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飞机螺桨声场的数值模拟方法

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【摘要】 本文给出了预测飞机螺桨在自由空间内幅射的气动声场的一种数值方法。即时域内进行延迟时间积分的一类方法。在该方法中使用片条假设，并考虑厚度声源和负荷声源项作为非紧致声源。计算与实验结果对比表明，该方法和相应软件可作为一种工程手段来使用。

一、前　言

因为螺桨是飞机的主噪声源。无论是从满足 CAAR36 及 FAR36 等国内外有关航空声学的适航性条例，还是从舱内声学环境满足乘客舒适性角度出发，都必须在飞机方案设计阶段就考虑到螺桨的声学性能。此外，螺桨所幅射的噪声也可能成为飞机构件声疲劳的元凶，所以从安全性和结构完整性角度也应予以关注。为满足我国国民经济对于交通运输进一步发展的迫切需求，近年来航空工业对于以螺桨为推进装置的民用飞机发展相当重视。因此，对螺桨所幅射噪声如何进行预测就成为民用飞机行业和螺桨行业普遍关心的问题。螺桨噪声的预测工作可追溯到本世纪四十年代以前，但基本上属于经验性工程方法，普遍应用时将具有明显局限性。1952 年 Lighthill 建立了气动声学基本方程组之后，气动声学已有长足进展。随着数字式电子计算机和计算物理的迅速发展，目前各发达国家广泛使用数值模拟方法来预测螺桨所幅射的声场。由于国内前几年尚未掌握螺桨噪声的预测方法，笔者在调查和分析[1、2]的基础上，独立发展了一种预测螺桨噪声的数值模拟方法[3]。这是一类在时域中通过延迟时间积分以获取在流场中由于固体运动边界而发生的声场的方法。在方法中把螺旋桨考虑为非紧致声源，所以具有计算声近场和声远场的能力。

在使用 Ffowcs Williams- Hawkings 方程(FW-H 方程)时将四极子声源项略去，厚度声源和负荷声源都包括在偶极子项之内。借助常用的片条假设，可将三维几何形状的螺桨所幅射的声场考虑为沿展向诸片条基元幅射效应的叠加。在求解声场时，每个基元沿叶型弦向的压力分布应为已知，我们使用一种带有贴体坐标的求解二维可压全速势方程的软件来计算压力分布。众所周知，声音乃是在介质中小扰动的传播。因此，在数值模拟过程中，声压的系统误差将会对于数值结果的精度有一定影响。为此本文进行了一点改进。改进点之一是使用沿桨叶表面的曲线坐标来代替弦向坐标。这样，在积分过程中在桨叶前缘和后缘处将不会出现奇点。

二、螺旋桨声场数值模拟的模型

螺旋桨声场乃是一类流场中运动固体边界发声问题。对于此类问题，目前广泛使用 FW-H 方程[4]

$$\square^2 p' = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} - \frac{\partial}{\partial x_i}\left[l_i \cdot |\nabla f| \cdot \delta(f)\right] + \frac{\partial}{\partial t}\left[\rho_o \cdot V_n \cdot |\nabla f| \cdot \delta(f)\right] \qquad (1)$$

式中p'—声压；$\Box^2$—D'Alembert 波动算子；T_{ij}—Lighthill 张量；$l_i = p_a - p_o$，其中p_a为物面上的空气压力，p_o为未扰动压力；δ—Dirac 函数；ρ_o—未扰动空气密度；V_n—叶片表面法向$\vec{n}$方向的分速；t—观测点处的时刻，并用方程$f_{(\vec{x},t)} = 0$来描述叶片表面的运动；$f < 0$表示外表面；$\vec{x}$—位于观测点的向量。

在 FW-H 方程中通过引入 Dirac 函数而把固体边界考虑在内，于是在求解此方程时就便于应用波动方程的Green 函数。为简化计算，通过引入 Isom 公式来将FW-H 方程中的厚度噪声项写成偶极子形式[5,6]：

$$\frac{\partial}{\partial t}\left[\rho_o V_n \left|\nabla f\right| \delta_{(f)}\right] = -\frac{\partial}{\partial x_i}\left[\rho_o C^2 n_i \left|\nabla f\right| \delta_{(f)}\right] \tag{2}$$

当略去（1）式中的四极子项之后，可将此波动方程表达为

$$\Box^2 \Phi = Q_{(\vec{x},t)} \cdot \left|\nabla f\right| \cdot \delta_{(f)} \tag{3}$$

