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双斜丝测量三维平均紊流流场方法的改进

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摘　要

本文提出一种改进的双斜丝测量三维平均、紊流流场方法。该方法的特点是根据热丝的方向特性确定方向系数 k 和 h，无需在每一测点处先测出气流偏角，然后在偏角方位上进行测量。对流向直角区的三维平均、紊流流场测量结果表明，该方法简便而有效。

一、前　　言

双斜热丝在三维紊流场测量上有过成功的应用，但有关双斜丝测量方法的文献，如文献[1]，要求在每一测点处先测出气流偏角，然后在偏角方位上进行测量，比较麻烦。有人假定有效冷却系数中的方向校准系数 k 为常数，h 取为 1，这样测量误差就比较大。本文提出一种改进的双斜丝测量三维平均和紊流流场方法，其特点是根据校准试验所得的热丝方向特性来确定方向校准系数 k 和 h 值，无需逐点先测出气流角[1]。用该方法测量了流向直角区的三维平均和紊流流场，所测结果与文献[2]提供的结果很相近，表明该方法简便而有效。

二、测量系统和试验模型

测量系统 Tsi 1241 型双斜丝经过 Tsi 1050 型热线风速仪产生模拟信号，经 Tsi 1052 型线化器线化后，由 IBM PC 机控制的 Tsi IFA 200 数据采集器采集和数化，存入磁盘，待进一步处理。同时可在 Tsi 1076 型均方根电压表上和用 DSS 6521 型数字存储示波器监视。热丝在 Tsi 1125 型校准风洞上校准。

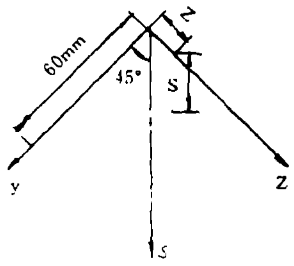

图 1　流向直角区模型

流向直角区模型见图 1。它是由两块有机玻璃粘结而成，流向长度 300mm，横截面尺寸及测点坐标表示见图。流向直角区试验是在截面为 120×450mm 的平面叶栅风洞上进行的。

三、测量方法和校准方法

1. **测量方法**　根据 Jorgenser[3] 提出的有关三维流场冷却速度关系有：

$$(E/s)2 = U_{eff}^2 = U_n^2 + k^2U_t^2 + h^2U_b^2 \tag{1}$$

其中 E 是与冷却速度 U_{eff}、校准系数 s 相关的热线风速仪的线化输出电压值，U_n、U_t、U_b、

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分别是沿 n、t、h 方向的速度分量（见图 2），k、h 为方向校准系数。

试验需要测定与试验模型相联系的坐标系下的各平均、紊流量，为此对（1）式作坐标变换。由图 2 可得：

$$
\begin{aligned}
U_n &= (-U_x\sin\alpha + U_y\cos\alpha\cos\theta + U_z\cos\alpha\sin\theta)\\
U_t &= (U_x\cos\alpha + U_y\sin\alpha\cos\theta + U_z\sin\alpha\sin\theta) \qquad (2)\\
U_h &= (-U_y\sin\theta + U_z\cos\theta)
\end{aligned}
$$

将（2）式代入（1）式，整理得：

$$(E/s)^2 = AU_x^2 + BU_y^2 + CU_z^2 + 2DU_xU_y + 2IU_xU_z + 2JU_yU_z \qquad (3)$$

其中：

$$A = \sin^2\alpha + k^2\cos^2\alpha,\ B = (\cos^2\alpha\cos^2\theta + k^2\sin^2\alpha\cos^2\theta + h^2\sin^2\theta)$$

$$C = (\cos^2\alpha\sin^2\theta + k^2\sin^2\alpha\sin^2\theta + h^2\cos^2\theta),\ D = \sin\alpha\cos\alpha\cos\theta(k^2-1)$$

$$I = \sin\alpha\cos\alpha\sin\theta(k^2-1),\ J = \sin\theta\cos\theta(\cos^2\alpha + k^2\sin^2\alpha - h^2)$$

