Paper 18

<u>*Session 6 - Pressure Probes*</u>

INVESTIGATION ON MINIMIZING BLOCKAGE EFFECTS OF MULTI-HOLE PRESSURE PROBES IN TRANSONIC FLOW

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1. Introduction

This paper presents some of the recent developments made at the institute of Jet Propulsion and Turbomachinery on the topic of miniaturized multi-hole pressure probes to be utilized in transonic turbine flows.

The application of multi-hole pressure probes is a wide-spread measuring technique on engine component testing in research institutes as well as in industrial laboratories though noncontacting measuring techniques are in progress.

One of the disadvantages of this measuring technique is due to the interference of the flow field by the probe introduced into the flow. Therefore there is a strong requirement to avoid the disturbance of the flow as much as possible, which can be met by a miniaturization and an adequate design of the probe head and shaft.

The first part of the presentation will be dedicated to the efforts made in regard to a further miniaturization. The second part of the paper deals with a correction method, which has been developed to eliminate the faults in the flow angle determination due to the finite size of probe heads.

2. Presentation of a New Three-Hole Pressure Probe

2.1 Design of a New Three-Hole Pressure Probe

High loaded transonic turbine stages are characterised by small channel heights with narrow axial gaps. To minimize the influence of the pressure probes on the flow field, efforts were made to miniaturize the probes. On the basis of the good experiences with the five-hole probe, which was presented at the 9th Symposium in Oxford, further developement aimed at reducing the size of the probe heads.

If the dimensions of the five-hole probes are reduced furthermore one comes across problems, which are due to the production. The smallest probe head, which was fabricated, had the diameter of 1.5 mm. This presents the state-of-the-art in miniaturization (Fig. 1).

Nevertheless investigations showed that the reasonable probe head diameter should not be smaller than 2.0 mm. This size refers to an acceptable response time of the pressure holes. The response time increased by a factor of 3, if the probe head diameter was reduced to 1.5 mm.

Due to the small channel heights in high pressure turbine stages the radial component of the flow vector can be neglected. Therefore the threedimensional measuring problem can be reduced into a plane problem without making substantial faults.

On the basis of the well-known five-hole probe the head geometry was changed in a way, that the upper and lower holes were removed (Fig. 2). This leads to a new type of a three-hole pressure probe with a conical head. This probe shows the same good aerodynamic behaviour in supersonic flows as the above mentioned five-hole probe.

2.2 Comparison of Different Probe Types

Four transonic pressure probes are presented as shown in fig. 3. A comparison of the probe characteristics was made between the five-hole /1/, the new three-hole probe /2/ the NASA three-hole probe /3/ and a cobra-type three-hole probe/4/. The calibration of three-hole probes are best evaluated by diagrams, which are a function of $K_\alpha = f(\alpha)$.

Definition of K_α: $$K_\alpha = \frac{p_3 - p_1}{\Delta p}$$

with : $$\Delta p = p_0 - \frac{p_3 + p_1}{2}$$

The indices refer to the pressure hole numbers in Fig. 4.

The characteristics of the probes were investigated at the Mach numbers M = 0.6 and M = 1.2. The user demands for a high angle resolution coupled with a low total pressure loss in pressure hole "0". The quantity of the gradient in Fig. 5 gives information about the resolution of the pressure probes. Analysing these diagrams the three-hole probe /4/ shows at M = 0.6 as well as at M = 1.2 the best resolution because of the axial arrangement of the pressure holes. The most unfavourable resolution can be stated for the probe /3/.

It is evident, that there is a mismatch at the origin of the characteristics for the probes /3/ and /4/ in supersonic flow (Fig. 5). To get more detailed information about the behaviour of probe /4/ in supersonic flow the Schlieren-technique was applied. By assistance of this technique the flow field around the probe could be visualized.

