

轴流压气机三维气动稳定性 及主动控制模型

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【摘要】 给出了考虑压气机径向扰动对失速影响的轴流压气机三维气动稳定性模型。计算结果表明压气机的失速特性与压气机基元叶栅特性密切相关。在轴流压气机三维气动稳定性模型的基础上,给出了考虑轴流压气机三维效应的主动控制模型及其传递函数。并在阶跃输入情况下,对轴流压气机二维和三维主动控制模型的开环系统在频域进行了响应分析。

主题词: 轴流式压气机 非定常流动 旋转失速 控制

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1 前 言

近年来人们一方面致力于发展更为精确的轴流压气机气动稳定性模型,力图从模型中反映更多的流动本质,更为精确地揭示压气机气动失稳的物理本质;另一方面,人们通过各种技术途径,如主动控制技术和被动控制技术,扩大压气机的稳定工作范围。特别是主动控制概念的提出,使得压气机设计时不用留太大的裕度,而是当压气机即将进入不稳定状态时采用一定的技术措施扩大压气机的稳定工作范围。这两方面问题的解决都必须建立在较为精确、能反映更多压气机流动特征的气动稳定性模型的基础上。本文提出了描述轴向速度扰动的轴流压气机三维气动稳定性及其主动控制模型,并进行了数值分析和讨论。

2 轴流压气机三维气动稳定性模型、计算结果与分析

压气机由上游管道、压气机及下游管道组成;三个方向的坐标分别定义为 ξ, θ 和 η, γ 为子午流线倾角。采用如下基本假设: (1) 压气机叶片排用一个激盘代替; (2) 压气机进口管道流动均匀,为位势流动;压气机出口管道流动有旋; (3) 考虑子午流线倾角 γ 及径向扰动 δw ; (4) 准定常压气机特性,考虑压气机的压升特性随流量、周向和展向位置的变化; (5) 不可压缩流动,周向和展向扰动波数相同。

轴流压气机三维气动稳定性模型可以表示为^[1]:

$$[(2/n) + \mu](\partial \partial \eta) + R(\partial \partial \theta) + S(\partial \partial \eta)] \delta \varphi = T \delta \varphi \quad (1)$$

式中

$$R = \lambda - \frac{\varphi_{\text{sec}^2 \alpha_2} \frac{\partial \alpha_2}{\partial \alpha}}{n \cos \gamma \frac{\partial \alpha}{\partial \alpha}} + \frac{\frac{\partial \alpha_2}{\partial \alpha_1} \frac{\varphi_{\sin \alpha_1 \cos \alpha}}{n \cos \gamma \cos^2 \alpha}}{\cos \gamma \cos^2 \alpha} - \frac{\frac{\partial \alpha}{\partial \alpha_1} \frac{\sin \alpha_1 \cos \alpha \sin^2 \gamma}{n \cos \gamma \cos^2 \alpha}}{\cos \gamma \cos^2 \alpha} + \frac{\frac{\varphi_{\sin \gamma}}{n \cos^2 \alpha}}{\cos^2 \alpha} - \frac{\frac{\tan \alpha \sin^2 \gamma}{n \cos \gamma}}{\cos \gamma} - \frac{\frac{\partial \Psi^s}{\partial \alpha_1} \frac{\cos^2 \alpha_1 \cos \gamma}{\varphi_{\eta}}}{\varphi_{\eta}}$$

$$S = \lambda - \frac{\mathcal{Q} \sin \gamma \cos \gamma}{|n| \cos^2 \alpha} + \frac{\partial \Psi^{ts}}{\partial \alpha} \frac{\sin \alpha \cos \alpha \sin \gamma \cos \gamma}{\varphi |n|}$$

$$T = \frac{\partial \Psi^{ts}}{\partial \varphi} - \frac{\partial \alpha}{\partial \varphi} \left(\frac{\mathcal{Q} \cos^2 \alpha}{|n| \cos^2 \alpha} - \frac{\partial \alpha}{\partial \alpha} \frac{\sin \alpha \cos \alpha \sin \gamma}{|n| \cos^2 \alpha} \right) - \frac{\partial \Psi^{ts}}{\partial \alpha} \frac{\sin \alpha \cos \alpha}{\varphi}$$

$$- \frac{\sin \alpha \cos \alpha \sin^2 \gamma}{\varphi} + \frac{\partial \Psi^{ts}}{\partial \gamma} \sin \gamma \cos \gamma$$

