

风扇/压气机转子叶片定常力 气动噪声数值研究

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【摘要】 从考虑了固体边界影响和均匀介质影响后的广义 Lighthill 方程出发,采用管道声学模型导出了风扇/压气机转子叶片定常力气动噪声传播方程,并通过涡喷 11 压气机单转子声学实验进行了数值模拟。结果表明,叶片定常力产生的气动噪声对风扇/压气机总噪声级有重要作用。

关键词: 风扇/压气机 转子叶片 定常力 气动噪声 数值模拟

1 转子叶片定常力的气动噪声传播方程

现代民航客机的涡扇发动机其主要噪声源是由风扇/压气机的气动噪声所产生^[1]。从现有的文献考察,风扇/压气机气动噪声历来被认为主要是由激波离散噪声、转子/静子干涉离散噪声和宽频噪声三部分组成^[2,3],而对于风扇/压气机转子叶片定常力气动噪声未予以充分重视。

本文从考虑了固体边界影响和均匀介质影响后的广义 Lighthill 方程出发,采用管道声学模型推导了风扇/压气机转子叶片定常力气动噪声传播方程,进而分析了叶片定常力气动噪声的频率特性和传播特性,并通过 WP11 压气机单转子声学实验进行了数值模拟。

文献[4]导出了考虑固体边界影响和均匀运动介质影响后的广义 Lighthill 方程解的表达式。对于实际风扇/压气机转子,其噪声主要是来自转子叶片与气流相互作用而产生的力声源,所以该表达式可简化,再利用特征函数法求解格林函数 $G(\bar{y}, \bar{x}, t)$, 得到方程:

$$\rho'(\vec{x}, t) = \frac{1}{4\pi C_0^2} \sum_{m=-\infty}^{\infty} \sum_{n=1}^{\infty} \frac{J_m(K_{m,n}r) \cdot e^{im\varphi}}{\Gamma_{m,n}} \int_{-\infty}^{\infty} \frac{e^{-i(\gamma_{n,m}^{\pm} x_1 + \omega)}}{K_{n,m}} \cdot \int J_m(K_{m,n}r') e^{i(\gamma_{n,m}^{\pm} x_1' - m\varphi')} \\ \times \int_T \left[\frac{m}{r} \tilde{f}_D - \gamma_{n,m}^{\pm} \tilde{f}_T \right] \cdot e^{i(\omega - m\Omega)\tau} \cdot d\tau' dr' d\varphi' d\omega \quad (1)$$

上式是只考虑偶极子声源项的风扇/压气机在直圆管内声传播的表达式,其中正号表示前传,负号表示后传。当风扇/压气机转子以 Ω 角速度旋转,则有上游 V 个静子叶片尾迹所引起转子叶片非定常力可以展开为

$$\tilde{f}_\alpha(\tau) = \sum_{P=-\infty}^{\infty} F_{PE}^\alpha e^{-iPV\Omega\tau} \quad (\alpha = T, D)$$

由关系式(1),上游 V 个静子叶片尾迹与下游 B 个转子叶片干涉。由转子叶片发生的干涉噪声传播方程为:

$$\begin{aligned} \rho'(\vec{x}, t) = & \frac{B}{2C_0^2} \sum_{p=-\infty}^{\infty} \sum_{s=-\infty}^{\infty} \sum_{n=1}^{\infty} \frac{J_{SB-PV}(K_{SB-PV, nr})}{\Gamma_{SB-PV, n} K_{n, SB-PV}} \cdot e^{i[(SB-PV)\Omega - \gamma_{n, SB-PV}^{\pm} x_1]} \\ & \times \int e^{i\gamma_{n, SB-PV}^{\pm} y_1} \cdot J_{SB-PV}(K_{SB-PV, nr}) \cdot e^{-i[(SB-PV)\Omega - \gamma_{n, SB-PV}^{\pm} y_1]} \cdot e^{-iSB\Omega} \\ & \times [(SB-PV)F_P^D - r\gamma_{n, SB-PV}^{\pm} F_P^T] \cdot dr d\Phi \end{aligned} \quad (2)$$

假设风扇/压气机进气来流完全均匀, 转子在恒定转速时, 沿叶片径向各截面上的气动力是定常的($\tilde{f}_D, \tilde{f}_T$ 不随 τ 变化)。

