

悬停状态下旋翼桨叶气动弹性 稳定性分析及试验

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【摘要】 研究直升机旋翼桨叶在悬停状态下挥舞-摆振-扭转全耦合运动的气弹稳定性。应用哈密顿原理推导桨叶运动的非线性偏微分方程,推导气动载荷时采用了准定常气动理论,并应用 Galerkin 有限元素法离散空间变量,利用特征值分析来研究系统的稳定性。以海豚直升机为工程实例,分析计算了其桨叶的气弹稳定性,还进行了旋翼模型气弹稳定性试验研究,确定旋翼结构参数对气弹稳定性的影响,并同计算结果进行了比较,得到了一些有意义的结论。

主题词: 直升机旋翼 悬停 气动弹性 稳定性
分类号: V215.3

1 桨叶运动方程及其求解

在国内,对铰接式旋翼的气弹稳定性问题的研究有了一定的基础,但对无铰式、星形柔性及无轴承等先进旋翼系统的研究尚在初始阶段。本文以海豚直升机旋翼桨叶为实例研究分析了在悬停状态下先进旋翼系统的气弹稳定性,并进行了旋翼模型气弹稳定性试验研究,以验证理论计算结果。旋翼桨叶的物理模型如图 1 所示,其假设为:(1) 桨叶根部简化为有弹性、阻尼约束的挥舞铰、摆振铰和变距铰,且 3 铰集中于一,铰以内的桨毂部分认为是刚硬的。(2) 考虑预锥角、预掠角和 3 个铰离旋翼中心外伸量的影响。(3) 桨叶剖面的气动中心与弹性轴重

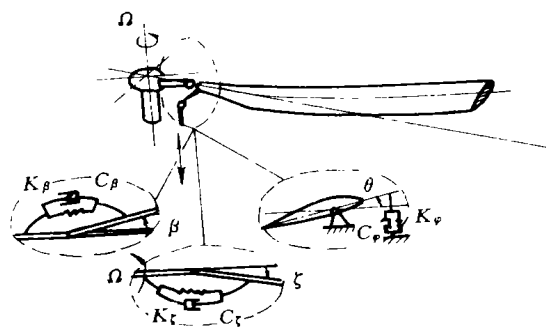


图 1 桨叶物理模型

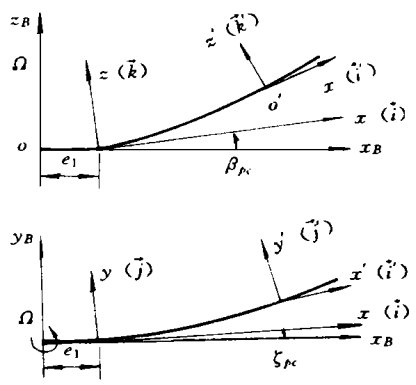


图 2 坐标系

合,其它各心均不重合,当弹性轴无变形时则与变距轴重合,弹性轴存在负扭转。(4)不计压缩性和气流分离的影响。本文推导公式中采用的坐标系如图 2 所示。

用哈密顿原理推导桨叶挥舞-摆振-扭转全耦合运动方程。该原理可用下式表达:

$$\int_1^2 [\delta U - T) - \delta W] dt = 0 \quad (1)$$

式中, U 表示应变能, T 表示动能, δW 为外力所做虚功, 下面分别给出 δU 、 δT 、 δW 。

桨叶变形后的应变能及桨叶在运动中所具有的动能的一阶变分分别为:

$$\delta U = \int (Y_u \delta u + Y_v \delta v + Y_w \delta w + Y_\varphi \delta \varphi) dx + b(u) \quad (2)$$

$$\delta T = \int \{ Z_u \delta u + [Z_v - (Z_u)] \delta v + [Z_w - (Z_u)] \delta w + Z_\varphi \delta \varphi + b(T) \} \quad (3)$$

$$\text{式中 } b(T) = (Z_v) \delta v \Big|_0^R + (Z_w) \delta w \Big|_0^R$$

基于二维非定常气动理论而来的准定常假设, 气动外力在桨叶剖面上的作用方向如图 3 所示。将气动力向桨叶剖面弦线方向(垂直和平行)进行分解, 并转换成不变形坐标中与 Y 轴和 Z 轴相平行的气动力分量, 就得到了所需的气动载荷