It is obvious, that the cobra-type probe has unfavourable characteristics in supersonic flow. At Mach number M = 1.2 one can find a detached shock at the probe head. Moreover there is a asymmetric shock configuration (Fig. 6), which must be explained by fabrication tolerances. Two tubes, which are grinded under the angle of 45^0, are soldered with the center tube. When producing the probe in that way, it is nearly impossible to get the same angle of attack at the right and the left tube. The consequence is an imperfect zero adjustement at a subsonic Mach number, which produces a severe effect in a supersonic flow.

The superior advantages of the new three-hole probe /2/ are the symmetric geometry of the head, which is a turned part, and with that the good arrangement of the pressure holes. In supersonic flows one good flow conditions can be observed because of the conical head of the probe. Moreover the length of the head could be reduced compared with that of the five-hole probe /1/.

The newly developed three-hole pressure probe represents related to its high resolution and its geometrical shape an improvement of the efficiency of the present existing pneumatic pressure probes.

3. A Computer Program for the Correction of Measurement Results at Flow Field Acquisition

3.1 Description of the Correction Method

By continuing the miniaturization of pressure probes the interaction flow phenomena in a turbine stage can be reduced to a minimum. Nevertheless the finite size of the probe leads to faulty measuring results in flow fields with great pressure gradients (Fig. 7). It is mainly caused by the fact, that the pressure holes do not survey exactly the flow condition in one point of the flow field (Fig. 8).

According to the pressure distribution and the wake of the blades a great pressure gradient is existing in the region of the trailing edge. It is the task of a computer program to correct the influence of pressure hole arrangement on the measuring results /5/.

This correction procedure is only available, if the measuring point is surrounded by a satisfactory number of neighbouring points. With the help of the neighbouring points the required pressures can be calculated with a suitable interpolation method by using the pressure distribution of the pressures p_1 to p_4.

The definitions of the angles used in the following considerations are mentioned in Fig. 4.

When making measurements with a multi-hole pressure probe the true measurement locations of the holes 1,2,3,4 are not the same as the one of hole 0. To evaluate the sliding distances, the geometry of the probe is described by two circles through the holes 0,1,3 and 0,2,4, which are perpendicular (Fig. 9).

Fig. 10 shows, that with a flow angle α the pressure holes 1 and 3 are off-center by the distance Δs_1 and Δs_3. These distances are only dependent on the head geometry and the flow angle. The angle can be calculated iteratively by the distances Δs_1 and Δs_3. By each step of the calculation not only the distances but also the pressure can be determined. The pressure is needed to get the values K_α, K_β, etc. by using the calibration function.

The following considerations use a system of coordinates with the origin in the pressure hole 0. The measuring plane is defined by the plane x-y.

Fig. 10 shows a probe head in a plane formed with the angle $\alpha_V = 0$. Below this figure one finds the projection of a circle in the x-z- plane, which is described through the holes 0,1 and 3. Beside these holes the position of the holes 2 and 4 can be perceived. That means, that the pressures of these holes must be shifted in circumferential direction. The pressure holes and the probe axis incline the angles γ_i. According to Fig. 10 the shifting of the pressures p_1 and p_3 in the x-direction can be written as:

$$\frac{\Delta u_i}{r_k} = \cos\beta_V \cdot \sin\alpha_V + \frac{\sin\gamma_i}{\sin\gamma_i'} \cdot \sin(\gamma_i' - \alpha_V) + \left[\frac{\sin\gamma_i}{\sin\gamma_i'} \cdot \cos(\gamma_i' - \alpha_V) - \cos\beta_V \cdot \cos\alpha_V\right] \cdot \tan(\alpha_V - \alpha)$$

with $\gamma_i' = \arctan \frac{\tan \gamma_i}{\cos \beta_v}$

$i = 1,3$

and the shifting of the pressures p_2 and p_4 in circumferential direction:

$$\frac{\Delta u_i}{r_k} = \left[\cos \beta_v - \cos(\gamma_i - \beta_v)\right] \cdot \left[\sin \alpha_v + \cos \alpha_v \cdot \tan(\alpha - \alpha_v)\right]$$

$i = 2,4$

If one imagines the circle with the holes 0,2 and 4 projected in the y-z-plane, the shifts in y-direction are obtained by changing the angles α and β as well as α_v and β_v. The total shifting distance can be determined by a vector addition of the components of the shifts in x- and in y-direction.