把 $P=0, m=SB$ 代入(2)式, 得到跨音转子定常力气动噪声传播方程:

$$\rho'(\vec{x}, t) = \sum_{s=-\infty}^{\infty} \rho_{SB}(\vec{x}) \cdot e^{-iSB\Omega} \quad (3)$$

$$\text{式中 } \rho_{SB}(\vec{x}) = \frac{B}{2C_0^2} \sum_{n=1}^{\infty} \frac{J_{SB}(K_{SB, nr})}{\Gamma_{SB, n} \cdot K_{n, SB}} \cdot e^{i[SB\Omega - \gamma_{n, SB}^{\pm} x_1]} \cdot [SB D_{n, SB}^{\pm} - \gamma_{n, SB}^{\pm} T_{n, SB}^{\pm}]$$

$$K_{n, SB} = \sqrt{(S^2 B^2 \Omega^2 / C_0^2) - \beta^2 K_{SB, n}^2}, \quad \gamma_{n, SB}^{\pm} = (Ma / \beta^2) (SB \Omega C_0) \pm (K_{n, SB} / \beta^2) \quad (4)$$

$$D_{n, SB}^{\pm} = \int J_{SB}(K_{SB, nr}) e^{i(\gamma_{n, SB}^{\pm} y_1 - SB\Phi)} F_0^D dr d\Phi, \quad T_{n, SB}^{\pm} = \int J_{SB}(K_{SB, nr}) e^{i(\gamma_{n, SB}^{\pm} y_1 - SB\Phi)} F_0^T dr d\Phi$$

由转子叶片定常力气动噪声传播方程(3)式, 得到声场的频率特性为:

$$f = SB \Omega 2\pi \quad (S = 0, \pm 1, \pm 2, \dots)$$

此频率为叶片通过频率及其谐波。

由方程(3)、(4)知其声场的“截止”条件为:

$$\beta^2 K_{SB, n}^2 > S^2 B^2 \Omega^2 / C_0^2 \quad (5)$$

对应 $n=1$ 时的最小特征根满足: $K_{SB, 1} > SB / r_d$, 代入(5): $1 - Ma^2 > r_d^2 \Omega^2 / C_0^2 = Ma^2$ 。所以, 满足条件 $Ma^2 = Ma^2 + Ma^2 < 1$ 时, 由叶片定常力产生的气动噪声将不向外传播。而且当叶尖相对马赫数超过 1 时, 由叶片定常力产生的声音将分别沿上下游传播。在此情况下, 就需要分析叶片定常力产生的声音与其他声源, 如激波噪声、转子/静子干涉噪声的相对关系。

2 实验与数值计算

涡喷 11 压气机单转子声学实验在北航单双级跨音压气机试验台上进行^[5]。测试选用 4 个 CH13 电容传声器, 传声器沿轴向分布, 并安装在机匣内同一侧面的同一条直线上。WP11 压气机转子在 $N=12000\text{rpm}$ 稳定运行时的状态, 其叶尖相对马赫数 $Ma_w = 0.6981 \sim 0.7047$, 气动参数变化与总声压级读数值列于表 1 前 5 行。WP11 压气机转子在 $N=20500\text{rpm}$ 稳定运行时测量, 其叶尖来流相对马赫数 $Ma_w = 1.1804 \sim 1.2144$, 气动参数变化与声压级读数值列于表 1 后 5 行。根据实验得到的各种气动参数数据, 对跨音转子定常力气动噪声进行编程计算。根据涡喷 11 压气机转子原设计叶片加功量沿径向分布以及实验测得的扭矩来确定叶片定常力。计算结果见表 2。此表是由跨音转子叶片定常力引起的、分布在 BPF 基频处向上、下游传播初始时的声级值。

跨音转子叶尖 Ma_w 在上述范围内时, BPF 基频处有一个传播模态(17, 1), 计算声压级与实验测得的声压级值比较接近。BPF 的二次谐波也有一个传播模态(34, 1), 声压级在 147~157dB 范围内变化。二次谐波有 3 个传播模态(51, 1)、(51, 2)、(51, 3), 声压级在 105~140dB 范围内变化。对于跨音转子在 $N=12000\text{rpm}$ 下运转时, 叶尖 $Ma_w < 1$, 计算知没有传播模态。

