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五孔探针的标定技术

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一、标 定 方 法

采用文献 [1] 标定七孔探针时所采用的多项式拟合技术。

1. 测量坐标系　建立在针头上 (图 1)。流动方向由侧滑角 β 和攻角 α 表示。测角范围限定在 $|\alpha|\leq 30°$, $|\beta|\leq 30°$(最大合角度 $|\gamma|\leq 41°$)。该范围基本能满足测量一般旋流流场需要。

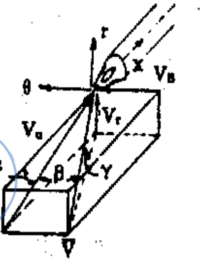

图 1　测量坐标系

2. 压力系数及其定义　参照文献 [2] 定压力系数:

$$C_\alpha = (P_4 - P_1)/(P_2 - \overline{P}), \quad C_\beta = (P_3 - P_5)/(P_2 - \overline{P})$$

$$C_{pt} = (P_2 - P_t)/(P_2 - \overline{P}), \quad C_{pq} = (P_2 - \overline{P})/(P_t - P_s)$$

式中: $\overline{P} \equiv (P_1 + P_3 + P_4 + P_5)/4$, P_t 是总压; P_s 是静压; P_i 是第 i 号孔的压力值, 见图 2。

严格讲, 此定义只适于不可压流。但对可压流, 只要使用 Ma 数与标定 Ma 数十分接近, 这套标定系数及相应的标定结果还可满足要求。新的问题是为使五针能测量不同 Ma 数的流场, 就必须在不同 Ma 数下对五孔针进行重复标定。工作量成倍增加。为此本文引用了可压缩性系数 $C_M = (P_2 - \overline{P})/\overline{P}$ [3], C_M 可由探针头上的五个压力值直接求出, 它和 C_α, C_β 一样, 在多项式拟合中可作为自变量。

3. 数学处理方法　五孔针的标定可分:

(1) 不变 Ma 数标定　根据文献 [2] 可用下式逼近流场参量和 C_α, C_p 的函数关系:

$$\begin{aligned} A = {} & K_1^A + K_2^A C_\alpha + K_3^A C_\beta + K_4^A C_\alpha^2 + K_5^A C_\alpha C_\beta \\ & + K_6^A C_\beta^2 + K_7^A C_\alpha^3 + K_8^A C_\alpha^2 C_\beta + K_9^A C_\alpha C_\beta^2 \\ & + K_{10}^A C_\beta^3 + K_{11}^A C_\alpha^4 + K_{12}^A C_\alpha^3 C_\beta \\ & + K_{13}^A C_\alpha^2 C_\beta^2 + K_{14}^A C_\alpha C_\beta^3 + K_{15}^A C_\beta^4 \end{aligned}$$

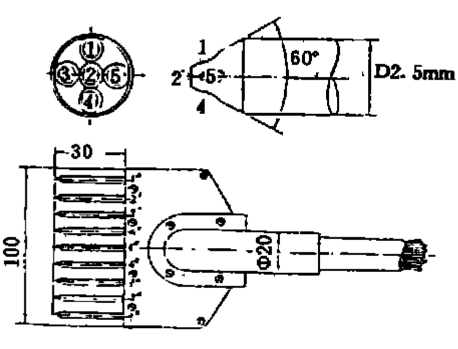

图 2　探针耙结构简图

式中: A 代表 α, β, C_{pt}, C_{pq}, K_i^A 代表相应系数。如果标定数据 $n > 15$, 则:

$$\begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_n \end{bmatrix} = \begin{bmatrix} 1 & C_{\alpha 1} & C_{\beta 1} & \cdots & C_{\beta 1}^4 \\ 1 & C_{\alpha 2} & C_{\beta 2} & \cdots & C_{\beta 2}^4 \\ \vdots & & & & \vdots \\ 1 & C_{\alpha n} & C_{\beta n} & \cdots & C_{\beta n}^4 \end{bmatrix} = \begin{bmatrix} K_1^A \\ K_2^A \\ \vdots \\ K_{15}^A \end{bmatrix}$$

