_{x,i,j} = (\tilde{P}_{2,i,j} - \tilde{P}_{1,i,j}) \tilde{\tau} + (\tilde{P}_{2,i,j} - \tilde{P}_{1,i,j}) \tilde{\tau} + \tilde{G}_{i,j}^{\text{rd}} (\tilde{\omega}_{1,i,j} - \tilde{\omega}_{2,i,j}) + \tilde{G}_{i,j}^{\text{rel}} (\tilde{\omega}_{1,i,j} - \tilde{\omega}_{2,i,j}) \\ \tilde{F}_{\theta,i,j} = - (\tilde{P}_{2,i,j} - \tilde{P}_{1,i,j}) \tilde{\tau} \frac{\partial \tilde{\omega}_{1,i,j}}{\partial \theta} \tilde{G}_{i,j}^{\text{rd}} (\tilde{\omega}_{1,i,j} - \tilde{\omega}_{2,i,j}) + \tilde{G}_{i,j}^{\text{rel}} (\tilde{\omega}_{1,i,j} - \tilde{\omega}_{2,i,j}) \end{cases} \quad (6)$$

沿周向求作用在叶片上的气动合力,沿径向积分得到气动合力矩。由于只研究弯曲振型的颤振,对沿周向求合力后产生的使叶片扭转的力矩忽略不计。

$$\begin{aligned} \tilde{M}_{x,J} &= \sum_{i=1}^{J_n} \left[\left(\sum_{j=J-n/2}^{J+n/2} \tilde{F}_{x,i,j} \right) l_i \right] \\ \tilde{M}_{\theta,J} &= \sum_{i=1}^{J_n} \left[\left(\sum_{j=J-n/2}^{J+n/2} \tilde{F}_{\theta,i,j} \right) l_i \right] \end{aligned} \quad (7)$$

式中 l_i 为气动力作用点相对叶根的高度, J 为叶片序号, N 为叶片间计算站数,为偶数。一个振荡周期内,各叶片的气动功和气动阻尼分别为

$$W_{\text{aero},J} = - \text{Re} \left[\int \left(\tilde{M}_{x,J} \frac{\partial \tilde{\omega}_x}{L \partial t} + \tilde{M}_{\theta,J} \frac{\partial \tilde{\omega}_\theta}{L \partial t} \right) dt \right] \quad (8)$$

$$\delta_{\text{aero},J} = - W_{\text{aero},J} / \overline{KE} \quad (9)$$

3 算例分析

在 0.5 mm 叶尖间隙时, BF-1-2 转子在转速 $n = 16000, 15000, 14300, 12000$ r/min 时都出现了颤振^[1]。叶片的振动相位参照 TS22 转子所测得的相位分布。图 2 给出了叶片最小气动阻尼随工况变化的情况(图 2 与图 4 中, $\circ$: $n = 1600$ r/min, $\bullet$: $n = 15000$ r/min, $\square$: $n = 14300$ r/min, $\blacktriangle$: $n = 12000$ r/min), 在每一条等转速线上, 随着流量的减小, 叶片的最小气动阻尼变小, 气动弹性稳定性变差。计算的颤振边界与试验结果对比如图 3 所示($\times$ 实验值, $\circ$ 不考虑二次流, $\triangle$ 考虑二次流)。不考虑二次流的影响所得到的预测边界在低转速时位于实验边界的上方, 说明在低转速区, 不考虑二次流效应不能正确的预估叶片颤振的发作。考虑二次流的预测边界则包括了所有的实验颤振点, 因而更符合实际情况。由于实验点不可能取到气动阻尼为零的颤

