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Engineering Notes

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New Method for Evaluating the Hemispheric Five-Hole Probes

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Nomenclature

C_p	=	pressure coefficient
K_{ma}	=	calibration coefficient for Mach number
K_p	=	calibration coefficient for static pressure
K_{pt}	=	calibration coefficient for total pressure
K_α	=	calibration coefficient for angle of attack
K_β	=	calibration coefficient for angle of sideslip
l, m, n	=	order of polynomial
p_i	=	pressure
T	=	temperature
α	=	angle of attack
β	=	angle of sideslip
∂_i	=	angle between surface normal at pressure orifice and flow direction

Introduction

FOR the exploration of three-dimensional flowfields in the cryogenic wind tunnel DNW-KKK,[1] a rake of 15 five-hole probes was manufactured (Fig. 1). The probe has a hemispheric head. Its outer diameter is 2.5 mm, provided with one central orifice and four orifices equally divided along the hemispheric head, 90 deg apart; the normal to the surface at an orifice position forms an angle of 45 deg with the probe axis. The diameter of the orifice is 0.4 mm. Each pressure orifice is connected to a pressure transducer.

The rake was calibrated in the low-speed wind tunnel of the Technical University of Darmstadt. In the calibration setup the rake is mounted on a rear sting. The calibration grid is established as following: the angle of attack from −34 to 34 deg with intervals of 2 deg; the angle of sideslip from −34 to 34 deg with intervals of 2 deg and three Mach numbers 0.126, 0.142, and 0.157. The total number of calibration points is 3678.

The uncertainty in the angle of attack and in the sideslip was determined to be on the order of 0.01 deg. The uncertainty in the Mach number is under 0.0001. The pressures were measured with a uncertainty of 1.5 Pa.

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Usual Method of Evaluation

To determine the flow conditions, three calibration coefficients are necessary, namely, two for the flow direction and one for the Mach number. They are defined as[2]

$$k_\alpha = (p_2 - p_1)/\Delta p \tag{1}$$

$$k_\beta = (p_3 - p_4)/\Delta p \tag{2}$$

$$k_{ma} = \Delta p / p_5 \tag{3}$$

with

$$\Delta p = p_5 - (p_1 + p_2)/2 \tag{4}$$

In addition, two coefficients are needed to determine the static pressure and the total pressure:

$$k_p = (p_5 - p)/\Delta p \tag{5}$$

$$k_{pt} = \Delta p / p_5 \tag{6}$$

The different flow quantities are functions of the calibration coefficients. A calibration yields the relationship between the flow quantities and coefficients. Usually the functions are expressed as polynomials, wherein the polynomial constants are determined by the global regression method. The functions have the form

$$Y = \sum_{i=0}^{l} \sum_{j=0}^{m} \sum_{k=0}^{n} \delta_{ijk} C_{Yijk} k_\alpha^i k_\beta^j k_{ma}^k \tag{7}$$

where Y can be one of the quantities α, β, Mach, K_p, or K_{pt}; and l, m, and n are the order of the polynomial and can be choosen from 3 to 6. The δ_{ijk} is defined as

$$\delta_{ijk} = \begin{cases} 1 & \forall \quad i+j+k \le \max(i,j,k) \\ 0 & \forall \quad i+j+k > \max(i,j,k) \end{cases} \tag{8}$$

During the evaluation of the calibration, it was found there were some problems with the definition of the calibration coefficients. The calibration coefficients are strongly nonlinear with the flow quantities (see Figs. 2 and 3), and they are not independent of each other.

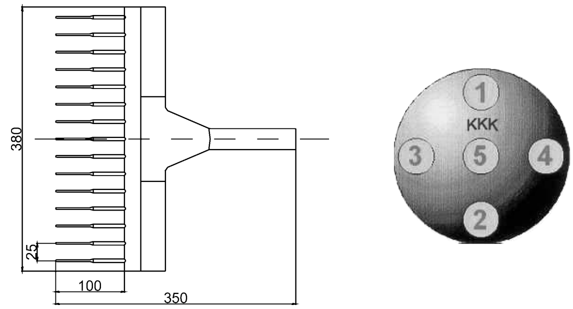

Fig. 1 Rake and front view of vive-hole probe with the numbering of the pressure orifices.