Using other probe head geometries this correction method is working likewise. The angle of the holes γ_i must be chosen according to the selected probe head geometry (Fig. 11).

The correction of a temperature measurement is made analogously to the pressure shift evaluation (fig. 11) of probe head geometries.

3.2 Results of Corrected Measurements

The correction method, which is described above, was applied to flow field measurements in the compressor of the jet engine ATAR 101 F2 /6/. The flow field covers 10 radial positions and 20 circumferential positions.

The effect of the correction is seen most clearly in the trailing edge region. Almost no change can be recognized in the region of homogeneous flow (Fig. 12). In order to detect the great gradient of the flow in the wake region, a lot of measuring points in circumferential direction were taken. The distances between the measuring points became so small, that they fall short of the distances between the pressure holes of the probe. This means, that the shifting distances of the pressures p_1 and p_3 get larger than the distances between the measuring points.

The results of the correction of the variables α, β and M can be taken from Fig. 13. It can be recognized that the variables in the region of the wake are overrated.

4. Summary

In this report the latest efforts on the topic of the miniaturization of pneumatic pressure probes are presented. The aim of the developement of the new three-hole pressure probe was to hold the quality-standard as was attained with the five-hole conical pressure probe presented on the 9th Symposium on Measuring Techniques /1/. Moreover it has been the intention to minimize the interference effects of the probe heads onto the flow. The aerodynamic characteristics were compared with the different probe types.

According to the finite size of the head of a multihole probe it is impossible to measure exactly one flow field point. This leads in flows with great pressure gradients to untolerable faults in the evaluation of the flow angles and velocities. A correction method to eliminate the influence of the finite distance of the pressure holes was presented. The improvement was achieved by applying this method to the evaluation of the flow field of a multistage axial compressor.

5. Bibliography

/1/ Koschel, W.; Pretzsch, P.
"Development and Investigation of Cone-Type Five-Hole Probes for Small Gas Turbines"
9th Symposium on Measuring Techniques for Transonic and Supersonic Flows in Cascades and Turbomachines, Oxford 1988

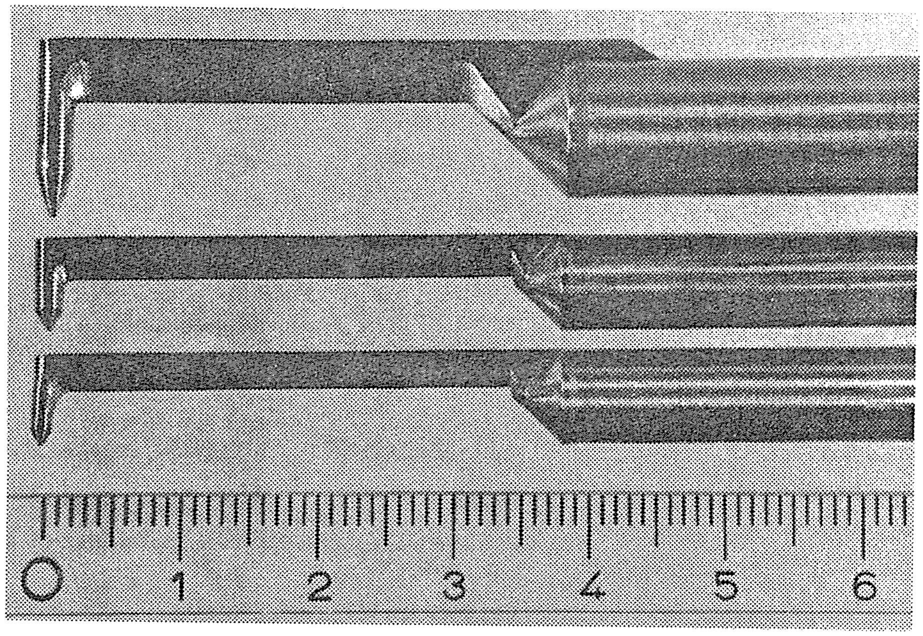
/2/ Pretzsch, P.
"Ein Beitrag zur Leistungsanalyse und Auslegung transsonischer Axialturbinenstufen"
Dissertation 1989, RWTH Aachen

