

轴流风扇旋转失速时的流场测量与分析

南京航空航天大学 葛 宁**

【摘要】 针对渐近型旋转失速在一轴流风扇上进行了一些测量工作,包括失速时的激光平均流场测量和热丝动态测量两大类。激光平均流场研究表明失速团主要活动在风扇转子前缘,而转子叶片通道中的流场则主要表现为叶尖间隙流的横向堵塞流动。热丝的动态流场分析表明失速团的运动可以用偶极子流动概念来描述。

主题词: 风扇 旋转失速 偶极子

分类号: V 231.3

1 前言

压气机有两种方式进入失速状态:一是失速团从占据部分叶高开始而后逐步向整个叶高发展的渐近型失速;二是失速团一开始就占据着整个叶高,并随着压气机反压的进一步提高其体积逐步扩大但并不堵塞整个通道的突变型失速。前者多半发生在轮毂比小的压气机中,失速时气流速度波动较小^[1];而后者则多半出现在轮毂比大的压气机中,失速时气流速度变化较大并伴有回流产生^[2-4],而且在失速团边界还出现脱落的旋涡^[5,6]。本文针对渐近型失速时的流场在一轴流风扇上做了一些实验和研究。实验所用的风扇为一小型轴流风扇,轮毂比为0.6,不带静子,转子有9个叶片。在设计转速为3000 r/min,流量系数 $\delta=0.66$ 时,测得的总压系数 $\eta=0.173$ 。叶片的几何参数为:叶片根、中、尖处半径分别为:89.4 mm, 119.2 mm, 149.0;根、中尖处的稠度分别为:1.256, 0.94, 0.76;根、中、尖处的安装角分别为:48.96°, 32.81°, 24.37°;根、中、尖处的弯曲角分别为:38.81°, 18.06°, 10.39°。

实验是在风扇转速为1530 r/min 旋转失速刚开始时($\delta=0.49$)进行的。旋转失速的特征参数是由二根热丝的方法来确定。信号分析和计算表明风扇在旋转失速刚开始时有一个失速团,其环向宽度为220度,旋转速度在绝对坐标系下为转子的63%。

2 失速时的热线信号特征

一根热丝被放置在风扇转子前缘叶尖附近。热丝平行于流场的轴向方向,垂直于转子的径向方向。若流场的径向速度忽略不计,则该热丝所测量的速度为流体的切向速度。

图1为风扇刚进入旋转失速时($\delta=0.49$)热丝所测到的切向速度时间记录。切向速度信号明显地表现出周期的特点。进一步的观察还可以发现每个周期信号大体上由14个幅值较小的振荡信号组成。实际上这些振荡信号是叶片通过时产生的,其中前9个振荡信号所对应的流体切向速度较大,故为失速团通过时的信号,而后5个所对应的流体切向速度较低,故为正常流

体通过时的信号。失速团中第一个振荡信号的左支对应着失速团的前缘,故该信号表示失速团的来到。此外,从信号的幅值来看,失速团前缘具有最大的切向速度变化。在随后的 7 次振荡过程中流体切向速度下降到某一水平并在最后的一个信号振荡(第 9 个)过程中降到最低点。这最后一个

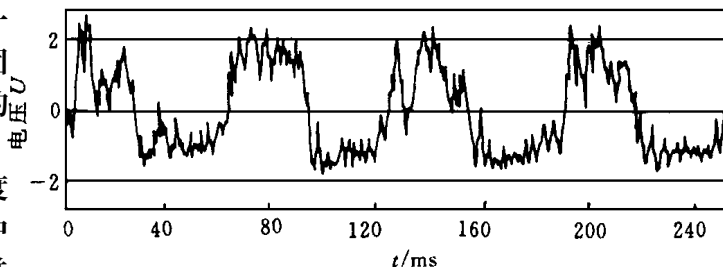


图 1 旋转失速时转子前缘流体切向速度热丝信号

振荡信号的右支对应着失速团的后缘,显然其切向速度要比前缘小得多。进入正常流动状态之后,流体的切向速度随着叶片的通过逐渐增大,在经过 5 次振荡之后流体又重新进入失速状态。