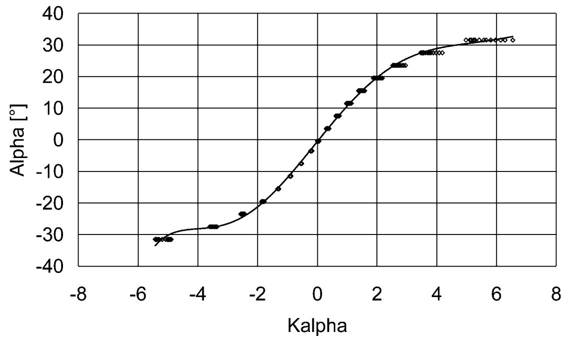

Fig. 2 Angle of attack as a function of K_α.

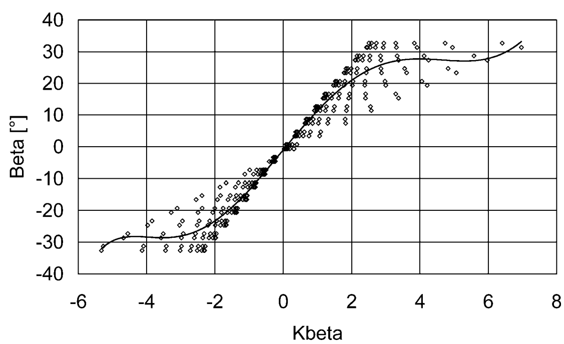

Fig. 3 Angle of sideslip as a function of K_β.

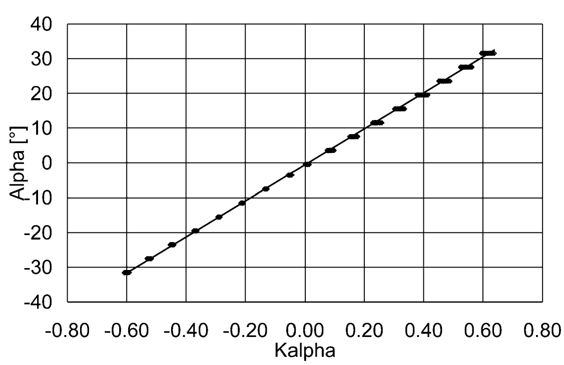

Fig. 4 Angle of attack as a function of K_α.

Method Based on the Theoretical Relations

The calibration coefficients just defined are applicable to all types of five-hole probes, such as conical, spherical, and ellipsoidal probes. For the hemispheric probes a set of specially defined calibration coefficients can be used to overcome the shortcomings of these general definitions. They are derived from the theoretical relations about the pressure distribution on the probe.

The potential flow solution for a hemispheric capped probe seems to be the first choice from which the calibration coefficients can be derived. The problem is that this relationship is too complicated to be used reasonably. In addition the five-hole probe is usually used to measure flow with angle of attack and angle of sideslip under 45 deg. Under such conditions, the pressure distribution on the head of the probe is similar to that on a sphere. As a compromise, the calibration coefficients for a hemispheric probe are derived from the potential flow around a sphere.

The pressure distribution on a sphere can be expressed as

$$C_{\mathrm{pi}} = (p_i - p_\infty)/q_\infty = 1 - \tfrac{9}{4}\sin^2\theta_i \tag{9}$$

where θ_i is the angle between the velocity and the normal to the surface at i.

The pressure coefficients at the five orifices can thus be described by

$$C_{p1} = -\tfrac{5}{4} + \tfrac{9}{8}(1 - \sin 2\alpha)\cos^2\beta \tag{10}$$

$$C_{p2} = -\tfrac{5}{4} + \tfrac{9}{8}(1 + \sin 2\alpha)\cos^2\beta \tag{11}$$

$$C_{p3} = -\tfrac{5}{4} + \tfrac{9}{8}(\cos\alpha\cos\beta - \sin\beta) \tag{12}$$

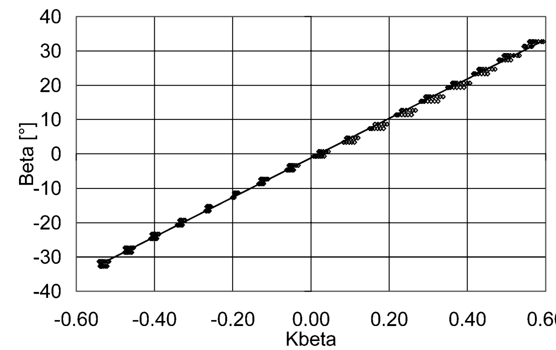

Fig. 5 Angle of sideslip as a function of K_β.