或写成 $[A] = [C][K]$, 当 $[C]$ 是非奇矩阵时, $[K]$ 的最小二乘解是 $[C]^+[A]$。$[C]^+$ 为广义逆矩阵。即: $[C]^+ = \{[C]^T[C]\}^{-1}[C]^T$,

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$\therefore [K] = \{[C]^T[C]\}^{-1}[C]^T[A]$，为了提高求解以上矩阵方程的精度，本文采用了逐步回归技术。

(2) 变 Ma 数标定　C_M 也作为一个自变量，令：

$$A = K_1^A + K_2^A C_\alpha + K_3^A C_\beta + K_4^A C_M + K_5^A C_\alpha^2 + K_6^A C_\beta^2 + K_7^A C_M^2 + K_8^A C_\alpha C_\beta + K_9^A C_\alpha C_M + K_{10}^A C_\beta C_M + K_{11}^A C_2^3 + K_{12}^A C_\beta^3 + K_{13}^A C_M^3 + K_{14}^A C_\alpha^2 C_\beta + K_{15}^A C_\alpha^2 C_M + K_{16}^A C_\alpha C_\beta^2 + K_{17}^A C_\beta^2 C_M + K_{18}^A C_\alpha C_M^2 + K_{19}^A C_\beta C_M^2 + K_{20}^A C_\alpha C_\beta C_M$$

式中：A 表示 α，β，C_{pt}，C_{pq} 处理办法与不变 Ma 数标定类似，不再赘述。

4. 流场特性与拟合误差　以上分析可得流场的 α，β，C_{pt}，C_{pq}。α 和 β 决定气流方向角，气流当地总压 P_t 和动压头 q 可由 C_{pt} 和 C_{pq} 的定义得到，气流 Ma 数也可由这一途径获得。以均方差直接表示参数 A（代表 α，β，C_{pt}，C_{pq}）的拟合精度，$\sigma^2(A) = \frac{1}{n}\sum_{i=1}^{n}(A_{expi} - A_{polyi})^2$，式中：$n$ 是测点个数，A_{expi} 是试验数据，A_{polyi} 是多项式在节点处的回代值。通过 C_{pt} 和 C_{pq}，可求出[1] $\frac{\sigma P_t}{P_t - P_s} \doteq \overline{C_{pq}}\sigma(C_{pt})$，$\frac{\sigma(P_t - P_s)}{P_t - P_s} \doteq \frac{\sigma C_{pq}}{\overline{C_{pq}}}$，式中：$\overline{C_{pq}} = \frac{1}{n}\sum_{i=1}^{n} C_{pqi}$

二、标 定 试 验

1. 实验装置　标定风洞为一个抽吸式风洞，直径 Φ100mm，精心设计制造的双曲螺线进气唇口能保证进气流场均匀。进气唇口外部加了一个整流网罩，以减小外部扰动对流场的影响。该风洞的 Ma 数范围为 0.1～0.47。探针耙能在俯仰偏航和上下三个方向运动。而被标定的针头始终处于流场的同一点。相应的度量机构能够以较高的精度测出 α，β 的值的大小。该风洞流场的品质分别经总压探针、静压探针和热线校测过。由于是抽吸式风洞，进口曲面很好选择和管道较短，故保证测量截面上的总压损失几乎为零。静压探针的校测结果是在探针所处的截面上至少有 Φ30mm 的范围流速均匀。经热校测，流场紊流度 < 0.3%。

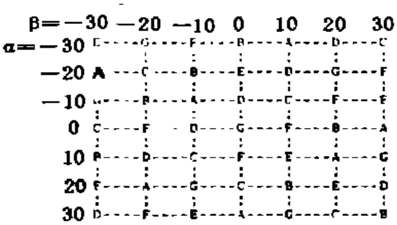

图 3　拉丁方实验方案

测压系统包括：低量程（0.4kg/cm²），测压传感器精度为 0.08%，48 点扫描阀和 IBM PC/AT 数据采集系统。为使气压信号稳定，在管路中安装了缓冲器，稳定时间约为 30 秒。

