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THE BEHAVIOUR OF PROBES IN TRANSONIC FLOW FIELDS OF TURBOMACHINERY

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ABSTRACT

A constraint exists for probes in transonic flow which leads to an insensitivity to Mach number variations at Mach number unity. Nearby Mach number unity different types of probes are affected more or less by the reduced sensitivity to Mach number. Probes aligned to flow direction exhibit the theoretically predicted behaviour of an insensitivity region centred at Ma=1. For application in axial turbomachines probes have to be inserted radially and then the probe shaft causes additional disturbances to the flow. In transonic flow the combined disturbances of probe head and shaft extend the insensitivity range up to a Mach number of 1.3. A closer look onto the pressure distribution of a blunt body reveals that only the front part of a probe is subject to the transonic constraint while base pressure is not affected. Therefore a new probe was designed where a base pressure tapping was added to a conventional probe with radial shaft. It is shown that the relation of Mach number to the base pressure coefficient is strictly monotonic and especially favourable in the transonic range where the conventional probe coefficient failed.

NOMENCLATURE

C_{Ma}	Mach number coefficient (equation 2)	Ma	Mach number
C_{Mab}	Mach number coefficient (equation 3)	p	static pressure
p_0	total pressure	p_{0s}	probe Pitot pressure
p_{sr}, p_{sl}	probe angle pressures	p_{bu}	probe base pressure
α	peripheral flow incidence angle	ϕ	peripheral probe angle
C_α	angle coefficient (equation 1)	β	radial flow angle
κ	ratio of specific heats		

INTRODUCTION

Probes are still an indispensable tool to determine flow values in turbomachines. Especially total pressure and temperature cannot be determined with sufficient accuracy by optical methods. If total pressure has to be determined at supersonic flow conditions then it is additionally necessary to have a knowledge of flow Mach number or static pressure as the Pitot pressure measured by the probe has to be corrected by a factor dependent on Mach number to get the true total pressure. Mach number dependent calibration factors are also necessary to get true total temperature or incidence angle. Though, in spite of the fact that probes inevitably disturb the flow and static pressure measurement is notedly error-prone (Fransson et al., 1988), there is no turbomachine investigation without probes. In many cases probes have to be inserted radially and then the probe shaft causes additional disturbances to the flow. This is usually 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 (1954) that the pressure distribution on a body is independent of Mach number near Ma=1. The effect on probes was described by Hancock (1988) who showed that in principle the sensitivity of any intrusive probe to static pressure must be zero at Mach number unity. It follows that the sensitivity near Ma=1 must be low. 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 Mach numbers slightly above unity standing far ahead of the body. Downstream of the detached shock the flow is subsonic and therefore the tappings on the body sense subsonic conditions. Increasing the Mach number leads to a movement of the shock closer to the body, but the shock remains normal and therefore 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 (or Mach number) in the vicinity of Mach number unity.

PROBE CALIBRATION

The Probe Calibration Facility at DLR, Göttingen, was built to calibrate probes in the Mach number range from 0.2 to 1.8 and in a total pressure range of 30 kPa to 300 kPa. An independent variation of the Mach and Reynolds number was achieved by designing it like a closed loop wind tunnel. Several nozzles of exit diameter 50 mm allow the calibration of probes at subsonic and supersonic Mach numbers. A specially designed slotted nozzle enables the calibration in the transonic range. The probes are calibrated in the free jet just downstream of the nozzle exit where a volume of constant flow conditions was determined by extensive investigations. The true Mach number of the calibration is determined from the pressure inside the chamber to which the nozzle discharges. Because it is crucial for the following discussion it is explicitly stated here that at least for Ma$>$1 the true Mach number in front of the probe head did not significantly differ from the Mach number calculated from chamber pressure — in supersonic flow the Mach number could be additionally calculated from the ratio of probe Pitot pressure to inlet total pressure by making use of the total pressure loss produced by a straight shock upstream of the probe Pitot tube. A detailed description of the probe calibration facility is available in Gieß et al. (2000) or on the Web site of the Turbine Department by starting navigation from the Institute's URL: `http://www.dlr.de/at/`. A lot of different probes have been calibrated and their behaviour has been compared. In this paper the sensitivity of probe coefficients to flow angle and Mach number and the resulting errors in determining the flow values from the probe coefficients are exemplified by the calibration results of four probes.