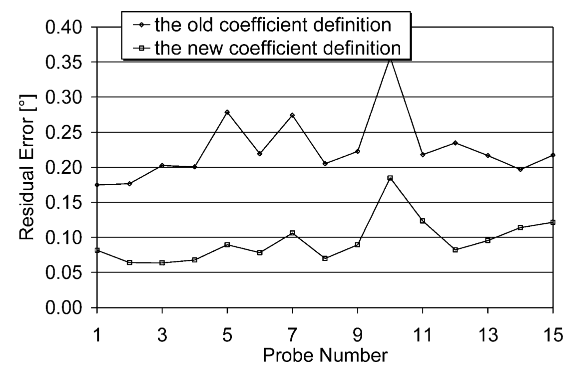

Fig. 6 Average residual error of the angle of attack for the 15 probes.

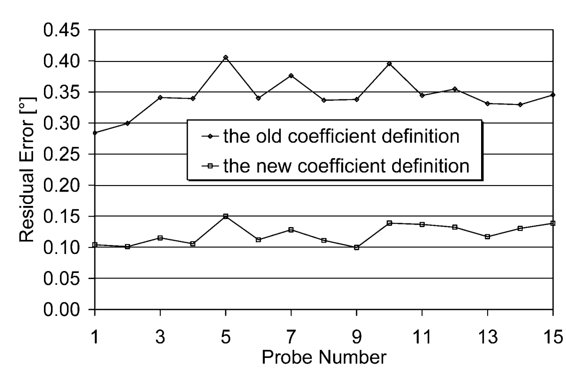

Fig. 7 Average residual error of the angle of side slip for the 15 probes.

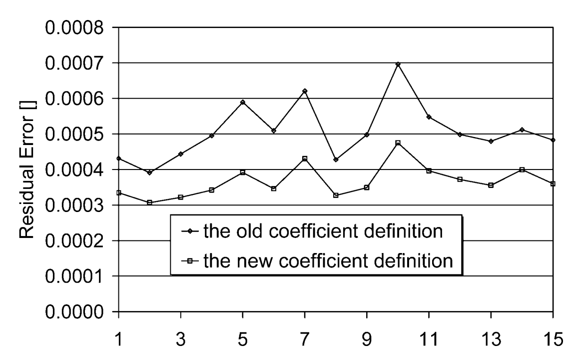

Fig. 8 Average residual error of the Mach number for the 15 probes.

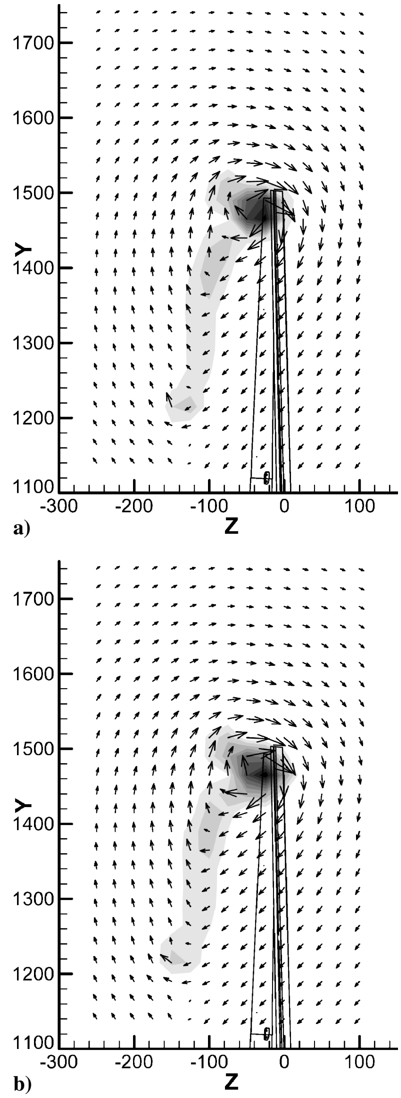

Fig. 9 Wake behind the tip trailing edge of a half-model: a) Mach = 0.15, T = 300 K, and α = 8 deg, b) Mach = 0.15, T = 100 K, and α = 8 deg.