借助Green 函数法，可得到方程（3）的解为

$$4\pi\Phi = \int_{f=0}\left(\frac{Q_{(\vec{y},\tau)}}{r\left|1 - Ma_r\right|}\right)_{ret} \cdot ds \tag{4}$$

式中Φ代表待求未知函数；Q代表源项；$\vec{r}$为沿声发射方向的一个向量；r为$\vec{r}$的模；Ma_r表示叶片运动马赫数的$\vec{r}$方向分量；下标ret表示延迟时间；ds为沿桨叶表面之微元；$\vec{y}$为位于声源点处的向量。使用卷积公式，可得

$$4\pi p'_{(\vec{x},t)} = \frac{\partial}{\partial t}\int_{f=0}\left(\frac{\rho_o V_n}{r\left|1 - Ma_r\right|}\right)_{ret} \cdot ds - \frac{\partial}{\partial x_i}\int_{f=0}\left(\frac{l_i}{r\left|1 - Ma_r\right|}\right)_{ret} \cdot ds \tag{5}$$

由于

$$-\frac{\partial}{\partial x_i}\left(\frac{\delta_{(g)}}{r}\right) = \frac{1}{C} \cdot \frac{\partial}{\partial t}\left(\frac{\hat{r}_i \cdot \delta_{(g)}}{r}\right) + \frac{\hat{r}_i \cdot \delta_{(g)}}{r^2}$$

且在

$$g = \tau - t + r/C = 0 \tag{6}$$

条件下，有 $\frac{\partial}{\partial t}(\;) = \left[\frac{1}{1 - Ma_r} \cdot \frac{\partial(\;)}{\partial \tau}\right]_{ret}$ 就可将（5）式改写为

$$4\pi p'_{(\vec{x},t)} = \int_{f=0}\left(\frac{\rho_o C^2 Q_A}{Cr} + \frac{\rho_o C^2 \cdot Q_B}{r^2}\right)_{ret} \cdot ds + \int_{f=0}\left(\frac{(p_a - p_o)Q_1}{Cr} + \frac{(p_a - p_o)Q_2}{r^2}\right) \cdot ds \tag{7}$$

式中

$$Q_A = \frac{\Omega(n_1\hat{r}_2 - n_2\hat{r}_1)}{(1 - Ma_r)^2} + \frac{\Omega\cos\theta(Ma_1\hat{r}_2 - Ma_2\hat{r}_1)}{(1 - Ma_r)^3}$$

$$Q_B = \frac{\cos\theta(1 + Ma_r) - Ma_n}{(1 - Ma_r)^2} + \frac{\cos\theta(Ma_r - Ma)^2}{(1 - Ma_r)^3}$$

$$Q_1 = \frac{\tilde{p}\cos\theta}{(1 - Ma_r)^2} + \frac{\Omega(n_1\hat{r}_2 - n_2\hat{r}_1)}{(1 - Ma_r)^2} + \frac{\Omega\cos\theta(Ma_1\hat{r}_2 - Ma_2\hat{r}_1)}{(1 - Ma_r)^3}$$

$$Q_2 = \frac{\cos\theta(1 + Ma_r) - Ma_n}{(1 - Ma_r)^2} + \frac{\cos\theta(Ma_r^2 - Ma^2)}{(1 - Ma_r)^3}, \quad \tilde{p} = \frac{1}{p_a - p_o} \cdot \frac{\partial(p_a - p_o)}{\partial \tau}$$

式中C—未扰动流的音速；Ω—螺桨的旋转角速度；Ma_i—叶片运动马赫数在$\vec{r}_i$方向的分量；$\vec{r}_i$—在x_i方向的$\vec{r}$分量；$\hat{r}_i = \vec{r}_i / r$；$Ma_n$—叶片运动马赫数的法向分量；$\theta$—$\vec{n}$与$\vec{r}$之间的夹角；$Ma$—叶片运动马赫数；$\tau$—声源幅射的时间。

方程（7）就是由螺旋桨所幅射的厚度噪声和负荷噪声的积分解表达式。

三、数值计算方法简介

积分是沿声源表面即桨叶表面进行的。设桨叶表面可表示为$f_{(\vec{y},\tau)} = 0$。现用p来代表在桨

叶表面上的一任意点，且向量 $\vec{p}$ 与点 p 相对应。在此向量中包含着两个参数，即经向坐标 x 和沿叶片表面的无量纲曲线长度 l。对应于 p 点的法向量为 $\vec{N}=\{N_1, N_2, N_3\}$，单位法向量为 $\vec{n}$，面积微元为 ds，它们可表达为

$$\vec{N}=(\partial\vec{p}/\partial x)\cdot(\partial\vec{p}/\partial l)\quad,\quad \vec{n}=\vec{N}/N\quad,\quad ds=N\cdot dx\cdot dl \tag{8}$$