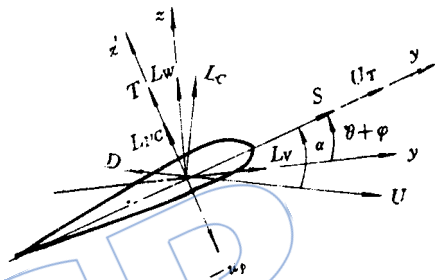


图 3 桨叶剖面上的气动力

$$\begin{cases} L_v \approx \left[\frac{\rho_\infty a c}{2} \right] \left\{ v_i - \Omega^2 x^2 \frac{C_{d0}}{a} - \Omega x v_i (\theta + \varphi) \right. \\ \quad \left. - \left[2\Omega x \frac{C_{d0}}{a} + (\theta + \varphi) v_i \right] \dot{v} + [2v_i - \Omega x (\theta + \varphi) \dot{w}] \right\} \\ L_w \approx \left[\frac{\rho_\infty a c}{2} \right] \left\{ -\Omega x v_i + \Omega^2 x^2 (\theta + \varphi) + \int v_i \dot{w} dx - \Omega^2 x v (\beta_{pc} + w) \right. \\ \quad \left. + \Omega^2 \frac{x c}{2} (\beta_{pc} + w) + [2\Omega x (\theta + \varphi - v_i)] \dot{v} - \Omega x \dot{w} + \frac{3C}{4} \Omega x \dot{y} - \frac{c}{4} \dot{w} \right\} \\ M_\varphi \approx - \left[\frac{\rho_\infty a c}{2} \right] \left[\frac{c^2}{8} \Omega x \dot{\varphi} \right] \end{cases} \quad (4)$$

式中, 透导速度为 $v_i = \Omega k \frac{\pi \sigma}{8} \sqrt{1 + 12 \left| \frac{\sigma}{\pi} \right| - 1}$, 其中 $\sigma = bc/\pi k$ 为实度。

得到了气动和力矩, 就可以得到气动载荷所做虚功的一阶变分:

$$\delta W = \int (L_v \delta v + L_w \delta w + M_\varphi \delta \varphi) dx \quad (5)$$

在桨根挥、摆、扭 3 个方向运动中都存在约束刚度和阻尼, 它们所做的虚功为:

$$\begin{aligned} b(M_0) = & - [K_\beta w(0) + C_\beta \dot{w}(0)] \delta w(0) \\ & - [K_\varphi \varphi(0) + C_\varphi \dot{\varphi}(0)] \delta \varphi(0) - [K_\varphi \varphi(0) + C_\varphi \dot{\varphi}(0)] \delta \varphi(0) \end{aligned} \quad (6)$$

式中, K_β 、 K_φ 、 K_φ 为桨根挥、摆、扭约束刚度系数; C_β 、 C_φ 、 C_φ 为桨根挥、摆、扭约束阻尼系数。

$b(M_0)$ 可随旋翼桨毂结构形式的不同而变化, 只要适当加以修正, 就可使该公式适用于不同旋翼形式。

桨叶运动方程及边界条件: 将(2)、(3)、(5)、(6)代入方程(1), 便得到桨叶的运行方程:

$$\left. \begin{aligned} \delta u: Y_u - Z_u &= 0 \\ \delta v: Y_v - Z_v + Z_v' - L_v &= 0 \\ \delta w: Y_w - Z_w + Z_w' - L_w &= 0 \\ \delta \varphi: Y_\varphi - Z_\varphi - M\varphi &= 0 \end{aligned} \right\} \quad (7)$$