$$C_{p4} = -\tfrac{5}{4} + \tfrac{9}{8}(\cos\alpha\cos\beta + \sin\beta) \tag{13}$$

$$C_{p5} = -\tfrac{5}{4} + \tfrac{9}{4}\cos^2\alpha\cos^2\beta \tag{14}$$

We define the following coefficients for the angle of attack α and angle of side slip β based on Eqs. (9–13):

$$k_\alpha = \frac{1}{2}\arctan\left(\frac{1}{2}\frac{p_2 - p_1}{\Delta p}\right) \tag{15}$$

$$k_\beta = \begin{cases} \arctan\left[\sin(k_\alpha)\dfrac{p_3 - p_4}{p_2 - p_1}\right] & \forall \quad p_1 \neq p_2 \\ \dfrac{1}{4}\dfrac{p_3 - p_4}{\Delta p} & \forall \quad p_1 = p_2 \end{cases} \tag{16}$$

Figure 4 shows the relationship between angle of attack and the calibration coefficient K_α; and Fig. 5 shows the relationship between angle of sideslip and the calibration coefficient K_β. It can be seen that the relationship is almost linear and independent.

For the sideslip there is obviously a large interference among the probes. Before the probes were fixed to the rake, five of the 15 probes were picked up randomly and calibrated. For the single probe the relationship between angle of attack and K_α and that of sideslip and K_β are almost identical. This indicates a high manufacturing accuracy of the probes. For a reasonable resolution of the measured flowfield, the spacing between the probes cannot be increased. This interference is taken into account by calibration.

Because the calibration rig was inverted for the range of positive angle of attack, the tolerance on fit makes the data scattering larger than that in the range of negative angle of attack. This leads to the phenomenon that the curve alfa-K_α has inverse curvature.

Results

The calibration data were evaluated using the coefficients defined according to Eqs. (15) and (16). For comparison the data were also evaluated using the old definition as described by Eqs. (1–3). The average residual errors of the 15 probes after approximation are shown in Figs. 5–7. It can be seen that by using the new calibration coefficients the errors of the flow quantities become smaller. The error of angle of attack is reduced by 0.1 deg. The error of angle of sideslip is reduced by 0.2 deg, and the error of Mach number is also reduced.

The five-hole probe rake was tested in the wake 190 mm behind the trip trailing edge of a half-model at a Mach number of 0.15, an angle of attack of 8 deg, and two Reynolds numbers: 1.3×10^6 (temperature 300 K) and 5.3×10^6 (temperature 100 K). The lift of both cases is almost the same, and the vorticity measured by the rake shows no significant influence of the Reynolds number (Fig. 9).[3] Resolving further details of the wake structure needs more refined traversing of the rake than in the present example.

Conclusion

Based on the theoretical pressure distributions around a sphere, a set of new calibration coefficients was defined for the hemispheric five-hole probe. By using these coefficients, a more precise relationship between the flow quantities and the five measured pressures can be established, and the accuracy of the probe is thus raised. It might be useful for wind-tunnel engineers who want to raise the accuracy of the five-hole probes. They do not need to perform the tedious calibration again. What they need to do is to reevaluate the available calibration data.

References

[1]Viehweger, G., "The Kryo-Kanal Koeln (KKK): Description of the Tunnel Conversion, Thermal Insulation, Instrumentation, Operational Experience, Test Results and Operating Costs," AGARD CP-744, Paper 4, June 1989.

[2]Buescher, C., and Emmrich, R., "Kalibrierbericht der Pneumatischen Fuenflochsonde ohne Temperaturmessstelle DNW_1 bis DNW_5," RWTH Aachen Report, Institute for Jet Propulsion and Turbo Machinery, Germany, Dec. 2000.

[3]Enders, G., Zhai, J., and Becker, W., "Inbetriebnahme des KKK-5-Loch-Sondenrechens und Vergleich mit dem DNW-Standardrechen," DNW, Report DNW-GUK-2002C09, Cologne, Germany, Aug. 2002.