Description of Probes

Probe name	**shaft orientation**	**application**	**probe head angle**
Wedge Probe	aligned to flow	2D flow	included angle: 30 deg
Pyramid Probe	aligned to flow	3D flow	included angle: 60 deg
Cylindrical Probe	perpendicular to flow	3D flow	position of angle holes at $\pm$60 deg
Cobra Probe	perpendicular to flow	2D flow	angle of bevelled tubes: 45 deg

Table 1: Probe features

Probes Aligned to Flow Direction

Such probes are used in DLR's Straight Cascade Facility where enough space enables the insertion of probes having a long shaft aligned to flow direction. Only the probe head differs according to its task. One of the probes shown in Figure 1 is a probe with a wedge type head used for exploring two-dimensional flow. The other probe has a pyramid type head which allows measurements in 3D flows.

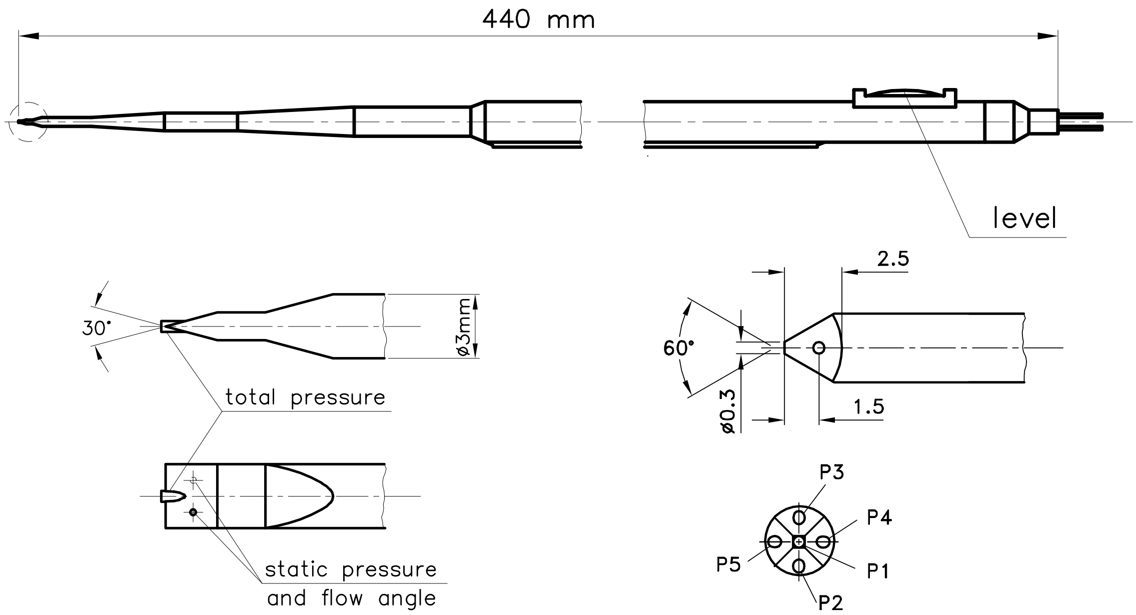

Figure 1: **Wedge Probe head on the left; probe shaft on top; Pyramid Probe head on the right;**

Probes with Shaft Perpendicular to Flow Direction

These probes can be inserted radially into an axial turbomachine thus providing access to locations between blade rows (Figure 2). The Cylindrical Probe has 4 holes and enables the determination of circumferential and radial flow angle together with total pressure and Mach number. The Cobra Probe can only determine 2D flow values, but it has additionally a thermocouple and it is possible to take measurements closer to the endwall compared to the Cylindrical Probe. With this probe it is possible to determine the flow Mach number, total pressure, total temperature and circumferential flow angle. The probe head is composed by three tubes where the middle tube is used for measuring the Pitot pressure and the two bevelled outer tubes are used for determining the flow angle.