式中 $N=\sqrt{N_1^2+N_2^2+N_3^2}$。于是可由 $x=$ const 与 $l=$ const 两个曲线族形成差分网格。考虑到气动声学数值模拟对于系统误差十分敏感，所以在每个方向上都采用精度与效率都较高的 Gauss-Legendre 积分，即

$$\int f_{(x)}dx=\sum_{i=1}^{m}f_{(x_i)}\omega\quad,\quad x_i=\frac{1}{2}(b+a)+\frac{1}{2}(b-a)\xi_i \tag{9}$$

式中 ξ_i 为 Legendre 多项式零点位置，$\xi_i\in(-1, 1)$；ω 为权系数；m 为 Ganss- Legendre 积分的阶数。对应于给定阶数 m，数组 $\{\xi_i\}$ 和 $\{\omega\}$ 均可由数学用表中查得。

在整个数值计算过程中，如何求解延迟时间 τ 乃是关键所在。延迟时间方程为 (8) 式，对于 $\partial g/\partial\tau=1-Ma_r>0$，在方法中使用 Newton 叠代法对 (6) 式求解。在本文介绍的数值计算方法中，积分方程 (7) 没有奇性问题。除计算法向量 $\vec{N}$ 之外，也无需其它偏导数计算。

四、数值举例

应用本方法已做过一些计算，现将一个算例描述如下。算例取自文献 [7]，此螺桨主要参数如下：桨叶数三片；桨尖直径—2.6m；螺桨轴转速 2145rpm；音速—345m/s；飞行速度—40.14m/s。在旋转桨盘面内的观测点与飞机一道运动，观测点与桨轴之间距离为 7.25m。螺桨三个主要几何参数沿展向分布如图 1 所示。图中的 CH 表示叶型弦长；TH 为叶型最大厚度；β 为螺桨之桨叶角，即弦线与旋转平面之间的夹角。

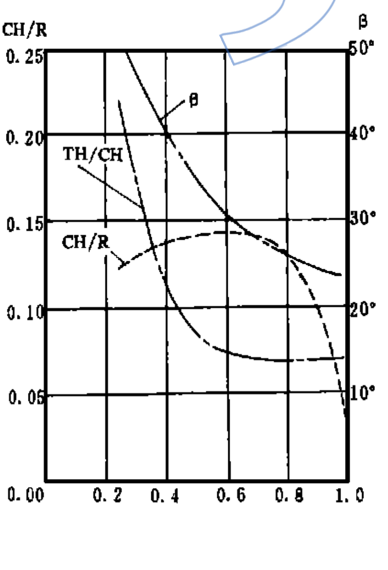

图 1　三个几何参数沿螺桨展向分布

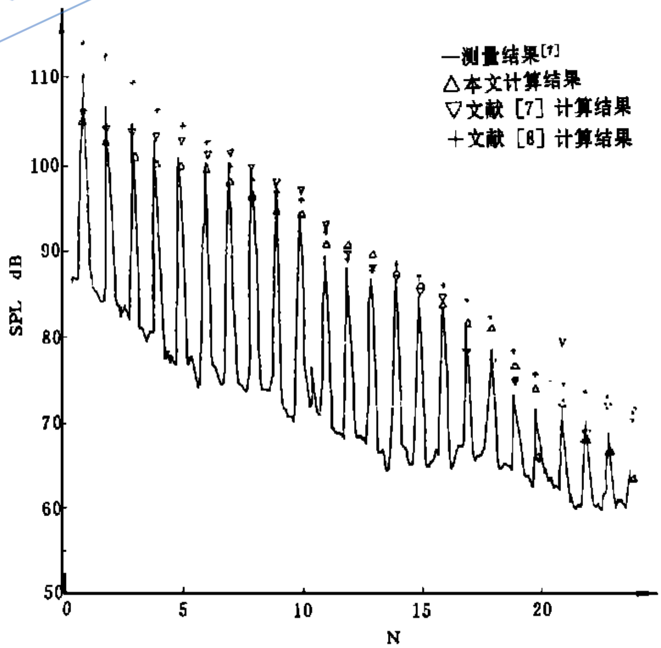

图 2　数值结果与实测数据对比

在图 2 所示的频谱图中给出了数值结果与实验结果之对比。在此图上同时也给出取自文献 [7、8] 的数值结果。实测频谱分布表明, 对应于桨叶通过频率及其谐波的纯音在宽频背景噪声之上出现明显的峰值突起, 而且纯音的声压级随谐波数增加呈单调减少。取自文献 [7、8] 的数值模拟结果和本文的计算结果都能抓住测量频谱分布的主要特征。