流体切向速度的振荡是由于叶片通道中叶盆和叶背对流体起不同的作用引起的。失速团中 9 个振荡信号分别对应着 10 个叶片组成的 9 个通道。而该风扇仅有 9 个叶片,所以第 10 个叶片也就是第一个叶片。这个结果意味着如果流体是从某叶片的叶背上开始进入失速,那么失速流体在绝对坐标系下旋转大约 220 度,同时风扇转子转过一圈后从同一叶片的叶盆下面进入正常流区域。如果单独观察该叶片在失速时的气流流动状态,那么失速的动态过程可以用一个偶极子的流动来描述,其中叶背是泉,叶盆是汇。

上述结果是通过实时信号的观察而得出的。旋转失速周期内所对应的叶片通道通过数(N_1)和失速团内所对应的叶片通道通过数(N_2)都可以通过测量到的旋转失速特征参数准确地计算出来,具体的计算公式如下:

$$N_1 = N / \gamma, \quad N_2 = \theta \gamma / 360 = \theta \gamma / 360$$

这里, N 为风扇的叶片数, θ 为失速团的周向幅值, γ 为失速团与转子的旋转速度之比。将测到的旋转失速特征参数代入上式即可得到 $N_1 = 14.28$, $N_2 = 8.73$ 。其中 $N_2 = 8.73$ 与实时信号所得到的通道数(9 个)相符,说明叶片在旋转失速时偶极子的流动现象自始至终是存在的。

3 激光测量与流场分析

所用的激光测速仪是一维的,通过转换激光波束平面,该测量系统可以获得速度的二个分量:轴向速度和切向速度。多普勒信号由 BSA DANTEC 电子系统来处理,并在计算机上进行数据分析。失速团前缘的热丝信号(图 1)被用作为激光测速的同步信号。但由于失速时流场的不稳定性(尽管风扇转速是不变的),所选用的同步信号并不是一个严格的周期信号,所以不能应用常规的外时钟锁相技术进行相对坐标系下的定点测量。实际测量中所采用的方法是利用 BSA 电子测量系统的内部时钟频率作为采样的触发信号。此时 BSA 不仅可以记录同步信号到达的时间,而且还对气流速度流场进行一种随机的测量,也就是说只要有一颗粒子通过激光测量控制体并被 BSA 电子后处理系统验证是合格的,BSA 就在它的硬盘中记录下该粒子的当地速度以及通过测量点的时间。在测量完毕之后,我们采用了一种准锁相的数据处理方法:即按同步信号将每一个旋转失速的周期 T 在时间上均分为 n 等份,即 $n \Delta t_i = T, i = 1, \dots, n$, 其中 Δt_i 表示第 i 个时间等份,并在对应的时间等份内(即相同 i 值)将所有不同旋转失速周期内的速度值都加起来取一平均值。因此,所分的 n 等份越多(即 Δt_i 越小),流场的空间分辨率越

高,这种数据处理方法就越接近严格的锁相技术。但由于所获得的测量参数总数有限,故增高 n 值就会降低速度平均值的重复性。所以必须在两者之间取一个折中的 n 值。显然,这种折中计算得到的速度值并不代表空间某点的速度平均值,但该处理方法允许我们观察一些关于失速团的宏观流动现象。

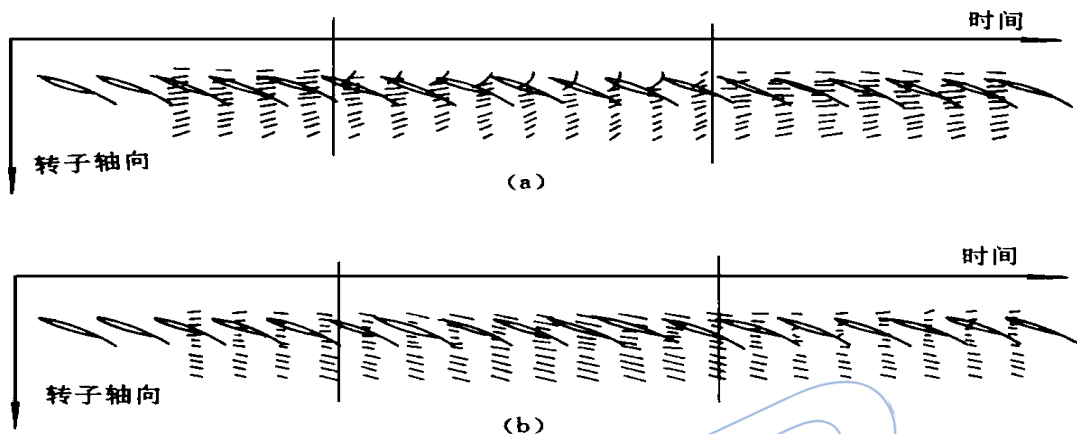


图 2 旋转失速平均绝对速度场(a)平均相对速度场(b)