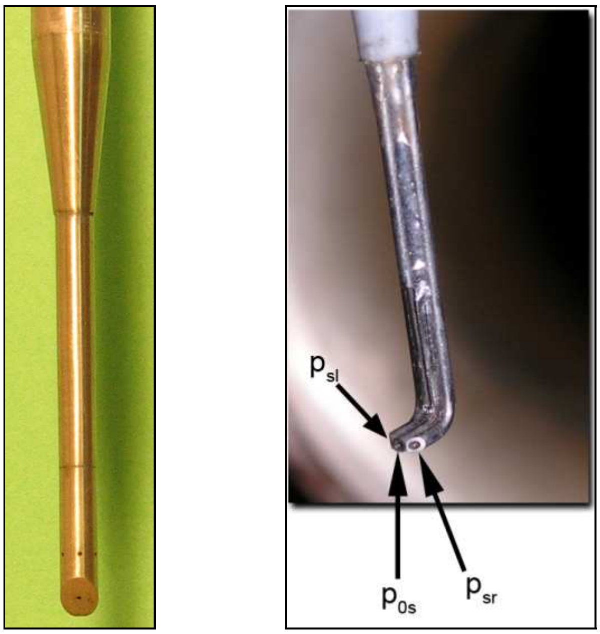

Figure 2: **Photos of Cylindrical Probe (left) and Cobra Probe (right)**

Calibration Procedure

From the pressures at the probe head following different probe coefficients are calculated (Main et al., 1994):

Angle coefficient: $$C_\alpha = \frac{p_{sl} - p_{sr}}{p_{0s} - p_{sm}} \quad \text{where} \quad p_{sm} = \frac{p_{sl} + p_{sr}}{2} \tag{1}$$

Conventional Mach number coefficient: $$C_{Ma} = \text{Ma}\,(p_{sm}, p_{0s}) \tag{2}$$

Mach number coefficient from base pressure: $$C_{Mab} = \text{Ma}\,(p_{bu}, p_{0s}) \tag{3}$$

where the Mach number is calculated according to following formula:

$$\text{Ma}\,(p, p_0) = \sqrt{\frac{2}{\kappa - 1}\left[\left(\frac{p}{p_0}\right)^{\frac{1-\kappa}{\kappa}} - 1\right]} \tag{4}$$

INCIDENCE ANGLE VARIATION

The probe angle coefficient C_α is utilized to get the flow angle from a probe measurement. The results of calibration of the four probes are shown in Figure 3, exemplarily for a Mach number of 1.0.