气流瞬时速度和电压瞬时值可表示为：

$$U_x=\bar{U}_x + u_x \qquad u_y = \bar{U}_y + u_y \qquad u_z = \bar{U}_z + U_z \qquad E = \bar{E} + e \qquad (4)$$

将（4）式代入（3）式，整理得：

$$(\bar{E} + e)/s = U_{eff} = (\bar{F}^2 + F + g)^{1/2} \qquad (5)$$

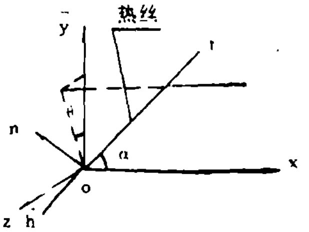

图 2　热丝自身坐标系（n、t、h）和流向坐标系（x、y、z）

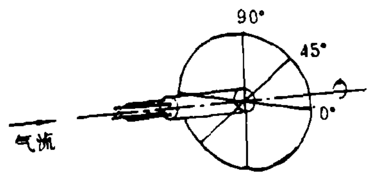

图 3　热丝绕轴线的三个方位

其中：

$$\bar{F}^{-2} = A\bar{U}_x^{-2} + B\bar{U}_y^{-2} + C\bar{U}_z^{-2} + 2D\bar{U}_x\bar{U}_y + 2I\bar{U}_x\bar{U}_z + 2J\bar{U}_y\bar{U}_z)$$

$$f = 2\ (A\bar{U}_x + D\bar{U}_y + I\bar{U}_z)\ u_x + 2\ (B\bar{U}_y + D\bar{U}_x + J\bar{U}_z)\ u_y + 2\ (C\bar{U}_z + I\bar{U}_x + J\bar{U}_y)\ u_z$$

$$g = Au_x^2 + Bu_y^2 + Cu_z^2 + 2Du_xu_y + 2Iu_xu_z + 2Ju_yu_z$$

对（5）式按泰勒级数展开，取平均，且在平均量方程中忽略二阶以上的高阶量，紊流量中忽略三阶以上的高阶量，得：

$$(\bar{E}_n/s)^2 = \bar{F}_n^2 \qquad (6)$$

$$\overline{e_n^2}/s^2 = (\overline{f_n^2}/\bar{F}_n^2)/4 \qquad (7)$$

$$\overline{(e_n \pm e_{n+90°})^2}/s = \overline{\left[\frac{f_n}{F_n} \pm \frac{f_{n+90°}}{F_{n+90°}}\right]^2}/4 \qquad (8)$$

其中，n 表示双斜丝某一丝的关系，而 n、$n+90°$则表示双斜丝两丝间的关系。

由方程(6)、(7)、(8)可见，要得到三个平均量和六个紊流量，双斜丝至少需放置 3 个角度位置，即需有六个紊流量独立关系式，才能求解。本文采用绕热丝轴线转 0°、45°、90°三个方向进行 测量，见图 4。

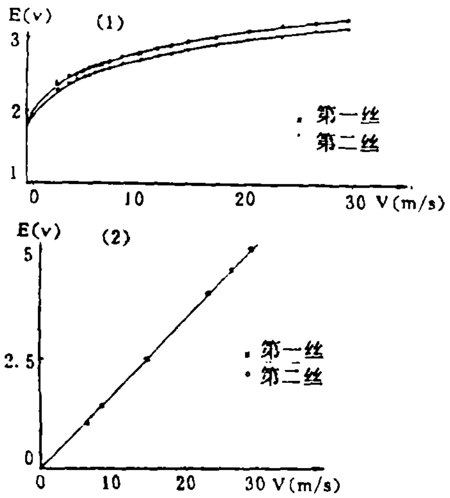

图 4　双斜丝校准曲线：(1) 速度与输出电压的关系；(2) 速度与线化输出电压的关系

这样，由(6)式可得到6个平均速度关系式，由(7)、(8)式可得到12个紊流量关系式。在求解平均速度时，采用非线性最小二乘法和牛顿迭代法，而求紊流量时，采用线性最小二乘法。