/3/ Glawe, G. E.; Krause, L. N.; Dudzinski, T. J.
"A Small Combination Sensing Probe for Measurement of Temperature, Pressure and Flow Direction"
NASA Technical Note TN-D-4816

/4/ Saravanamuttoo, H. I. H.
"Recommended Practice for Measurement of Gas Path Pressures and Temperatures for Performance Assessment of Aircraft Turbine Engines and Components"
AGARD Advisory Report No. 245

/5/ Vinnemeier, F.; Simon, L; Koschel, W.
"Correction Method for the Head Geometry Influence of a Five-Hole Pressure Probe on the Measurement Results"
Technisches Messen tm 57, Juli/August 1990

/6/ Gallus, H.E.; Koschel, W.; Vinnemeier, F.
"Theoretische und experimentelle Untersuchung der Seitenwandgrenzschichtentwicklung und der Auswirkung radialer Mischungsvorgänge in mehrstufigen Verdichtern"
Abschlußbericht experimenteller Teil
FVV Forschungsberichte Heft 380-2, Frankfurt 1988



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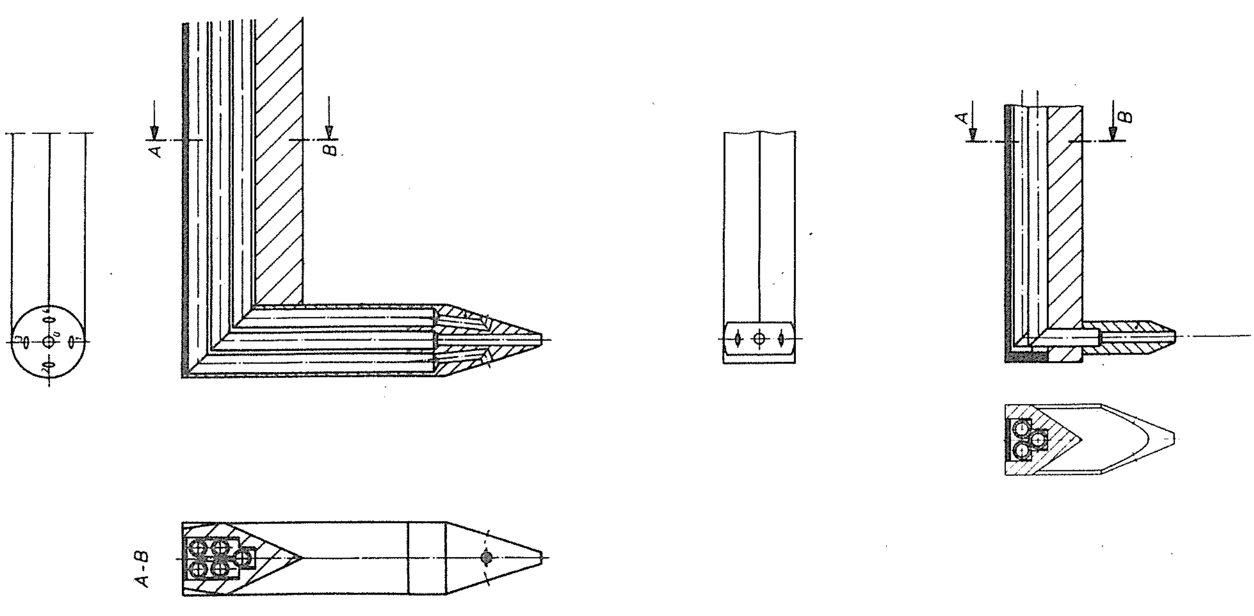
Development of Miniaturization of Conical Five-Hole Pressure Probes