图 2(a)和(b)分别为风扇在旋转失速刚开始($\delta=0.49$),半径 $r=0.98$ (相对于叶尖半径), $n=20$ 时的绝对和相对速度场(相对转子)。速度场的横坐标轴为时间,纵坐标轴为转子的轴向方向。由于速度场是将空间局部的流场进行时间平均获得的,故图 2(a)和(b)所表示的叶片与流场相互关系并不代表某一时刻的真实关系。转子前缘绝对速度场(图 2(a))很明显地表现出两个不同性质的流场:两线之间轴向速度较大的被称作为正常流区域的流场和两线之外绝对切向速度很大的失速团流场。但叶栅通道中的流场并不存在这样的差别,而有一个共同的特点即在半弦长附近的整个叶栅通道内的流体相对速度比转子进出口处的流体相对速度要小得多(图 2(b)),而且流动方向与叶片运动方向恰好相反。这些流动特点表明这股低相对速度流是叶尖间隙流。它在叶片通道内的横向流动有堵塞通道的趋势。如果把每个通道内的这种堵塞连起来看,它们就可能在风扇转子壁面附近形成一个随转子一起运动的堵塞环,而该环的存在将会导致风扇喘振的发作而不是旋转失速的出现。但实际上正好相反,叶尖间隙流所形成的堵塞在空间上存在着周期性的波动,正是这种堵塞的周期性变化导致旋转失速的存在。

4 失速团运动模式的讨论

针对流体在叶片通道内形成的堵塞,目前有 3 种理论:一是 Emmons^[7]的叶背失速理论(Blade Stall),二是 Greitzer^[8]的机匣壁面附面层分离理论(Wall Stall),三是 Freeman^[9]的叶尖间隙流涡破碎理论。因第 3 个堵塞理论无法得到验证,故不在此讨论。根据 Greitzer^[8]的实验结果,稠度 $\sigma \leq 1$ 为 Blade Stall 型, $\sigma \geq 2$ 为 Wall Stall 型。因该风扇叶尖处的稠度仅为 0.76,此值比产生 Blade Stall 失速类型的临界稠度 $\sigma = 1$ 还要小,所以 Wall Stall 在该风扇中不具备形成的条件,或者说该风扇叶尖处所形成的堵塞与机匣壁面附面层的分离无关。Emmons 的 Blade Stall 理论虽然说明了叶片通道内流体堵塞的原因以及失速团传播的机理,但该理论仅适用于失速团覆盖少数几个叶片通道,或者说失速团的周向幅值同其所在位置的圆周长相比

小得多的失速类型(也称之为局部失速^[10])。而本实验所用的风扇失速时的失速团环向宽度为 220 度, 占据近 61% 的周向长度, 显然该风扇的失速不属于局部失速。此外, 该风扇在叶尖处的安装角(与叶片额线夹角)较小, 这将会增大叶尖间隙流的倒流量, 因而更容易在通道内形成堵塞。如果叶尖间隙流所形成的堵塞不在空间上产生周期性的波动, 将不会形成旋转失速。显然叶尖间隙流本身是不会有这样的波动, 故在流场中一定还存在着一个周期性的扰动波。

从热丝所测到的流体切向速度可知(图 1), 失速团前缘的流体切向速度变化最大。如果考虑到失速团中流体的轴向速度很小(或者几乎等于零), 那么该变化意味着失速团前缘的流体攻角发生了突变, 因而流体不再进入风扇而开始偏转, 并随着风扇一起旋转从而导致失速的产生。攻角的突变可能同叶片通道内的旋涡有关。流体的旋涡运动堵塞整个叶片通道从而使前方来流沿叶背方向产生较大的偏转。图 3 是一张用流场可视化技术获得的风扇旋转失速时的流体图像, 该图像清楚地表明在叶片通道内存在着旋涡运动。

