PROBES IN TRANSONIC FLOW

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ABSTRACT

A constraint exists for intrusive probes in transonic flow which leads to a complete insensitivity to static pressure at Mach number Ma=1. Nearby Mach number unity different types of probes are affected more or less by the reduced sensitivity to static pressure or Mach number. In this paper three types of probes are compared and it is shown that the reduced sensitivity near Ma=1 causes large errors when the flow Mach number is determined by a conventional probe. A closer look onto the pressure distribution of a blunt body reveals that only the front part of a probe is subject to the constraint while base pressure is not affected. Therefore a base pressure tapping was added to a conventional Cobra type probe. The new probe was calibrated in the Probe Calibration Facility of DLR Göttingen at a wide range of Mach numbers and at two Reynolds numbers.

INTRODUCTION

Probes are still an indispensable tool to determine flow values in turbomachines. In most cases they have to be inserted radially and then especially the probe stem causes some disturbances to the flow. This is normally accepted, but in transonic flow the disturbance by an intrusive probe makes it impossible to determine the flow Mach number at all. It was already mentioned by Shapiro [1] that the pressure distribution on a body is independent of Mach number near Ma=1. The effect on probes was described by Hancock [2] who showed that in principle the sensitivity of any intrusive probe to static pressure must be zero at Mach number unity. This constraint is due to the detached shock standing ahead of a body in supersonic flow. When beginning from subsonic conditions the flow Mach number is increased, a shock appears at Ma=1 standing infinitely far ahead of the body. Downstream of the detached shock the flow is still subsonic and therefore the tappings on the body still sense subsonic conditions. Increasing the Mach number leads to a movement of the shock closer to the body but still subsonic flow conditions exist at the front of the body. At a sharp-nosed body the shock finally attaches and becomes an oblique shock downstream of which the flow is fully sensitive to upstream Mach number variations. Blunt bodies always develop a detached shock in front of the body, but the subsonic region at the nose diminishes in size with increasing Mach number. It is therefore clear that different types of probe shapes generate varying magnitudes of insensitivity to static pressure in the vicinity of Mach number unity.

In DLR's Probe Calibration Facility (see Gieß et al. [3]) several nozzles allow the calibration of probes in the Mach number range of 0.2 to 1.8. A specially designed slotted nozzle enables the calibration in the transonic range. A lot of different probes have been calibrated and the results of three of them are presented here.

RESULTS AND DISCUSSION

A Mach number coefficient, $C_{Ma,}$ is derived from the probe pressures by calculating a Mach number from the ratio of the averaged angle pressures, $p = (p_{sl}+p_{sr})/2$, (see Fig. 4) to the central pressure $p_{0} = p_{0s}$.

$$C_{Ma} = Ma\left(\frac{p}{p_0}\right) = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{p}{p_0}\right)^{\frac{1-\gamma}{\gamma}}-1\right]} \quad \text{, with } \gamma = 1.4$$

In Fig. 1 the Mach number coefficient C_{Ma} plotted versus Mach number is shown for three probes. One clearly observes that the C_{Ma}-curves display a flat part near Mach number unity. The gradient of the C_{Ma}-curve determines the sensitivity of the probe to flow Mach number variations and therefore the gradient is plotted in the next Fig. 2. The gradients are calculated from the difference of the measured points therefore the plotted gradients are not very exact but nevertheless give an adequate impression. According to Figure 2 the cylindrical probe head is superior at subsonic flow, but really bad near Mach number Ma=1.1. The Cobra probe is the worst one. The wedge probe is aligned to the flow (like a lance) because it is a probe used in DLR's Straight Cascade Facility where enough space enables such a solution. The wedge probe results are only shown for comparison as such a probe stem cannot be realized in a turbine stage. One may conclude that probe configurations which can be used in a realistic turbomachine geometry are inevitably insensitive not only at Ma=1, but also in a Mach number range from 1 to 1.3.