Brussels '90

figure 1



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Three-Hole and Five-Hole Probe

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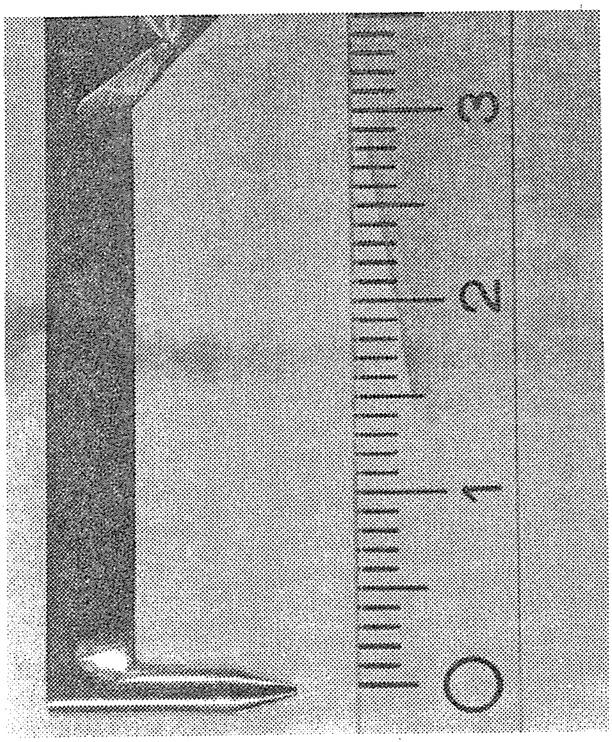
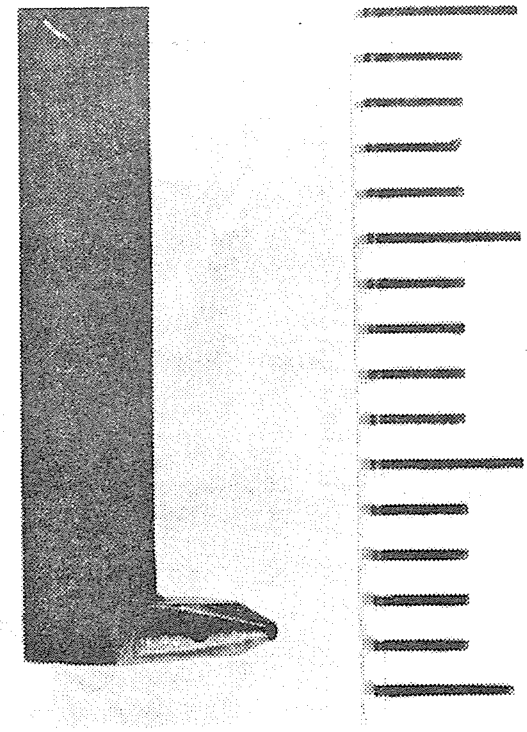
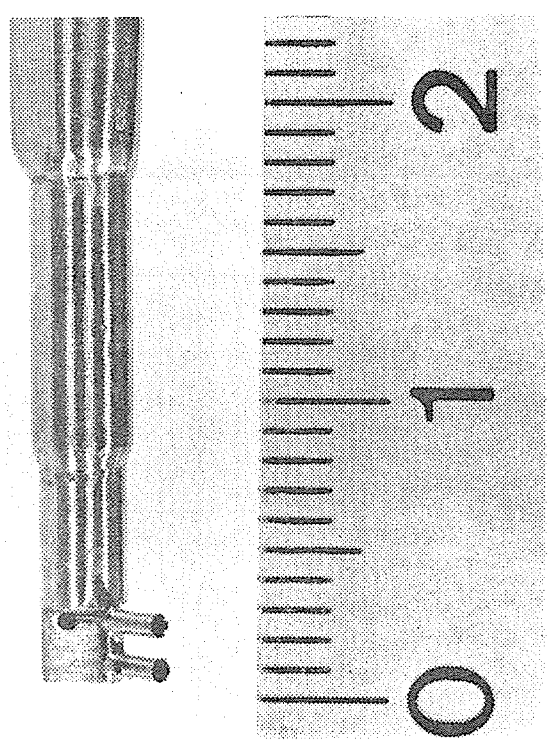
figure 2