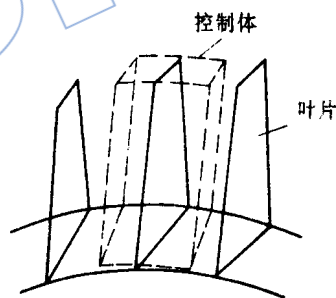


图 1 控制体

振临界点,而按气动阻尼为零得出的颤振边界应在图中所示实验边界的下方。

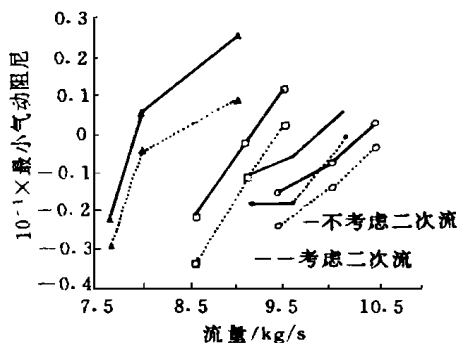


图2 叶片最小气动阻尼随工况的变化

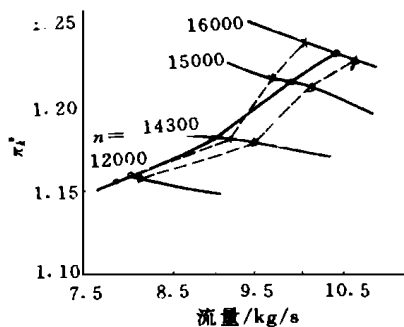


图3 计算的颤振边界与试验结果

图4为分别考虑3种二次涡与考虑综合效应的最小气动阻尼的比较(—综合效应, ···主流二次涡, — · — · —尖部漏流涡, - - -端壁二次涡)。与其他两种二次涡相比,尖部漏流涡对叶片气弹稳定性的影响最大,且使叶片的气弹稳定性提高;端壁二次涡的影响较小,在低转速时,它使叶片气动弹性稳定性降低,高转速小流量时,气动阻尼有上升的趋势,说明二次涡对气弹稳定性的影响与工况有密切的关系;主流二次涡的影响最小,它使叶片气动弹性稳定性降低。综合效应则考虑了不同二次涡的相互作用。从有限的计算结果来看,尖部的二次涡对气弹稳定性影响较大,这与试验中尖部流场畸变比根部畸变对气弹稳定性影响大是一致的。

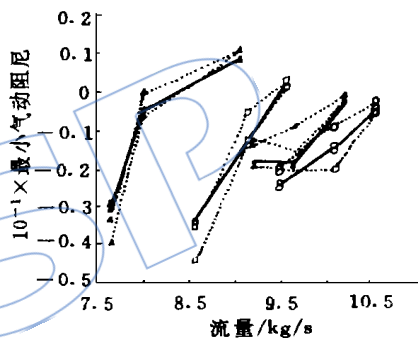


图4 最小气动阻尼的比较

小结: (1) 二次流强烈的转子颤振预测应使用考虑二次流的方法。(2) 尖部漏流涡对叶片气弹稳定性影响较大。

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count, such as the collective pitch, precone, sweep, and so on. Finally, the aeroelastic stability of Dolphin's Rotor blades is analysed. The experiment shows that the aeroelastic stability of the rotor blade in hover is influenced small by the blade sweep, but strongly by the collective pitch and precone. The experimental results verify the feasibility of the analysis and applicability to rotor design.

Key words Helicopter rotor Hovering Aeroelastic dynamics Stability

A BLADE FLUTTER PREDICTION METHOD INCLUDING SECONDARY FLOW EFFECTS

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ABSTRACT

In order to obtain a better understanding of the secondary flow effects on blade stall flutter, this paper presents an approximate method to analyse the effects of secondary flow on blade aeroelastic stability. The method combines conventional stream-line curvature methods with the secondary flow model to obtain the stationary flow with circumferential nonuniformity, and then incorporates the non-constant phase angle deforming actuator disk method. Several secondary flow effects on aeroelastic stability were analysed respectively. The results show that the effects of the secondary flow on the aeroelastic stability are different. The tip leakage vortex may have greater effect than other vortices, that is consistent with the experimental results.

Key words Secondary flow Blade Aeroelastic Stability Predictions

NUMERICAL ANALYSIS OF FLOW FIELD ABOUT SWEEP-FORWARD BLADES OF COMPRESSORS OR FANS

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ABSTRACT

A numerical analysis of the flow field about sweep-forward blades has been carried out. Time marching method is used to calculate the three-dimensional inviscid flow field. Boundary layer parameters are calculated with integrated boundary layer equations in non-orthogonal axes. The calculated results show that in axial compressors and fans with sweep-forward blades the intensity of passage vortex, secondary flow and tip losses are decreased, the early separation from the blade surface is protected, the flow field in tip area is improved obviously. As a result, the aerodynamic efficiency of axial compressor or ventilator is enhanced.

Key words Sweep-forward blades boundary layer Numerical analysis

HIGH-RESOLUTION IMPLICIT PROCEDURES FOR CASCADE FLOW CALCULATIONS

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ABSTRACT

Based on the high-resolution difference scheme structured from characteristic flux difference splitting, the implicit algorithm of the scheme has been developed. The implicit characteristic boundary procedures consistent with the scheme have been implemented as well. The implicit boundary procedures proposed in this paper eliminate the