边界条件方程:

$$b(u) - b(T) - b(M) = 0 \quad (8)$$

该方程为非线性偏微分方程组, 考虑了桨叶的挥舞-摆振-扭转耦合, 并计入了旋翼结构参数的影响。

在求解方程之前, 本文采用 Galeskin 有限元素法离散空间变量, 使偏微分方程组转化为常微分方程组, 然后利用有限元素法中一般的刚度组合法把元素方程组合成系统的整体方程

$$[M^g]\{\ddot{a}^g\} + [C^g]\{\dot{a}^g\} + [K^g]\{a^g\} = \{F^g\} \quad (9)$$

式中 $[M^g]$ 、 $[C^g]$ 、 $[K^g]$ 为非线性矩阵。利用桨叶不耦合自由振动振型对整体方程进行模态缩减, 使方程的自由度数大大降低。

$$\text{设} \quad \{a^g\} = [\wedge]\{q\} \quad (10)$$

式中 $\{q\} = (f_0 f_1 l_0 l_1 p_0 p_1)^T$, 把(10)式代入(9)式, 并左乘 $[\wedge]^T$, 就得到模态缩减方程:

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{F\} \quad (11)$$

$$[M] = [\wedge]^T [M^g] [\wedge], [C] = [\wedge]^T [C^g] [\wedge], [K] = [\wedge]^T [K^g] [\wedge], [F] = [\wedge]^T \{F^g\}.$$

为了求解桨叶非线性运动方程, 应先求出桨叶的平衡位置。设 $q = q_0 + \Delta q$, 将其代入(11)式, 并略去高阶项和时间导数交叉乘积项, 得到:

$$[K(q_0)]q_0 = \{F\} \quad (12)$$

$$[M(q_0)]\{\ddot{\Delta q}\} + [C(q_0)]\{\dot{\Delta q}\} + [K(q_0)]\{\Delta q\} = 0 \quad (13)$$

(12)式为桨叶运动的平衡方程, 它是一个非线性方程。(13)式是桨叶的扰动方程, 求解它的特征值就可以判断运动的稳定性。由(12)式解出平衡位置 q_0 , 代入(13)式就可以得到一个拟线性化的常微分方程。把(13)式转化成一阶状态方程:

$$\begin{bmatrix} M & 0 \\ 0 & I \end{bmatrix} \begin{Bmatrix} \dot{\Delta q} \\ \Delta q \end{Bmatrix} = \begin{bmatrix} -C & -K \\ I & 0 \end{bmatrix} \begin{Bmatrix} \dot{\Delta q} \\ \Delta q \end{Bmatrix} \quad (14)$$

这是一个实广义特征值问题, 最后求得共轭特征值 $\lambda_k = \eta_k \pm i\omega_k$, 若 η_k 都小于0, 则系统是稳定的, 否则是不稳定的。

2 计算结果分析

用本文提供的分析方法对“海豚”旋翼桨叶气弹稳定性进行了计算, 表1给出了主要计算结果, 从中可以看出, 所有特征值实部都是负的, 所以运动是稳定的, 这完全符合“海豚”直升机旋翼的实际情况; 另外, 特征根虚部即模态运动频率与“海豚”旋翼桨叶的固有频率十分吻合, 说明计算结果是正确的。从表中还可以看出, 摆振运动稳定性边界最低, 所以在桨叶运动中摆振运动稳定性最差。

表1 特征根实部、虚部计算值

	η_k	ω_k
挥舞	-0.3788454	1.041980
摆振	-0.0909647	0.654717
扭转	-1.2386240	2.806301

计算结果见图4(预锥角 β_{pc} 、总距角 θ 的影响)根轨迹曲线, 可以看出: (1) 桨叶总距角增

大, 桨叶摆振运动趋于稳定。(2) 桨叶预掠角增大或减小, 其计算结果基本无变化。(3) 桨根预锥角增大, 桨叶摆振运动也趋于稳定。

3 试验研究

试验研究是在南航直升机技术研究所旋翼模型试验台上进行的, 旋翼模型直径 2 米, 桨毂参数可以改变, 以满足预锥角、预掠角变化的要求。试验采用液压作动筒对自动倾斜器作周期变距激振。当激起稳定摆振运动后, 即停止激振, 并记录桨根摆振弯曲应变的时间历程。如果应变时间历程是衰减的, 则旋翼运动是稳定的; 如果是发散的, 则旋翼运动是不稳定的。将记录的时间历程在动态应变仪上进行分析, 便可获得桨叶运动模态的频率及阻尼比。本试验在保持旋翼转速不变的情况下, 改变旋翼总距角、预掠角、预锥角, 最后通过比较桨叶运动模态阻尼比, 则可确定上述参数对旋翼气弹稳定性的影响。试验结果列于表 2, 在表 2 中还给出了试验用模型桨叶气弹稳定性的计算值与试验结果的比较。