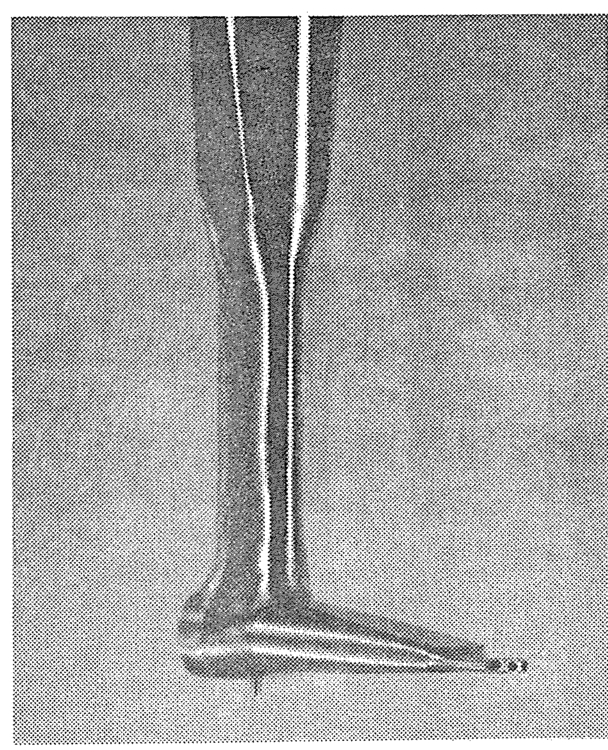
five- hole- probe /1/



three- hole- probe /2/



NASA- probe /3/



Cobra- probe /4/

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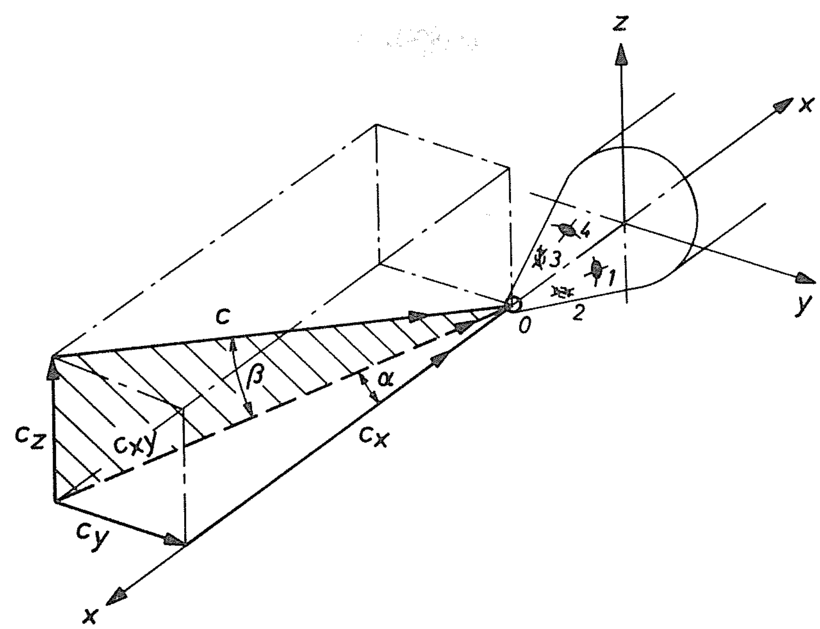