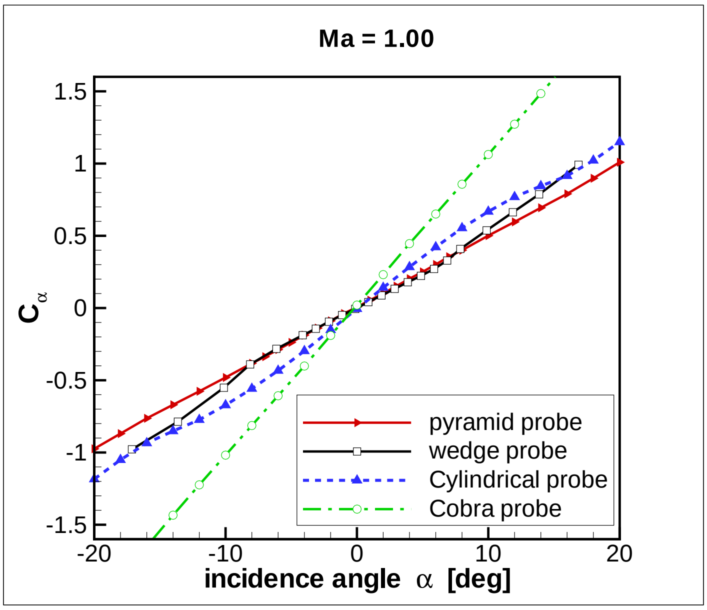

Figure 3: **Angle coefficient C_α at Mach number 1.00**

The sensitivity of the probe coefficient C_α to flow angle is best for the Cobra Probe (the gradient is the steepest). Furthermore, the probe coefficient is linear and according to the calibration in the whole Mach number range, the probe coefficient C_α of the Cobra Probe is nearly independent of Mach number. The gradients of probe coefficient C_α of the other probes are rather similar among each other. The Pyramid Probe exhibits a linear probe coefficient, too. The linear range of the probe coefficient of the Wedge Probe is much narrower, due to the smaller inclined angle at the probe head. The gradient (sensitivity) of C_α is dependent on the inclined angle at the probe head, the shape of the probe head and on the distance of the pressure tappings to the wedge (or pyramid) apex. The large inclined angle of 90 deg at the head of the Cobra probe compared to 30 deg of the Wedge Probe leads to a superior sensitivity and linearity, but the sensitivity of the Pyramid Probe (60 deg inclined angle) is not superior to the Wedge Probe. After all, the probe coefficient C_α of the Cylindrical Probe is nonlinear, due to the position of the angle holes at $\phi = 60$ deg, i.e. far from the central hole (p_{0s}).

MACH NUMBER VARIATION AT ZERO INCIDENCE

In Figure 4 the Mach number coefficient, C_{Ma}, plotted versus Mach number and its gradient are shown for the four 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. The gradients are calculated from the difference of measured points at discrete Mach numbers therefore the calculated gradients are not very exact but nevertheless give an adequate impression. According to Figure 4 the Cylindrical Probe head is superior at Mach numbers less than 0.8, but really bad near Mach number Ma=1.1. The Cobra Probe which was superior in angle sensitivity is the worst one regarding Mach number determination. In case of the Cobra Probe the gradient of the C_{Ma}-curve near Ma=1.1 is even slightly negative.

Probes aligned to flow direction like the Wedge and the Pyramid Probe exhibit the theoretically predicted behaviour of an insensitivity region centred at Ma=1. For probes that have to be inserted radially like the Cylindrical and the Cobra Probe, the probe shaft causes additional disturbances to the flow. In transonic flow the combined disturbances of probe head and shaft extend the insensitivity range up to a Mach number of 1.3. Some probes even show a non-monotonic relation of probe coefficient to Mach number as for example the Cobra Probe.

The practical implications of the low gradients in the transonic range is best seen in Figures 5 and 9 where the resulting probe error due to error propagation regarding the Mach number is depicted. These error curves of the Mach number are obtained by utilizing the evaluation programs normally applied at the wind tunnel. The measured probe pressure values of the calibration are used as input to the evaluation program. Then in the ideal case the evaluation program will compute a Mach number equal to the true Mach number at calibration. Subsequently a further computation with the evaluation program will be conducted with a slightly changed probe pressure as input. For example by changing a probe pressure (p_{0s} in the present case) by 0.1% the deviation of the newly obtained 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. Of course, the measurement scatter of the calibration produces a scatter of the error values, too.

For Mach numbers Ma>0.8 the Wedge Probe obviously has the lowest Mach number error. But even for this probe the 0.1% error of the pressure p_{0s} is magnified by a factor of 20 to obtain an absolute Mach number error of 0.02 near Ma=1. For the Pyramid Probe the error propagation factor