本文研制并标定的是一字形九针五孔探针耙，耙宽为 100mm（图 2）。耙上 9 根探针的间距为 11.25mm，最外边的探针距耙边 5mm。探针针头外径 Φ2.5mm，针头锥半角为 30°。

2. 实验程序　(1) 不变 Ma 数标定　先固定一个 α，然后转动 β，逐一进行标定，直到全场扫遍为止。本文标定的角度范围是：$-30° \le \alpha \le 30°$，$-30° \le \beta \le 30°$。标定 Ma 数为 0.45。(2) 变 Ma 数标定　因工作量太大，要在 α，β，Ma 三维方向上逐一扫描标定是不实际的。为此本文采用了拉丁方技术[3]。标定的 Ma 数范围从 0.15 到 0.45。ΔMa 取 0.05，采用如图 3 所示的拉丁方进行选点实验。标定时在相应的角度上调节好相应的气流 Ma 数即可。

3. 标定结果　(1) 五孔探针的特性　图 4 到图 5 给出了探针耙上 7# 针的特性曲线。这是一典型情况，其余 8 针也有类似性质。由于整体标定整体使用。探针的相互影响直接考虑在标定结果中。

以上均是不变 Ma 数标定的结果。对于变 Ma 数标定引起的特性新问题，还有待研究。

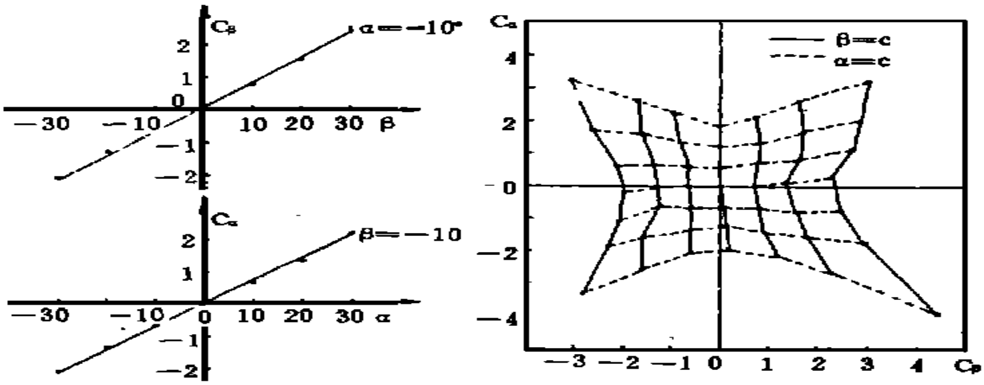

图 4　7 号针的角度系数曲线和特性曲络图

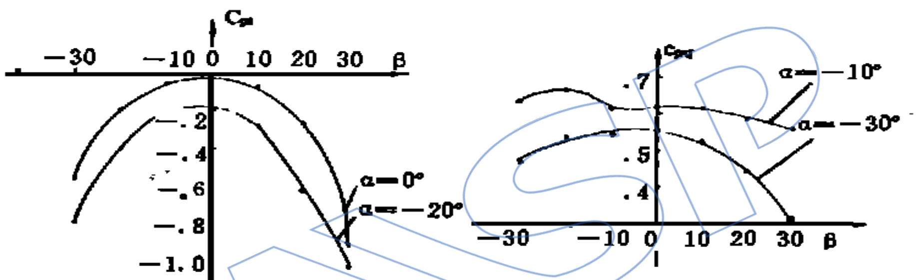

图 5　7 号针总压系数 C_{pt} 和动压系数 C_{pg} 的特性曲线

表 1　Ma= 0.45 时探针耙上 9 根针标定的拟合方差

表中 $A=\sigma(P_t)/(p_t-P_s)$，$B=\sigma(P_t)/(p_t-P_s)$

$No.$	1	2	3	4	5	6	7	8	9
$\sigma(\alpha)$	0.16	0.61	0.47	0.27	0.56	0.64	0.56	0.30	0.39
$\sigma(\beta)$	0.43	0.54	0.40	0.31	0.21	0.25	0.38	0.57	0.46
A	0.003	0.007	0.001	0.002	0.003	0.004	0.003	0.005	0.002
B	0.024	0.049	0.018	0.020	0.027	0.033	0.040	0.027	0.024