方程(1)为描述轴流压气机三维气动稳定性的控制方程。其中, α 为绝对气流角, γ 为子午流线与轴线的夹角, 脚标 1 表示压气机进口, 2 表示压气机出口参数。 Ψ^{ts} 是压气机总—静升压系数, λ 为压气机转子惯性参数, μ 为整个压气机的惯性参数。

图 1 表明了节流流量系数为 0.47 时压气机叶根、中径、叶尖 3 个流面轴向速度扰动沿周向随时间的变化(图中—叶根流面, --- 叶中径流面, - · - 叶尖流面)。图(a)为初始扰动

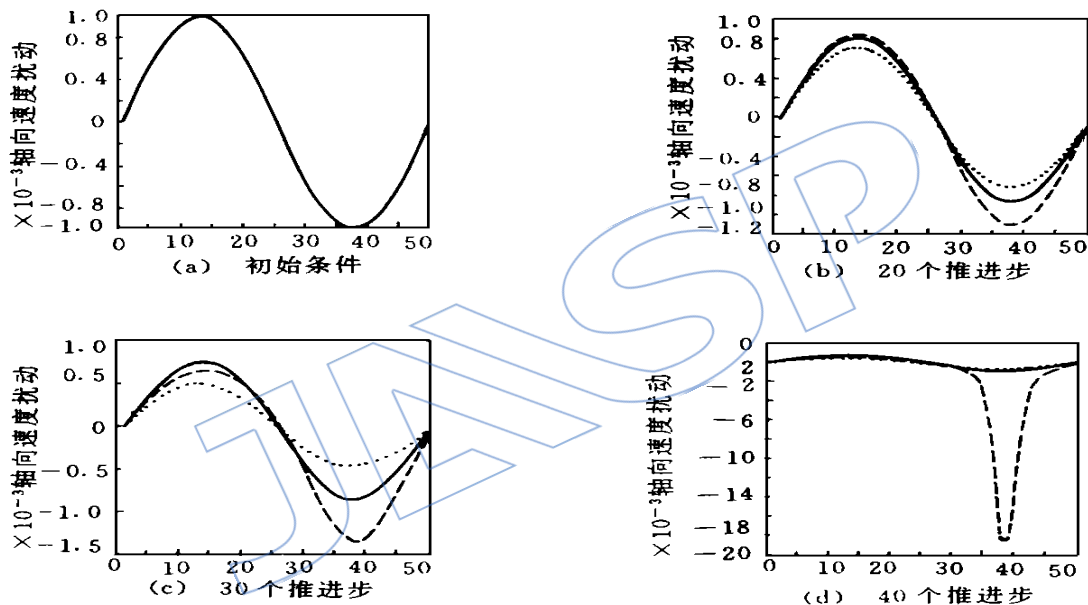


图 1 $\mathcal{Q}_0 = 0.47$ 时轴向速度扰动的变化

值, 图(b)–(d)为轴向速度扰动随时间的变化。从图中可以看出, 叶根处的轴向速度扰动随时间变化不大, 中径处的扰动不但没有扩展, 还有衰减的趋势。叶尖流面的扰动发展随时间逐渐增大, 而且开始时比较缓慢, 当发展到一定时间, 轴向速度扰动扩展速度加快。因此, 当节流流量为 0.47 时, 压气机进入不稳定工作状态。扰动的发展沿叶高表现出不同的敏感性。叶根、中径对扰动的发展不敏感, 叶尖扰动的发展决定了压气机的失速特性。因为从叶根到叶尖, 各基元叶片具有不同的压气机压升与流量和压升与攻角的特性, 叶根处负荷较低, 压升特性较平缓, 而叶尖负荷较大, 对流量的敏感性最强, 特性线较陡, 所以叶尖处最先出现旋转

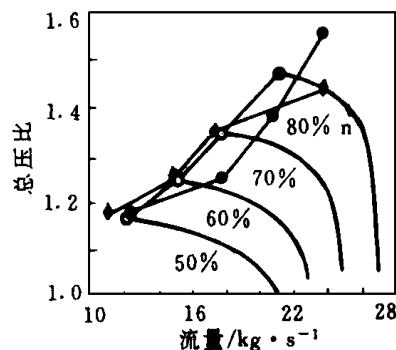


图 2 失速边界试验值与计算值对比

失速。这说明了叶片负荷或环量沿叶高的分布对压气机气动稳定性有重要的影响。

根据文献[2]的二维气动稳定性模型与文献[1]的三维气动稳定性模型,对文献[3]提供的轴流压气机单转子进行了失速边界的预测。从图2可以看出,在3个转速范围内预测值与试验值的相对误差较小,二维与三维模型的预测值与试验值的趋势吻合较好,但是,三维模型的计算值与试验值更接近,二维模型预测的结果误差大一些。