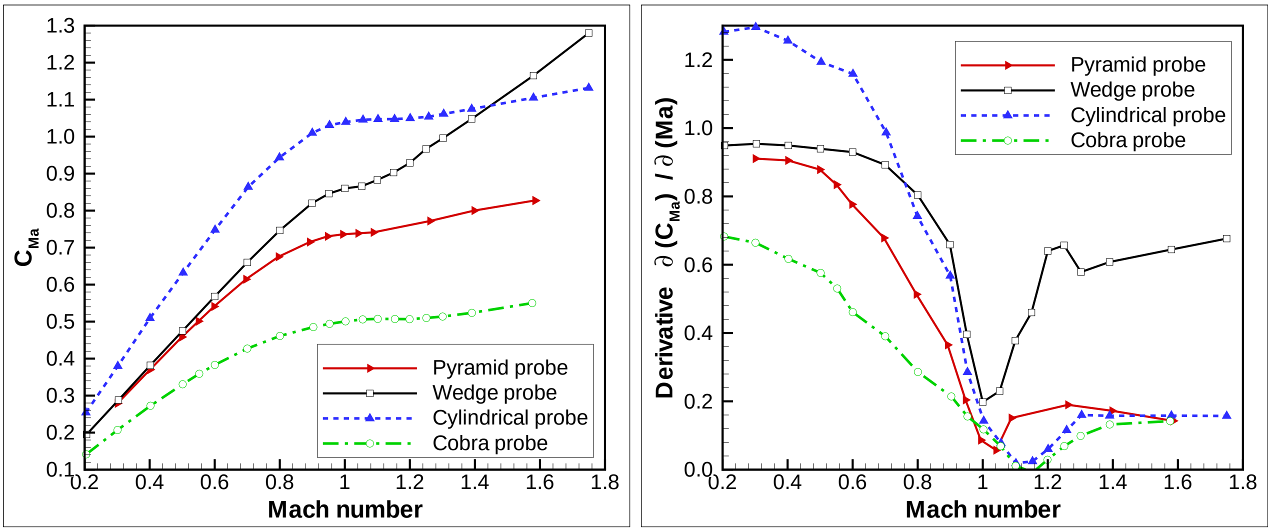

Figure 4: **Mach number coefficient, C_{Ma}, at zero incidence and its gradient**

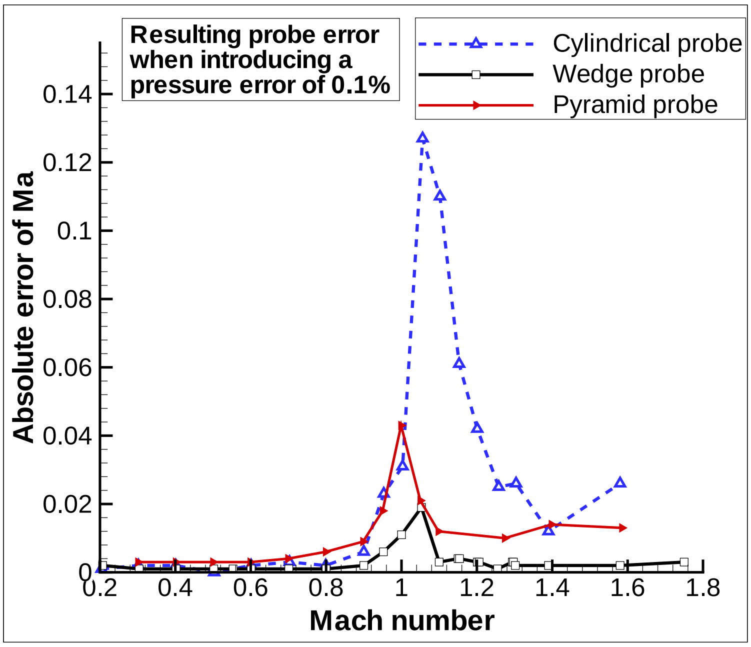

Figure 5: **Probe error due to error propagation**

is 40. The difference between the Pyramid and the Wedge Probe is due to the larger included angle of the Pyramid Probe at the probe tip. For the Cylindrical Probe and similarly for the Cobra Probe the error propagation factor is ≈140. One may conclude that probe configurations with an intrusive probe shaft which can be easily inserted in realistic axial turbomachine geometries are inevitably insensitive not only at Ma=1, but also in a Mach number range from 1 to 1.3.

The above statement is further supported by Figure 6 where the pressure distribution at the probe