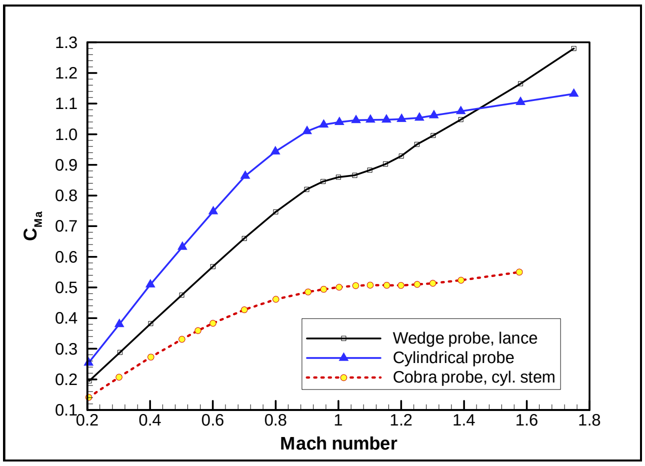

Fig. 1: Mach number coefficient at zero incidence

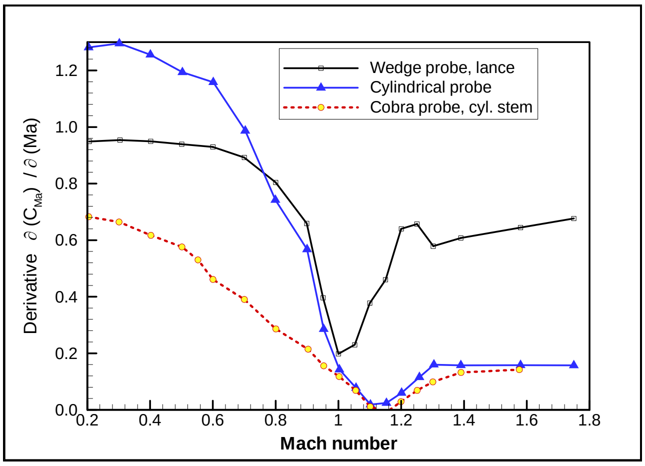

Fig. 2: Gradient of C_{Ma} versus Mach number

The above statement is further supported by Fig. 3 where the pressure distribution at the probe head of the cylindrical probe is shown. At the front side of the probe head where the pressure tappings are located the pressure distribution is nearly unchanged for Mach numbers from 0.9 to 1.2.

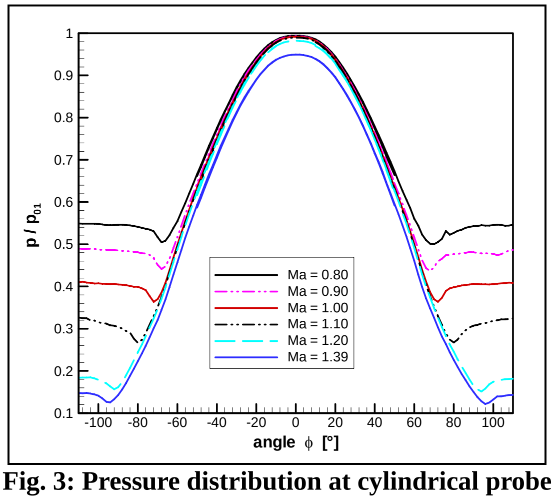

Fig. 3: Pressure distribution at cylindrical probe

On the other hand, from the same figure it is obvious that the pressure at the rear side of the cylindrical probe head is very well reacting to a flow Mach number change. The location of separation at the surface of the cylinder and the pressure in the separated region (base pressure) are changing with flow Mach number. This cannot be caused by a changed boundary layer upstream of the separation as the flow in the forward part of the cylinder is still unchanged. A physical explanation has to take into account that the wake downstream of the cylinder is subsonic and that on this path the static pressure from the 'far field' of the probe is influencing the base pressure. It is therefore possible to design a probe for transonic flow by adding a base pressure tapping.

Nevertheless some care has to be taken. A cylindrical probe is not the appropriate candidate for a base pressure tapping as it is known that the base pressure of a cylinder reacts to Reynolds number and furthermore to the turbulence level of the flow. Whereas a Reynolds number effect can often be simulated during calibration it is not possible to simulate the very special turbulence field of a turbomachine during calibration.

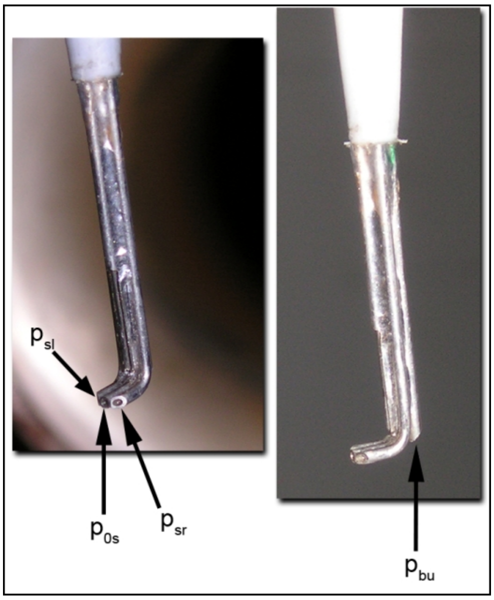

Fig. 4: Cobra type probe with added base pressure tapping

It was decided to add the base pressure tapping to a conventional Cobra type probe (see 'p_{bu}' in Fig. 4). Conventional Cobra probes are worse compared to cylindrical probes but they are easy to manufacture and enable measurements close to the endwalls. Furthermore all tubes of the Cobra probe shown here are sharp-edged and it is believed that this leads to certain insensitivity to Reynolds number and turbulence variations as the separation locations are determined by the sharp edges.