表 1 测量的气动参数与总声压级

叶尖 Ma_r	转速 (rpm)	流量 (kg/s)	压比	效率	声压级 SPL (dB)			
					1 [#]	2 [#]	3 [#]	4 [#]
0.7047	12045	7.4126	1.1008	0.4541	144.6	141.9	141.4	138.5
0.7046	12086	7.0046	1.1113	0.4506	147.6	143.4	142.9	139.5
0.7010	12057	6.6681	1.1308	0.4963	146.6	143.9	142.4	139.0
0.6975	12033	6.2670	1.1472	0.5041	147.6	143.4	143.9	139.5
0.6981	12060	6.0752	1.1433	0.4763	148.6	144.4	144.4	141.0
1.2144	20714	12.5790	1.3824	0.6249	157.10	158.9	153.9	155.5
1.1966	20465	12.5540	1.4817	0.7186	157.4	158.7	153.4	154.5
1.1985	20465	12.4082	1.4872	0.7074	157.6	157.9	153.6	154.7
1.1851	20252	12.2834	1.5426	0.7529	157.6	158.1	153.9	154.5
1.1804	20208	11.9704	1.5704	0.7556	159.6	158.4	155.9	156.5

表 2 涡喷 11 压气机转子叶片定常力声场计算值

叶尖 Ma_r	声功率级 SWL (dB)		声压级 SPL (dB)	
	上游	下游	上游	下游
1.2144	160.2	155.63	142.32	135.76
1.1966	161.73	157.80	143.22	137.56
1.1985	161.76	157.79	143.32	137.62
1.1851	162.90	159.46	143.87	138.93
1.1804	163.48	160.28	144.19	139.61

3 结 论

(1) 风扇/压气机转子叶片定常力气动噪声频率离散地分布在叶片通过频率及其谐波处。
(2) 风扇/压气机转子叶片定常力气动噪声存在有“截止”条件。当转子叶片来流相对马赫数小于 1 时,转子叶片与气流作用的定常叶片力产生的声波将被“截止”。
(3) 当风扇/压气机转子来流相对马赫数大于 1 时,转子叶片定常力产生的气动噪声是传播波,对风扇/压气机总噪声级仍具有相当重要的作用,在数值分析中应予以相当的重视。

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NUMERICAL PREDICTION OF STEADY FORCE NOISE ON A COMPRESSOR ROTOR BLADE

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ABSTRACT Sources of compressor noise are usually considered as multiple pure tone noise, interaction noise and broadband noise. In the paper, the noise propagation equation of steady force on the compressor rotor blade is derived. The numerical results are compared with the WP-11 compressor rotor acoustical experiment. The theoretical and experimental investigations indicate that the steady force noise on the compressor rotor blade is an important source of the compressor noise.

A NEW TYPE OF FUEL CONTROL MODEL

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ABSTRACT A new type of fuel control model is developed without the conventional fuel cock and pressure drop valve. It consists of a high-precision electronic block, a micro-computer and an actuator. The actual fuel flow calculated by the micro-computer or checked from the data chart against the parametric signals fed out from the digital-type transducer in relation to the fuel supply is compared with the required fuel flow and the actuator then balances the actual flow with the required by adjusting the pumping flow or return flow according to the amount of deviation and its characteristics if there is any deviation. The fuel of control unit built with the new model features high precision, low weight, compact size and good adaptability, and is especially suitable to the application of digital control project of aircraft and engine. The new type of fuel control model has been testified for about 100 hours on the digital control research test bed for a type of aeroengine.

FAULT-TOLERANT CONTROL OF RECONFIGURING RULE

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ABSTRACT A new method of fault-tolerant control for multiloop SOSI system is suggested. A reconfiguration control rule is applied to the neighbouring loop of any fault sensor for compensating its effect. The suggested method is able not only to maintain the stability of the system but also to keep the controlling quality to be the same as that before the fault happens. This method is suitable for both minimal and non-minimal phase systems. The results of the numerical simulation show that the method is of good compensating function.

"WINDAGE" FOR HIGH GEAR SYSTEMS IN AVIATION

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ABSTRACT The problems about "Windage" and churning for high-speed gear systems in aviation are considered. The domestic and foreign technical projects are introduced. The structural measures for depressing and using "Windage" in high-speed gear systems in aviation are presented.