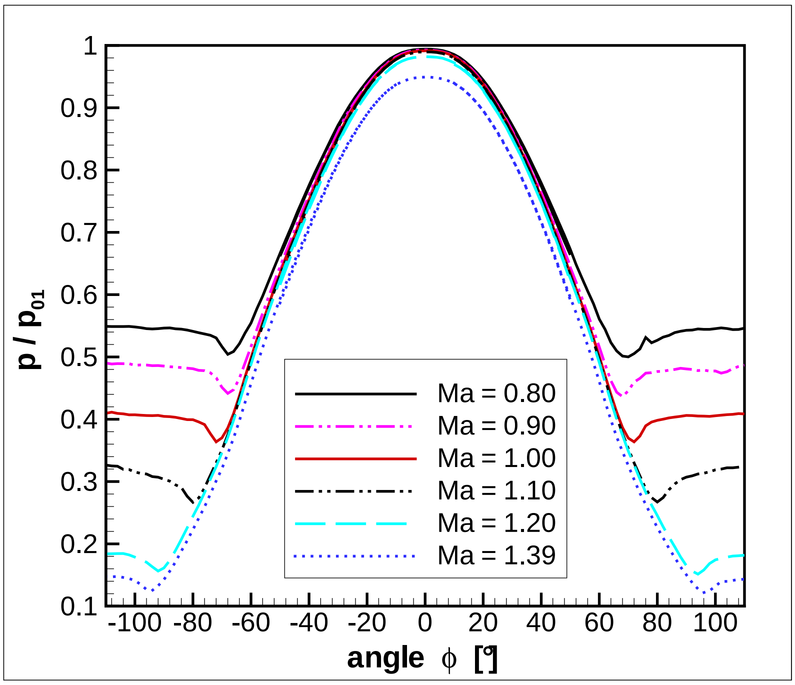

Figure 6: **Pressure distribution at cylindrical probe head**

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.

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 change of the Mach number. 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 front 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.

THE UTILIZATION OF BASE PRESSURE

When using base pressure as an additional probe pressure 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.

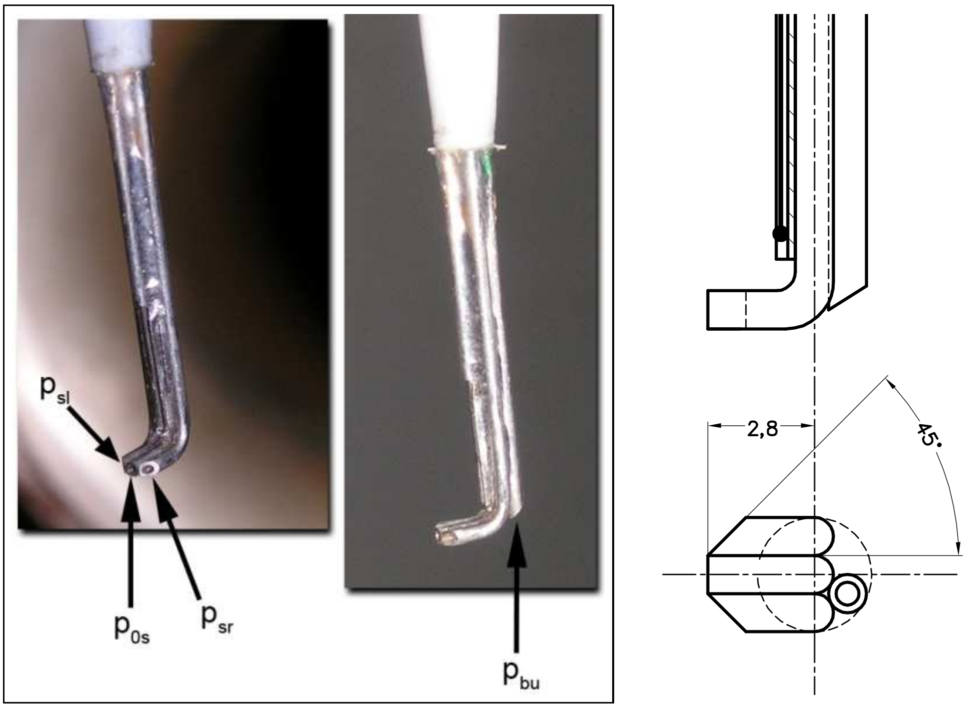

Figure 7: **Cobra Probe with added base pressure tapping**

Transonic Cobra Probe

It was decided to add the base pressure tapping to a conventional Cobra type probe (see 'p_{bu}' in Figure 7). Conventional Cobra probes are worse compared to cylindrical probes but they are easy to manufacture and enable measurements close to endwalls. Furthermore all tubes of the Transonic 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. The base pressure of the Cobra Probe is taken with an additional pressure tube at the back of the original Cobra Probe stem. It is cut obliquely in order to produce a separation at the sharp edge in case a flow velocity appears at this location, e.g. if a positive radial flow angle occurs.