2. **校准方法** 由(1)式可见，有三个校准系数 s、k、h 需要确定。

首先将双斜丝的每根丝分别与校准风洞轴线垂线放置，找出速度与输出电压的关系，用最小二乘法求得线化系数 A_1、B_1、C_1、D_1，并置入线化器，使得速度与线化输出电压成线性关系（图4），同时得到 s。

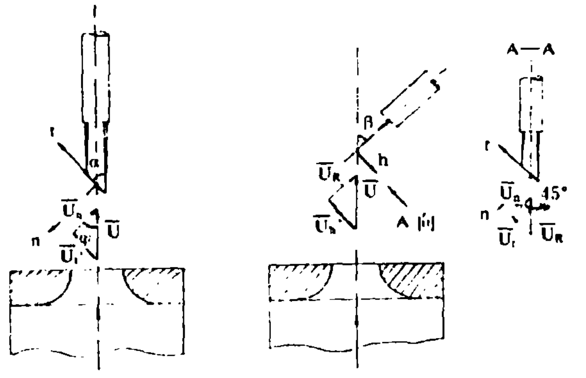

图5 以斜丝在校准方向校准系数 k 时的方位(1)和 h 时的方位(2)

然后在双斜丝每根丝的所在平面内，速度不变，改变气流方向 φ（图5），得到线化输出电压与角度 φ 的关系，从而可求得：

$$k^2 = [(E/s)^2/U^2 - cos^2\varphi]/sin^2\varphi \tag{9}$$

最后校准 h 值，先将双斜丝支杆置于与校准风洞平行，速度不变，改变气流方向，使双斜丝每根丝的所在平面与气流方向成 β 角，见图8，得到线化输出电压与角度 β 的关系，从而可求得：

$$h^2 = [(E/s)^2 - U^2cos^2\beta(cos^2\varphi + k^2sin^2\varphi)]/U^2sin^2\beta \tag{10}$$

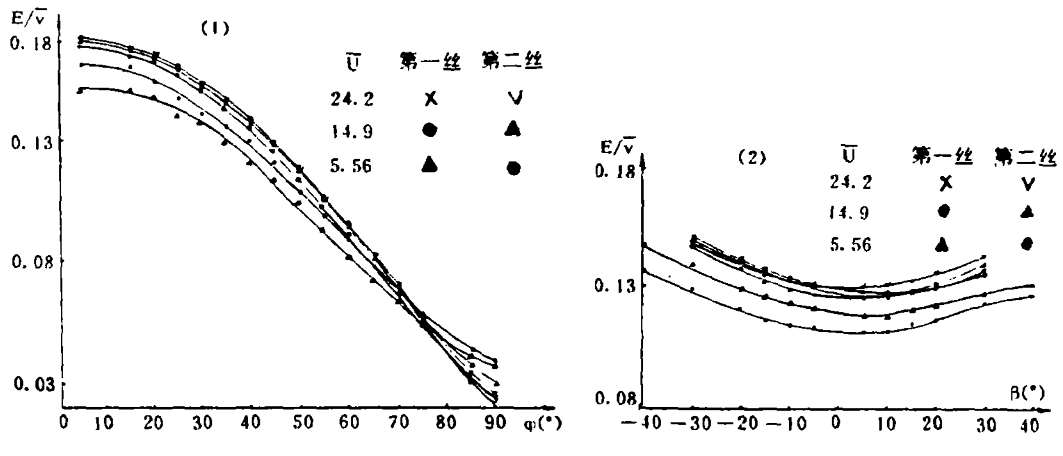

图6 双斜丝校准曲线：线化输出电压 $E/\overline{V}$ 与 φ 和 β 的关系（1）和 $E/\overline{V}$ 与 β 的关系（2）与角度 β 的关系