图 3 展现了螺桨厚度声源项与负荷声源项分别对于声场的影响。对比图 3 (a) 与 (b) 两图可注意到, 对于厚度声源说来, 相应声压级随谐波数递减的趋势慢于负荷声源项所对应的声压级变化趋势, 而且厚度声源项所幅射的声压级峰值不在最小谐波数处。

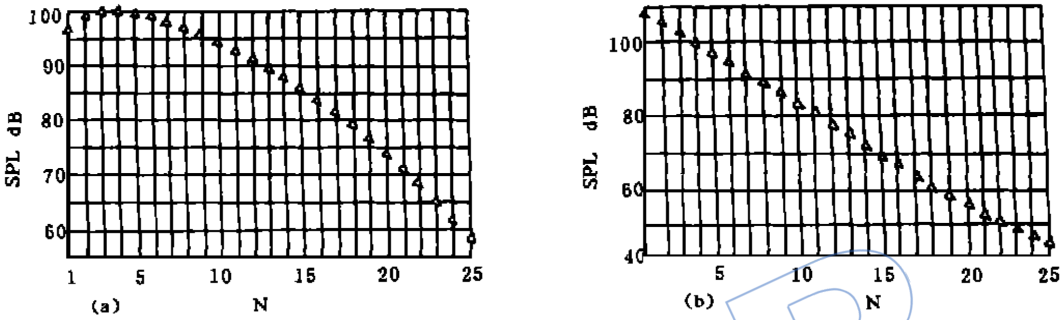

图 3 在每个谐波处计算的声压级 (a. 厚度纯音; b. 负荷纯音)

总之, 计算与实验结果对比表明, 本文所描述的数值方法和相应软件可作为工程工具来使用。

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AERODYNAMIC DESIGN OF PROPELLER BY NUMERICAL OPTIMIZATION

Pan Jieyuan and Qian Huede (*APRDC, BUAA*)

ABSTRACT A numerical optimization method is presented for aerodynamic design of propeller. As the basis of optimization, the strip theory based on Goldstein theory is applied to prediction of the propeller aerodynamic performance. The comparison of calculated results with experimental data shows that, the strip theory is appropriate to the optimization. The mixed penalty function method is used for the optimization. By the means of the method presented here, two propellers have been designed and redesigned under identical flight conditions. The calculated results indicate that the variation of efficiency with geometry parameters is more gradual in the vicinity of efficiency maximum. It is also shown, if both chords and twists in different sections are taken as design variables, the blade of the optimized propeller would be more narrow than that if only the twists are taken as design variables. Therefore the optimized propeller would be lighter and more efficient at cruise conditions.

AERODYNAMIC MODIFICATION OF A PROPELLER

Zeng Ming and Gu Gaochi (*APRDC, BUAA*)

ABSTRACT The aerodynamic design features of the propeller have been analysed at first. According to the analytical results and the modern advancements in propeller technology, the specifications of its expected modification have been proposed. In its overall design the important parameters have been determined. The principles of optimization and the version selection are outlined. From the comparison between the wind tunnel testing results of both scaled models of the propeller and its modification, it is concluded that the modification is a great success. Its static thrust and takeoff climb efficiency are increased by 13.8% and 8.76% respectively. Its cruise efficiency and noise level are also slightly improved. All they exceed the expected ones.

SURFACE FLOW VISUALIZATION OF ROTATING PROPELLER

Mao Xichang, Zeng Ming, Gao Chunfeng (*APRDC, BUAA*)

ABSTRACT Surface flow visualization has been carried out with tufts adhered to the surfaces of the rotating propeller blades. From the experimental results it is found that in part of four fifths of blade surface from hub to tip, the air flow runs from leading edge to trailing edge in the outward direction with some inclination to chord. In the region of one fifth near the blade tip, flow separation and reverse flow occur at the blade surface, circulation appears even in the serious case, in consequence negative thrust emerges, which cuts down the efficiency of the propeller obviously.