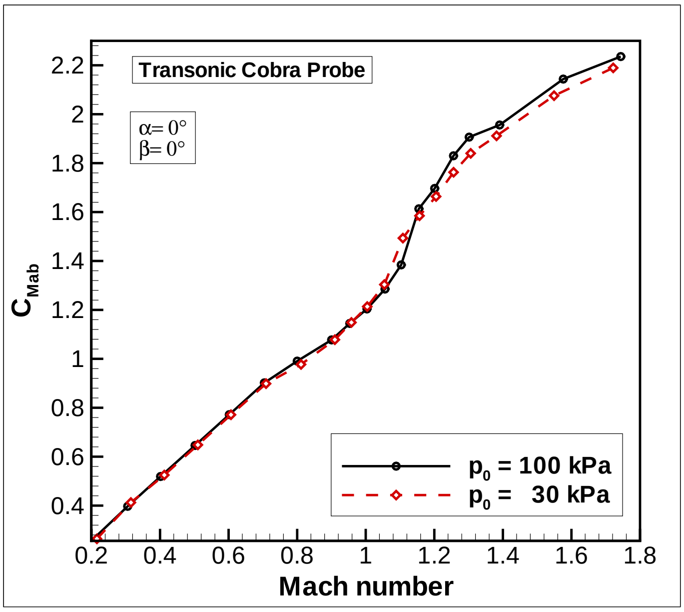

Figure 8: **Mach number coefficient, C_{Mab}, at zero incidence**

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}). The calibration of the new probe was conducted at several peripheral angles, α, and radial angles, β, at two Reynolds numbers and at 19 Mach numbers. In Figure 8 the Mach number coefficient, C_{Mab}, is shown for incidence angle zero. 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.

The probe error due to error propagation regarding the Mach number was calculated for the conventional and the new Cobra Probe in the same way as for the other probes (see Figure 5) and the resulting probe errors are shown in Figure 9. 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 0.8. In a recent measurement campaign only by using the base pressure tube reasonable results for the Mach number could be obtained in the transonic regime.

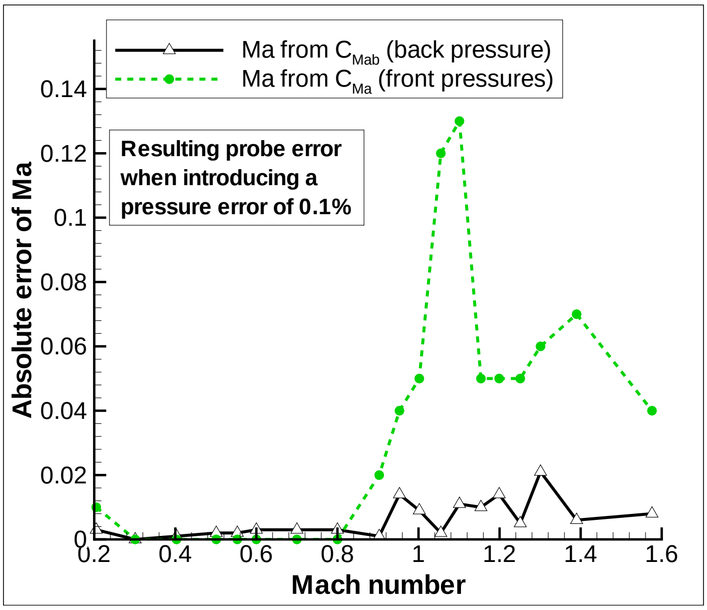

Figure 9: **Comparison of probe errors for the Transonic Cobra Probe**

Single-Sensor Kulite Probe

To measure the unsteady flow downstream of a rotor a Single-Sensor (Kulite) unsteady pressure probe was designed and manufactured (see Figure 10). The probe head comprises a steady Pitot tube and below a differential Kulite sensor. The steady Pitot pressure is the reference pressure of the Kulite sensor. The probe is inserted radially into the flow accordingly its shaft is disturbing the flow, too. This probe was originally designed to determine the unsteady total pressure in subsonic flow. In order to obtain a frequency response as high as possible the Kulite sensor is flush-mounted and not recessed (Sieverding et al., 1995). This has the consequence that the probe is more sensitive to incidence angle, which is not a desirable feature for a Pitot probe. Accordingly probe measurements had to be performed at several circumferential angles of the probe and it suggests itself to perform at least three measurements at different angles to derive not only the phase-resolved total pressure, but yaw angle and Mach number, too (Kupferschmied et al., 2000).