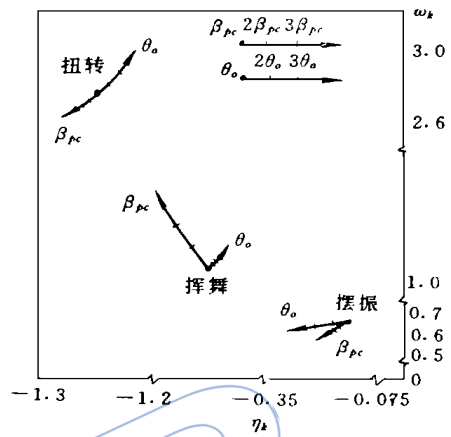


图 4 根轨迹图

表 2 摆振阻尼比随总距角 θ_0 、预掠角 ζ_c 及预锥角 β_{pc} 的变化

参 数		$\theta_0 = 0^\circ$	$\theta_0 = 3^\circ$	$\theta_0 = 6^\circ$	$\zeta_c = -2^\circ$	$\zeta_c = 0^\circ$	$\zeta_c = +2^\circ$	$\beta_{pc} = 0^\circ$	$\beta_{pc} = 5^\circ$
摆振频率 $w \text{ } \Omega$	计 算 值	0.700	0.700	0.698	0.690	0.690	0.690		
	试验结果	0.700	0.700	0.700	0.700	0.700	0.700	1.464	1.456
摆振阻尼比 η	计 算 值	-0.0030	-0.0043	-0.0054	-0.0063	-0.0063	-0.0062		
	试验结果	-0.0027	0.0040	0.0045	-0.0045	-0.0045	-0.0045	-0.0031	-0.0096

从表中可以看出, 试验结果与前面理论分析的结构参数对稳定性的影响规律是完全吻合的。从表中还可以看出试用模型桨叶稳定性计算值与试验结果的比较是令人满意的, 这也进一步说明理论分析方法是可行的, 结果是正确的。因此, 本文所提供的理论分析方法和所得的结果可用于先进旋翼系统的气弹稳定性分析, 并可用于指导旋翼设计中的参数选择。

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FULL- LENGTH PAPERS

NUMERICAL COMPUTATION OF 3D TURBULENT FLOW IN A TRANSONIC SINGLE ROTOR COMPRESSOR

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ABSTRACT The 3D turbulent flow in a transonic single rotor is computed numerically by use of an explicit 3D turbulent time- marching Navier- Stokes solver in finite volume form with the option of applying Baldwin- Lomax turbulent model. This rotor served as the blind test case organized by the ASME Turbomachinery Committee. Its purpose was to provide a forum for a careful assessment of the ability of the various turbomachinery CFD codes available to predict the flow field in modern blading. The computational results by the authors' method were compared with the experiment and presented in the present paper. It is demonstrated that the present method can be used for checking the aerodynamical design.

Key words Rotors Transonic compressors Numerical computation Tree-dimensional flow

EXPERIMENTAL RESEARCH ON NOISE REDUCTION OF A COUNTER-ROTATING VENTILATOR

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ABSTRACT A counter-rotating ventilator with high efficiency has been made, but its noise level is too high. This paper analyzes the noise generation and noise frequency characteristics. A lot of noise experimental researches on noise suppression have been carried out successfully by the aid of acoustic liner or appropriate increase of the duct length. As a result, overall sound pressure level is reduced from 101dB (A) to 88dB (A).

Key words Axial ventilator Frequency characteristic Noise control

STUDY ON AEROELASTIC STABILITY OF ROTOR BLADE IN HOVER

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ABSTRACT The aeroelastic stability of coupled flap- lag- torsion dynamics of rotor blades in hover is studied in this paper. According to Hamilton principle, nonlinear partial differential equations of motion for elastic flap bending and torsion of the blade are derived. The spatial dependence of the partial differential equations is discretized by use of the Galerkin finite element method. The effects of some structural parameters are taken into ac-

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