NUMERICAL PREDICTION OF SOUND FIELD GENERATED BY PROPELLER

Zhou Sheng and Huang Lixi (*APRDC, BUAA*)

ABSTRACT A fast and accurate numerical method is presented for predicting the sound field generated by subsonic propellers. The free space field, including the near and far sound field radiated by noncompact sources, is calculated by means of a retarded time integration in time domain. The FW-H equation is applied to solving the sound field generated by moving boundaries of solid body in the flow field, but its quadrupole term is neglected, thus the noncompact sources mean the thickness source and the load source both included in the dipole term. According to the assumption, the sound field generated by a 3-D shaped propeller is considered as the sum of the terms radiated by each strip element located spanwise. The pressure chordwise distribution at each element should be known before solving the sound field. For this purpose a code solving 2-D compressible full velocity potential equation with body-fitting coordinates is used which has been developed by BUAA previously. Comparison of calculated results with test data proves the present method and the code to be useful engineering tools. This conclusion has been also testified in the design of a propeller.

AEROACOUSTICAL MODIFICATION OF A PROPELLER

Li Xiaodong, Yang Xiaodong, Hu Zongan (*APRDC, BUAA*)

ABSTRACT An aeroacoustical modification of a propeller is considered with the aim of great enhancement of its takeoff efficiency and appropriate cutdown of its noise level when its blade number, blade hub and cruise efficiency are kept unchanged. A time domain method is applied to predicting near and far the sound field. From iterative aeroacoustical and aerodynamical optimization an optimum design scheme has been obtained. And two 1/3-scaled model propellers were made to simulate the original and modified propellers respectively. The results of comparative ground experiments show that the OASPL (Overall Sound Pressure Level) decreases by 1 to 1.5 dB while other technical spesifications are met.

EXPERIMENTAL CHARACTERISTICS COMPARISON BETWEEN TWO SCALE-MODEL PROPELLERS

Mao Xichang, Wang Jiebing, Li Hongmin (*APRDC, BUAA*)

ABSTRACT The aerodynamic and acoustic charaeteristics of two scale-model propellers are compared experimentally. A three blades model (Model A) is a scale-model of a production type. A four-blades model (Model B) is a scale-model of a new designed propeller. Their rotational speeds vary between 1500 to 3000rpm. Experimental results indicate that under identical operational conditions the four-blades propeller has higher thrust coefficient but lower noise level than the three-blades propeller and also has lower noise level at the same power coefficient. The four-blades propeller, of course, is superior to the three-blades one in the efficiency and overall performance.

STRESS ANALYSIS OF A PROPELLER BLADE

Xiong Changbing (*APRDC, BUAA*)

ABSTRACT Three-dimensional finite element method is applied to stress analysis of the original and the redesigned propeller blade taking the loads, such as centrifugal and dynamical loads. In respect of stress distribution, the airfoil of the redesigned propeller blade is more reasonable. Its stress distribution approaches to isostrength, and safety coefficient also meets the given specification. Therefore, the redesigned propeller blade is an quite advanced design.

STRESS ANALYSIS OF A PROPELLER HUB

Xiong Changbing (*APRDC, BUAA*)

ABSTRACT Three-dimensional finite element method is applied to stress analysis of a propeller hub taking centrifugal load, aerodynamical moment and blade centrifugal tension load. Since its construction is complicated, loads are various and its stress distribution is hard to analyze, the elastic stress plus principle is employed for this purpose. The analytical results show that the blade centrifugal tension load is predominant and its construction has been optimized to a certain extent due to current improvements during long time of its service and modifications so the stress distributions of its parts are quite even and reasonable, moreover safety coefficients are large enough.

DIGITAL SIMULATION AND EXPERIMENTAL MODAL ANALYSIS OF DYNAMIC CHARACTERISTICS OF A PROPELLER HUB

Li Kedong and Du Binlao (*APRDC, BUAA*)

ABSTRACT The finite element method with 8-nodes three-dimensional isoparametric elements and subspace iteration is applied to digital simulation of dynamic characteristics of a propeller hub. The sizes of the stiffness matrices [K] and mass matrices [M] in the equations are very large. The natural frequencies of the first six orders and its corresponding modes of the hub have been obtained from the experimental modal analysis. By comparison the results of the experimental modal analysis and the digital simulation are of the same order.