其中取 $\varphi=45$，k 为速度 $U1=U\cos\beta$、$\varphi=45°$下的值。

图6是线化输出电压与 φ 和 β 的关系。

试验温度与校准温度往往有差别，采用经验公式修正线化输出电压：

$$E_{修} = E \cdot \lambda \tag{11}$$

其中 $\lambda = [(T_{热丝} - T_{校准})/(T_{热丝} - T_{实测})]^2$

四、流向直角区出口流场测量

为检验本方法的有效性，对流向直角区出口流场进行了测量，测量平面选在离直角区出口 3mm 处，平面上布点见表 1，其中 s 和 z 见图 1 上示意。直角区进口速度 18. 5m/s，流场中心区紊流度 0.8%。

表 1　直角区出口测量面上测点分布

s	0.5、0.6，0.8，1.0，1.5，2.0，2.5，3.5，4.5，5.5，7.5，9.5，11.5，20.5 mm
z	0，　0.3、1.0、2.0，4.0，5.0，11.0，mm

测量结果图 7 和图 8，其中各速度分量 U、V、W 所参照坐标系为 x（流向）、y、z（y、z 见图 2 所示）。

文献［2］在进口紊流度为 0.03%条件下，用单、x 型热丝对直角区内（在进口截面后 1.091m）流场进行了测量，其结果见图 9 和图 10。

比较图 7 与图 8 和图 9 与图 10 可见，各物理量的量级和定性分布基本一致，在邻近角区，雷诺正应力等值线都向对角线偏斜而形成平行于对角线的等值线。应该说明的是，本试验条件受平面叶栅风洞流场影响，与文献［2］的有差别。

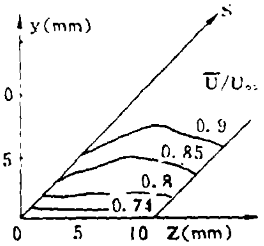

图 7　流向直角区出口 (z=3mm) 处流向平均速度等值线分布

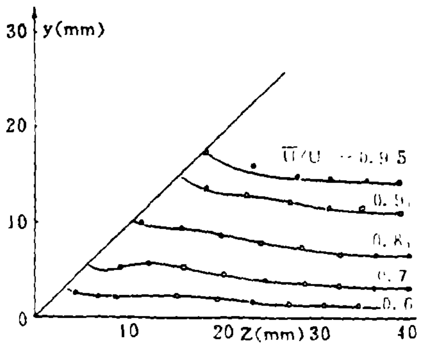

图 8　流向直角区内 (x=1. 091m) 流向平均速度等值线分布

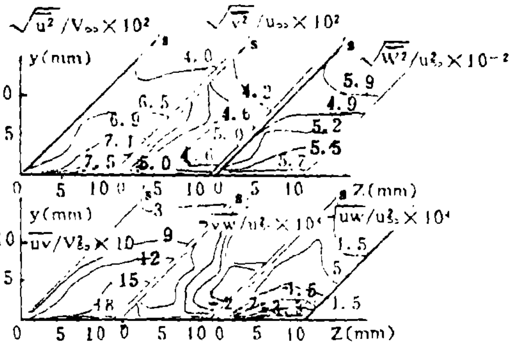

图 9　流向直角区出口 (z=3mm) 处雷诺应力等值线分布（本文）

五、测量误差估计

在 Tsi 1125 型校准风洞上，用双斜丝测量了 8 组不同速度、不同角度下的流动，其结果见表 2，平均误差为 1.4%，最大误差小于 3%。

表 2　双斜丝测量速度值与实际速度值的比较（速度单位 m/s）

	1	2	3	4	5	6	7	8
实际速度 $U_{实}$	24.2	14.85	14.85	11.04	5.58	5.58	5.58	5.58
测量速度 $U_{测}$	24.04	14.92	14.79	10.92	5.50	5.47	5.74	5.48
$\lvert U_{测}-U_{实}\rvert/U_{实}$	0.7%	0.5%	0.4%	1.1%	1.4%	2.0%	2.9%	1.8%