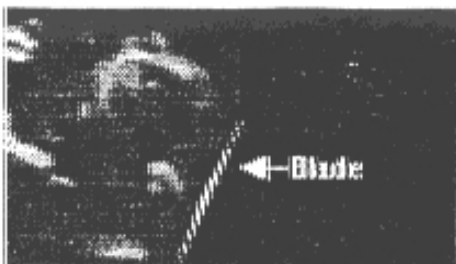


图 3 风扇失速时叶片通道涡的图像

结论 结果分析表明旋转失速的产生可以用 Emmons^[7]的极限攻角理论来解释, 但失速团沿风扇周向运动的方式同 Emmons 的理论有所不同。该风扇失速团的运动机理在于流体环绕叶片的偶极子流动, 即当来流攻角突变而导致流体沿叶背方向偏转时, 流体离开叶背相当于泉的流动, 而偏转后的流体在风扇转子一圈后从同一叶片的叶盆下进入转子则相当于汇的流动, 从而构成偶极子的运动模式。

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FULL - LENGTH PAPERS

A STUDY ON MECHANISM OF ACOUSTIC CONTROL OVER AIRFOIL FLOW IN UNIFORM INCOMING FLOW

Zhong Fangyuan, Dong Guoping, Ju Hongbin

(Dept. of power, Shanghai Jiaotong University, Shanghai 200030)

ABSTRACT An experimental study on the acoustic control of separated flow on a 2-dimensional airfoil at low speed ($Re = 3-6 \times 10^5$) and high angle of attack was completed at the Turbine Aero-Acoustics Laboratory, SJTU. Based on the comparison of test results with or without the acoustic control in uniform incoming flow, the benefits of the acoustic control (improvement of lift and drag coefficients), the effects of the parameters of exciting sound (sound pressure level SPL and frequency f_s) and the variation of flow parameters in the boundary layer on the suction side of airfoil (mean flow velocity, turbulence and the spectrum of fluctuating velocity) have been investigated, and some valuable conclusions have been obtained for exploring the mechanism and exploiting the acoustic control. Two threshold values of SPL for the exciting sound have been defined. There is only one optimum frequency, corresponding to the fundamental frequency of acoustic cross-resonance of the testing tube, at which the SPL of exciting sound and the enhancement of lift coefficient will approach maximum value simultaneously. It is evident that the optimum frequency of exciting sound depends not only on the cross-resonance of the testing tube, but also on the dimension of Large Scale Organized Structure Vorticity (LSOSV) induced by the exciting sound. Finally, a tentative idea on the non-linear analysis of sound-turbulence interaction in the separated boundary layer has been proposed.

Key Words Acoustics Flow separation Control problems

AN EXPERIMENTAL INVESTIGATION ON FLUTTER OF A HELICOPTER BLADE MODEL

Xia Ping and Xu Guqi

(1st Dept. Nanjing University of Aeronautics and Astronautics, Nanjing 210016)

ABSTRACT An experimental technique and method for flutter research of helicopter blade model are proposed. In the result of a series of experiments the relationships of blade flutter margin with rotor rotational speed, effective CG position of blade in chord and torsional stiffness of blade have been obtained. Some important conclusions have been reached.

Key Words Propeller blades Flutter tests Model tests

FLOW MEASUREMENTS AND ANALYSIS OF ROTATING STALL IN AN AXIAL FLOW FAN

Ge Ning

(2nd Dept. Nanjing University of Aeronautics and Astronautics, Nanjing 210016)

ABSTRACT The flow measurements of part-span stall were accomplished in an axial flow fan test. The measurements include laser anemometer measurement of the stall

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

Cao Renjing

(Institute of Energy and Environmental Science, Shantou University, Shantou 515063)

Zhou Sheng

(4th Dept Beijing University of Aeronautics and Astronautics, Beijing 100083)

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

Li Jun, Xu Gang, Zhu Junqiang, Liu Zhiwei

(7th Dept Northwestern Polytechnical University, Xi'an 710072)

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