3 轴流压气机主动控制模型特征方程及其传递函数

基于轴流压气机三维气动稳定性模型的主动控制模型的特征方程^[1]可以表示为:

$$(A - s_n B) \delta \bar{x} = 0 \quad (2)$$

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 \\ a_{31} & 0 & a_{33} & a_{34} & 0 \\ 0 & 0 & 0 & 0 & a_{45} \\ a_{51} & 0 & 0 & a_{54} & a_{55} \end{bmatrix}, \quad B = \begin{bmatrix} 1 & 0 & 0 & 0 & X_3 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad \delta \bar{x} = \begin{bmatrix} \delta \varphi \\ \delta L_s \\ \delta L_r \\ \delta \beta \\ (\partial/\partial \eta) \delta \beta \end{bmatrix}$$

式中, $a_{11} = (1/\zeta) X_0'$, $a_{12} = -1/\zeta$, $a_{13} = -1/\zeta$, $a_{14} = (1/\zeta) (\partial \varphi_{isen}/\partial \beta)$, $a_{21} = (1/\bar{\tau}) X_0'$, $a_{22} = -1/\bar{\tau}$, $a_{31} = (1/\bar{\tau}) X_r'$, $a_{33} = -(in + 1/\bar{\tau})$, $a_{34} = (1/\bar{\tau}) (\partial L_r/\partial \beta)$, $a_{45} = 1$, $a_{51} = Ze^{-|\eta|\xi_{igv}} \omega^2$, $a_{54} = X_0$, $a_{55} = -2\zeta\omega$ 。方程(2)为压气机三维气动稳定性的主动控制特征方程。在实施主动控制过程中,特征向量 $\delta \bar{x}$ 起关键作用,其中根据感受的压气机前方轴向速度扰动而施加一定规律的控制导叶安装角扰动 $\delta \beta$ 是该控制模型的控制因素之一。对于每一空间谐波扰动存在5个特征值,判断每一特征值的实部是否为负,若实部为负则压气机稳定,反之则不稳定。从另一方面出发,主动控制的特征方程,考虑了扰动的三维性和压气机的非定常损失。从(2)中A的元素可以看出,与不考虑压气机进出口气流角非均匀分布的主动控制模型^[4]相比,(2)式更能揭示压气机稳定性的客观规律,能更精确地运用于压气机的主动控制中。

在方程(2)的基础上,给出轴流压气机三维气动稳定性模型的传递函数表达式^[1]

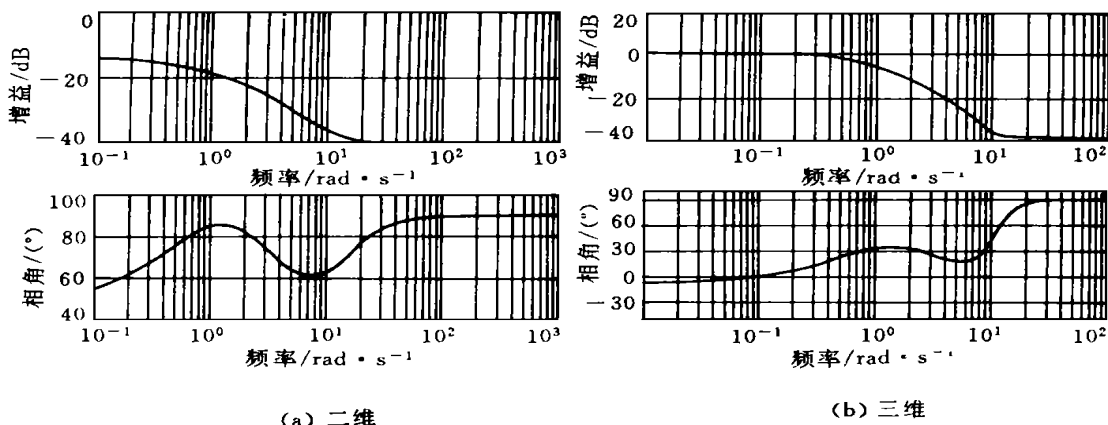
$$\frac{\delta \varphi}{\delta \beta} = in \varphi_{igv} + \frac{\frac{\partial \varphi_{isen}}{\partial \beta} - \frac{\partial L_r / \partial \beta}{1 + \bar{\tau}(s + in)} - in \varphi_{igv} \left(\frac{1}{|n|} + \frac{\mu_{igv}}{2} \right) s}{\zeta - X_0' + \frac{X_r'}{1 + \bar{\tau}} + \frac{X}{1 + \bar{\tau}(s + in)}} \quad (3)$$