对流向直角区中，z=0 上不同 s 下的雷诺应力分布，采用 h=1.0、k=常数，h=1.15、k

＝常数，$h=1.15$、$k=k(\alpha、U)$，$h=h(\alpha、U)$、$k=(\alpha、U)$ 四组不同系数进行数据处理，结果表明，用前三组系数算出的雷诺应力几乎相同，说明对 k 值不敏感，但用第四组系数算出的雷诺应力中，雷诺正应力 $\sqrt{\overline{u^2}}/U_\infty$ 和 $\sqrt{\overline{W^2}}/U_\infty$ 相差不大，$\sqrt{\overline{v^2}}/U_\infty$ 和雷诺剪应力都相差较大，差别达 30%，这说明考虑 h 值随 β 角的变化是必需的。

六、结　论

1. 本文所述双斜丝测量三维平均、紊流流场的方法，考虑了热丝方向特性的影响，比文献[1] 的方法测量更方便，测量结果表明，它是一种切实有效的方法。

2. 方向校准系数 k 值对雷诺应力测量影响不大，而 h 值随 β 变化对雷诺应力测量的影响比较显著。

3. 流向角区三维平均、紊流流场测量结果与文献[2] 提供的一致。从雷诺正应力分布可见，在邻近角区，形成了平行于对角线的等值线。

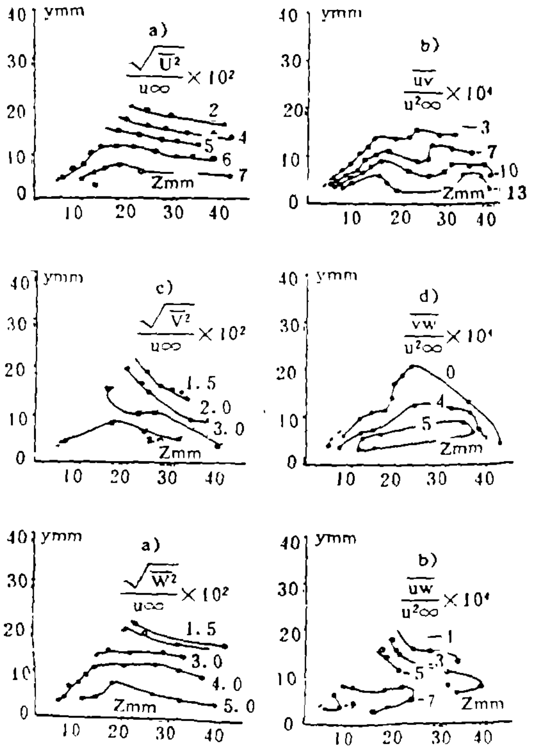

图 10　流向直角区内（$x=1.091$m）雷诺应力等值线分布[3]

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[2] O. O. Mojla and A. D. Young, "An Experiment Investigation of the Turbulence Boundary Layer along a Streamwise Corner", AGARD CP No. 93.

[3] F. E. Jorgenser," Directional Sensitivity of wire and Fiber-Film Probes", DISA Info. No. 9 1971.

INVESTIGATION ON UNSTEADY FLOW FIELD AND ENDWALL BOUNDARY LAYER IN AXIAL FLOW COMPRESSOR WITH HOT-WIRE ANEMOMETER

Lin Qixun, Guo Ningfang, Li Yaping, Xiao Ningfang

(Northwestern Polytechnical University)

ABSTRACT The measurement method of rotating stall is presented. The [illegible] difference between two signals and its frequency are determined correctly on the basis of the cross correlation and spectrum analysis. Then, the number of rotating stall regime, its spread velocity and its form are obtained. The methods of the two-dimensional unsteady flow measurement are described. The velocity distribution of the unsteady flow, for example a rotating stall cell, is obtained. A rotating single wire method is applied to measuring the two-dimensional boundary layer. The results measured behind a single rotor and a stator are shown in the paper. The contamination from dirt, the influence of air flow temperature and the boundary layer flow field disturbance caused by probe hole had been considered.