(2) **多项式拟合结果**　表 1 给出了探针耙上所有 9 根针在不变 Ma 数 (0.45) 标定时的拟合方差。是 $|\alpha|\leq 20°$，$|\beta|\leq 20°$ 范围内的结果。在 $|\alpha|\leq 30°$，$|\beta|\leq 30$ 时，其均方差略有增大。角度范围 $|\alpha|\leq 30°$，$|\beta|\leq 30°$，Ma 数范围 0.15～0.45，$\Delta M=0.05$，变 Ma 数标定的精度略低于不变 Ma 数标定，如 4# 针的变 Ma 数标定拟合均方差为 $\sigma(\alpha)=1.09$，$\sigma(\beta)=0.85$，$\sigma(P_t-P_s)/(P_t-P_s)=0.003$，$\sigma(P_t-P_s)/(P_t-P_s)=0.027$。变 Ma 数标定可以节省大量的标定时间和费用。从而为工程上进一步广泛应用五孔针提供了有利条件。

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TECHNICAL NOTES

EVALUATION OF PARTICLE SIZES AND POSITIONS BY THEIR COHERENT IMAGES

Fang Jinyan, **Yan Chuanjun**, **Wang Hongji** (Northwestern Polytechnical University)

ABSTRACT A new approach to evaluate the particle sizes and positions has been developed on the basis of their coherent images. According to the experimental and calculated results about the coherent images of steady particles, the paper described the features of coherent images of particles. It is concluded that the characteristics of the coherent images are different from those in incoherent cases, and the more the image deviates from the focus, the more obvious the differences are. From theoretical analysis, the conclusion has been drawn and proved that the normalized intensity distributions of coherent images of particles are the same when their recording far-field conditions are identical. The new method to determine the particle sizes and positions is just based on this conclusion.

THE CALIBRATION TECHNIQUE OF FIVE-HOLE PROBE

Lin Feng, **Zhang Kunyuan**, **Pen Chengyi** (Nanjing Aeronautical Institute)

ABSTRACT A Calibration technique is developed to make the five-hole probe applicable to both definite and variable Mach numbers. A rake composed of 9 five-hole probe is calibrated. The diamelter of the probe is 2.5mm and the width of the rake is 100mm. The range of yaw angle is from $-30°$ to $+30°$, so is the range of pitch angle. The minimum calibration Mach number is 0.15 and the maximum is 0.45. The standard deviations of yaw angle and pitch angle of each probe are less than 1.0°. The experimental results shows that this technique is suitable for engineering measurement.

EXPERIMENTAL TECHNIQUE FOR INVESTIGATION ON FOREIGN OBJECT DAMAGE OF AEROENGINE

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Xiong Changbing (Beijing University of Aeronautics and Astronautics)

ABSTRACT A method to determine the size of notch on first stage blade of compressor with a stress concentrated factor (K_t) of three is briefly introduced, which is required for foreign object damage (FOD) testing of aeroengines. It is based on 8-node and 20-node finite element appoaches respectively. The 8-node super-parameter element approach is used to calculate the stress distribution of a whole blade without and with notch, and the 20-node 3D iso-parameter finite element programm is applied to computation of local stress distribution around a notch of blade. The practical testing techniques and test results are also presented.

VIBRATION DIAGNOSIS AND VIBRATION SOURCE ANALYSIS OF AIRCRAFT ENGINE

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ABSTRACT This paper presents a progress in aircraft engine vibration monitoring and diagnosis in flight. Essentiality of the in-flight vibration monitoring and vibration source analysis and the features of the system used are discussed. An airborne vibration data acquisition unit, the ground analysis equipments and the method for analysing vibration signal are given. Its applications prove that it is feasible for vibration signal recording in flight and frequency spectrum analyzing.

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