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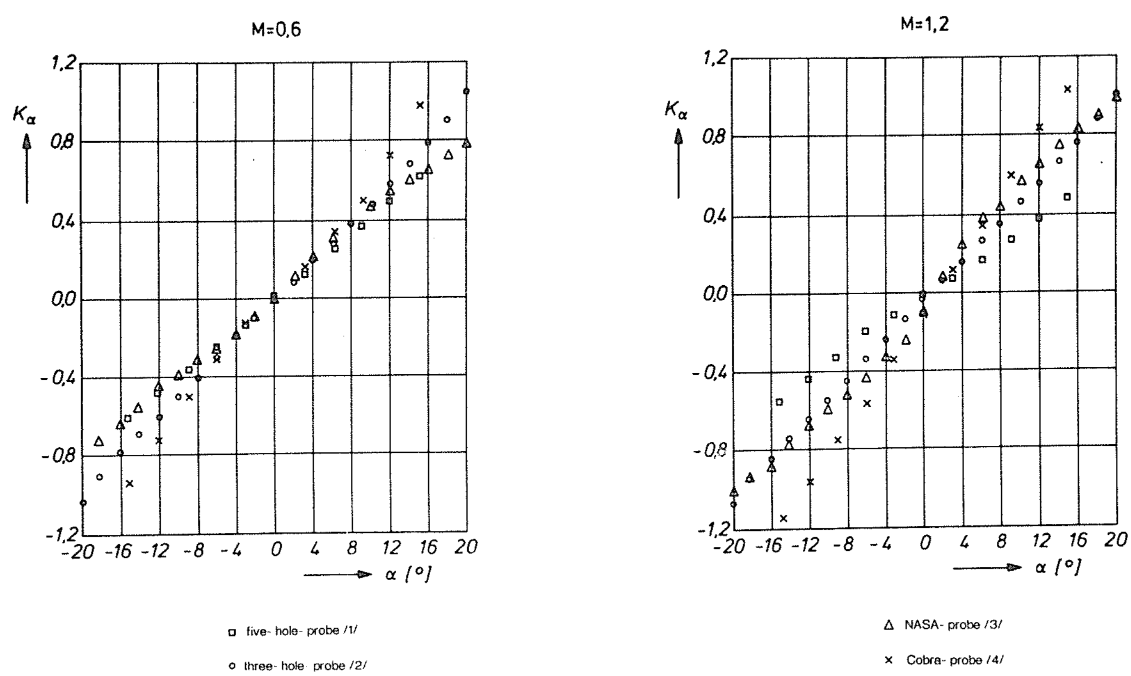

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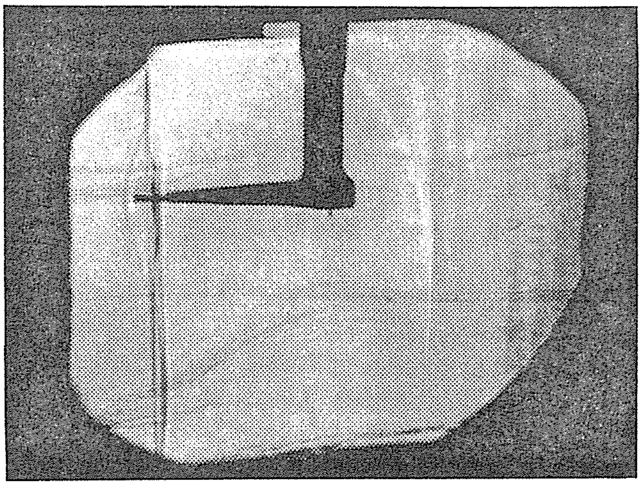
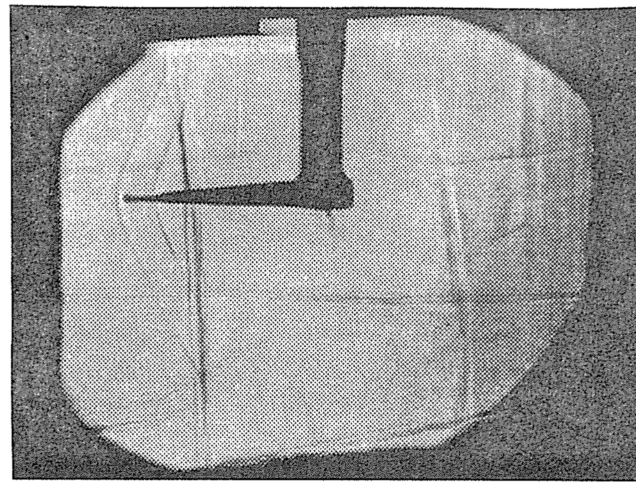