A new Mach number coefficient, $C_{Mab,}$ is derived from the probe pressures by calculating a Mach number from the ratio of the base pressure (p_{bu}) to the central pressure (p_{0s}). In Fig. 5 the Mach number coefficient, $C_{Mab,}$ plotted versus Mach number is shown for two Reynolds numbers. It can be seen that the gradient of the new Mach number coefficient, C_{Mab}, is especially favourable in the transonic flow range where the conventional Mach number coefficient fails.

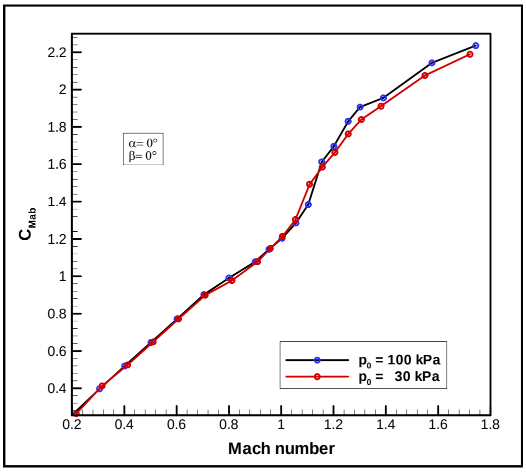

Fig. 5: Mach number coefficient, $C_{Mab,}$ **at zero incidence**

By utilizing the calibration values a sensitivity check of the different evaluations can be performed. The measured probe pressure values of the calibration are used as input to the evaluation program normally applied at the wind tunnel where the probe is inserted. By changing only one probe pressure (e.g. p_{0s}) by 0.1% the deviation of the Mach number from the original one denotes an error in Mach number and simultaneously the sensitivity of the evaluation to an ordinary pressure measurement error.

The result of such a sensitivity check is shown in Fig. 6. Of course the measurement scatter of the calibration produces a scatter of the error values, too. It can nevertheless be seen that the Mach number error of the conventional evaluation amounts to considerable values whereas the new evaluation using the back pressure is much more favourable for Mach numbers above 0.9.

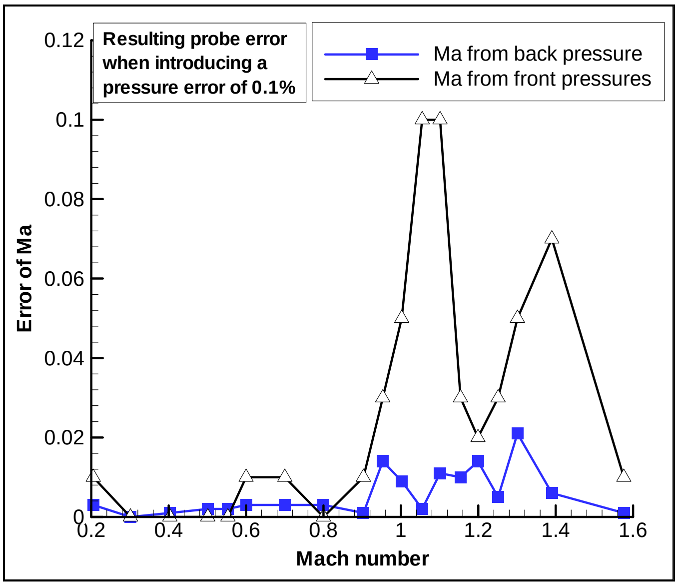

Fig. 6: Comparison of Probe errors for the Cobra probe

The new probe was applied in a recent measurement campaign and only by using the new Mach number coefficient, C_{Mab}, reasonable results for the Mach number could be obtained in the transonic regime.

The results for the new probe show exemplarily that a Cobra type probe can be modified easily to obtain a well-performing probe for the transonic regime. It was already mentioned that there are some doubts about the application of the same procedure to a cylindrical probe. But, for a probe with an intrusive stem (blunt, cylindrical or wedge type) and a wedge type head the addition of a base pressure tapping should be advantageous, too.

REFERENCES

[1] Shapiro, A.H., 1954, “The Dynamics and Thermodynamics of Compressible Fluid Flow”, Volume II, p.846, The Ronald Press Company, New York.

[2] Hancock, P.E., 1988, “A Theoretical Constraint at M=1 for Intrusive Probes and Some Transonic Calibrations of Simple Static-Pressure and Flow-Direction Probes”, Proceedings of the 9th Bi-Annual Symposium on Measuring Techniques in Transonic and Supersonic Flow in Cascades and Turbomachines, Oxford, UK

[3] Gieß, P.-A., Rehder, H.-J., Kost, F., 2000, “A New Test Facility for Probe Calibration Offering Independent Variation of Mach and Reynolds Number”, Proceedings of the XVth Bi-Annual Symposium on Measuring Techniques in Transonic and Supersonic Flow in Cascades and Turbomachines, Firenze, Italy