MEASUREMENT OF THREE-DIMENSIONAL FLOW IN TURBOMACHINERY WITH A SINGLE SLANTED HOT-WIRE

Li Yuchun and Jiang Haokang

(Beijing University of Aeronautics and Astronautics)

ABSTRACT An improvement to measuring three-dimensional mean flow field in turbomachinery with a single slanted hot-wire is presented. The method features high accuracy and broad angular measuing range. In order to obtain the three-dimensional flow field, the single slanted wire sets in several positions around the probe axis. The data are sampled with the help of a high speed data acquisition system and the phase-locked ensemble average technique. Then, the three-dimensional mean flow field is calculated by means of a data processing program developed by the authors. A periodic three-dimensional flow field at the exit of an axial-flow compressor rotor successfully measured. A proof calculation against the calibration data shows that the errors in velocity measurement are less than one percent of the mean velocity and the errors in the flow direction are less than one degree.

MEASUREMENT OF THREE-DIMENSIONAL MEAN AND TURBULENT FLOW FIELD WITH A DOUBLE SLANTED HOT-WIRE PROBE

Chen Fan and Jiang Haokang

(Beijing University of Aeronautics and Astronautics)

ABSTRACT A method to improve the measurement of three-dimensional mean and turbulent flow field with a double slanted hot-wire probe is presented. A prominent feature of the method is that the coefficients of direction k and h are determined according to the directional characterisitics of the wires. Therefore, there is no need to measure the flow direction at each measuring point prior to the velocity measurement along this predetermined direction. The measurement of three-dimensional mean and turbulent flow in a streamwise corner region shows that the present method is effective and simple to use.

UNSTEADY THREE-DIMENSIONAL TURBULENT FLOW MEASUREMENTS WITH A SINGLE HOT-WIRE

Din Chen and Zhang Shiying *(Nanjing Aeronautical Institute)*

ABSTRACT Periodic flow appears in many practical flow fields, such as the flow in compressors. The unsteady flows induced by both periodic fluctuation and the turbulence may dramatically affect the flow which is often three-dimensional . A modification to the single hot wire technique developed in Ref. [1] has been made to measure time mean 3-D turbulent flow field. It incorporates computer-controlled sampling, disposing and analyzing. The Triple Decomposition method has been further incorporated into the technique to treat 3-D unsteady turbulent flow. The measuring system is fully automized. The experiments done in authors' laboratory have demonstrated the advantages of the technique.

EFFECTS OF AXIAL VELOCITY DENSITY RATIO ON CASCADE PERFORMANCES

Liu Qianzhi and Yan Ruqun *(Northwestern Polytechnical University)*

ABSTRACT In turbomachinary cascade flows, the effects of Axial Velocity Density Ratio (AVDR) on cascade performances are very important. The theoretical and experimental studies of the problem are presented in this paper. The theoretical correlations of major cascade performances with AVDR are obtained. The comparisons of calculations and experiments are in good agreement.

PREDICTION OF SPANWISE LOSS DISTRIBUTION OF COMPRESSOR ROTOR WITH A SEMIEMPIRICAL LOSS MODEL

Fan Sixin and Chen Maozhang

(Beijing University of Aeronautics and Astronautics)

ABSTRACT Systematically checking calculations have been conducted to compare the semiempirical loss models available in literatures for compressor rotors. It is found that neither the accuracy nor the scope of feasibility of these models can meet the demand of engineering prediction. A new model is developed on the basis of powered averaging of these models and employing the part-span damper loss model. The model can give quite accurate estimation for the spanwise loss distribution of a rotor, and has been successfully used in a streamline curvature method to predict the loss and flow field of an axial compressor rotor.