由于在可控导叶前距离 ξ_0 处传感器感受的轴向扰动与可控导叶前缘的轴向扰动不相同,压气机进口管道的流动为无旋,所以扰动往前呈衰减趋势,因此,可控导叶前缘扰动与传感器感受的轴向扰动之间的关系为 $\delta \varphi = \delta \varphi_{\xi_0} e^{|\eta|\xi_0}$, 将之代入(3)得:

$$\delta \varphi_{\xi_0} / \delta \beta = (\delta \varphi / \delta \beta) e^{-|\eta|\xi_0} \quad (4)$$

式(4)为考虑压气机进出口气流角脉动和非定常损失的三维主动控制模型的传递函数。

图3表示了 $\varphi = 0.47$ 时,二维和三维开环压气机响应分析。其中图3(b)的幅频特性幅值为零对应的频率值在 10^{-1} 和 10^0 之间,而相频特性的相位 -180 度对应的频率值在左边无穷远,因此,压气机是不稳定的。图3(a)表示的3D开环压气机响应的幅频和相频特性却过渡较为平缓。从图3(b)幅频特性可以看出,低频特性和高频特性分布较为平坦,说明压气机的低频特性和高频特性好。对于中频特性,三维开环压气机响应的幅频特性和相频特性有较大的转折点。这说明基于压气机三维气动稳定性的开环系统的稳定性比二维模型所预测的压气机稳定

图 3 $Q=0.47$ 压气机开环系统相步和幅频特性

性更差一些。

4 结 论

(1) 扰动沿叶高表现出不同的敏感性, 叶根、中径对扰动的发展不太敏感, 叶尖区扰动的发展决定了压气机的失速特性。(2) 对真实轴流压气机单转子的失速边界进行了预测, 结果表明三维气动稳定性模型能给出比二维模型更为理想的结果, 预测值与试验值更为吻合。(3) 在单位阶跃激励下, 二维和三维压气机开环系统的频域响应结果说明, 基于三维气动稳定性模型的开环系统与二维开环系统相比, 具有更好的动态特性。

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cell in the mean flow with an ensemble averaging technique and instantaneous flow measurement with hot-wire and flow visualisation technique. The mean flow field measurement indicates that the stall cell appears mainly in the front of the rotor, while the flow field in the tip region of the rotor features essentially the cross blockage of the tip clearance flow. The instantaneous flow measurement shows that the kinetics of the stall cell can be described by using two fundamental concepts of dipole.

Key Words Fans Rotating stall Dipoles

A 3D AERODYNAMIC STABILITY ACTIVE CONTROL MODEL FOR AXIAL FLOW COMPRESSOR

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ABSTRACT

A new three-dimensional aerodynamic stability model for an axial flow compressor to study the effects of radial disturbance on the rotating stall is presented. The calculated results show that the stalling characteristics of the compressor is closely related with its cascade characteristics including total pressure rise versus the flow rate and inlet flow angle. Based on the 3D aerodynamic stability model, the related active control technique and the open-loop transfer function have been provided, in which the three dimensional flow effects are involved. The response analyses of the open loop systems for the 3D stability active control model with step impulse were conducted in different flow ranges.

Key Words Axial flow compressors Non-steady flow Rotating stall

INITIAL DISTURBANCE FORMS OF ROTATING STALL IN AXIAL FLOW COMPRESSOR

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ABSTRACT

The process of rotating stall developing in a single-stage axial-flow compressor was investigated experimentally. By means of eight dynamic pressure transducers equally located circumferentially in the inlet section of the compressor, the dynamic pressure signals of the rotating stall developing process were measured. The data have been analyzed with the SFC (Spatial Fourier Coefficient) method and the variation of the circumferential phase of initial disturbance signals with time have been obtained. So, it was found that there are two initial disturbance forms of rotating stall, rotating waves and small stall cells. In order to study the factors influencing the initial disturbance forms, the compressor was tested under 55 conditions combining four types of compressor configuration, two solidities of rotor, three rotation speeds, different IGV outlet angles. According to the experimental results, the initial disturbance form of single-stage compressor without IGV was rotating waves. For the isolated rotor without IGV, the forms were rotating waves at high rotor speeds, and small stall cells at low rotor speed. For the compressor with IGV, negative prewhirl angles of IGV enhanced the rotating waves, and increased the pretelling time of stall. Decreasing the solidity of rotor almost did not affect the form of stall initial disturbance.

Key Words Rotating stall Initial conditions Disturbances