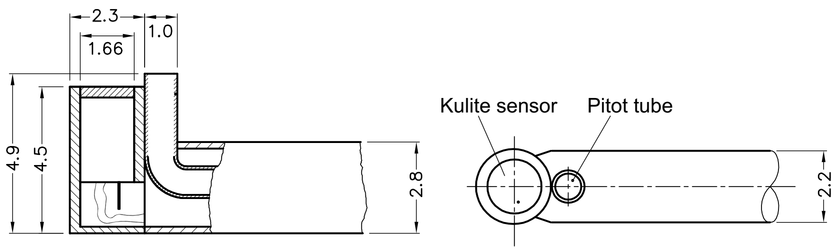

Figure 10: **Head of the Single-Sensor Kulite Probe**

It is absolutely necessary that the three probe circumferential angles have to include the real flow angle, one probe incidence angle should be near ($\pm 10°$) to the instantaneous flow angle, the other two should be at least $\pm 30°$ away from it (Kost, 2005). Therefore you have to have an a priori knowledge of the unsteady flow angle range. This is normally not fulfilled. Accordingly it turned out to be necessary to measure at four probe circumferential angles in order to get a satisfactory result. Even then the scatter of the phase-resolved flow quantities may be rather large especially for the Mach number (accuracy 5%) whereas total pressure (in the absolute system) can be determined rather well (accuracy 0.4%). The scatter of the resulting instantaneous flow angle is in-between. The interpretation of the unsteady flow results is much easier if the flow values can be converted from the absolute to the relative system (rotor fix frame). But by this conversion large errors in the absolute Mach number cause large errors in all relative flow quantities.

The large scatter of the unsteady Mach number became unbearable if locally the absolute Mach number exceeded 0.85 and it seemed advisable to add a further measurement turning the Single-Sensor Kulite Probe by 180 deg to measure a pressure trace in the base region. First tests of such a procedure yielded satisfactory results. The measurements at a 5th probe angle in the base region of the Single-Sensor Probe diminished the scatter of the results not only at Mach numbers $>$0.8, but also at lower Mach numbers. It is possible to average over the Mach number derived from the front pressures and the Mach number derived from the ratio of base pressure to total pressure thereby getting a more reliable result. Of course the procedure takes more time if the Single-Sensor Probe measurement has to be carried out at more angles.

CONCLUSIONS

- A constraint exists for probes in transonic flow which leads to an insensitivity to Mach number changes at Mach number unity.
- Probes with an intrusive shaft (perpendicular to flow direction) exhibit an insensitivity region at Mach numbers 0.9 - 1.3 which causes very large errors regarding the determination of Mach number nearly independent of the shape of the probe head.

- Probes aligned to flow direction exhibit the theoretically predicted behaviour of a small insensitivity region centred at Ma=1. For such probes the error regarding Mach number determination increases with the included angle at the probe head.
- A closer look onto the pressure distribution of a blunt body reveals that only the front part of a probe is subject to the transonic constraint while base pressure is not affected.
- A new probe with radial shaft was designed where a base pressure tapping was added to a conventional Cobra type probe. The relation of Mach number to the base pressure probe coefficient is strictly monotonic and especially favourable in the transonic range where the conventional probe coefficient fails. Regarding Mach number error the use of the base pressure is favourable for Mach numbers above 0.8.
- 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. There are some doubts about the application of the same procedure to a cylindrical probe. But, for a probe with an intrusive shaft and a wedge type head the addition of a base pressure tapping should be advantageous, too.
- When measuring with a Single-Sensor (Kulite) probe downstream of a rotor the additional measurement of base pressure improves the determination of unsteady Mach number at subsonic conditions, too.

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