Yaw Angle = 15°



Yaw Angle = -15°

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Schlieren-Picture of Three-Hole-Pressure-Probe /4/

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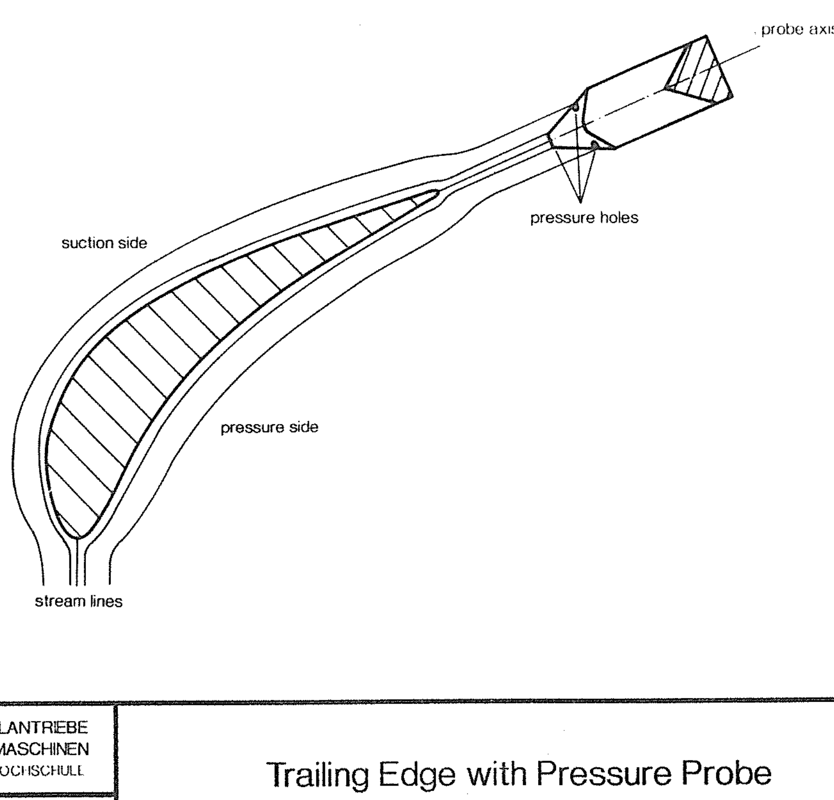
figure 6



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Trailing Edge with Pressure Probe

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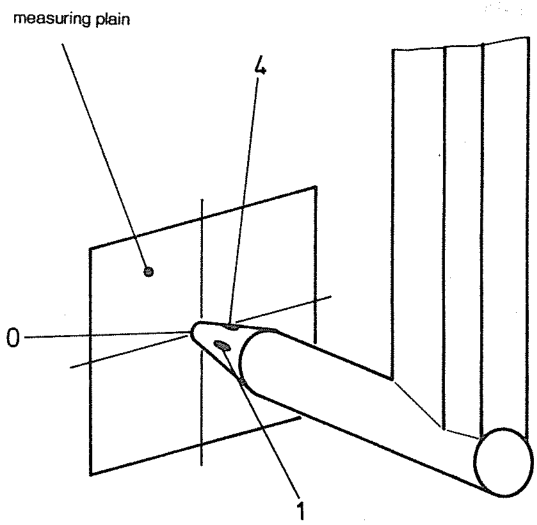
figure 7



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Measurement Plain

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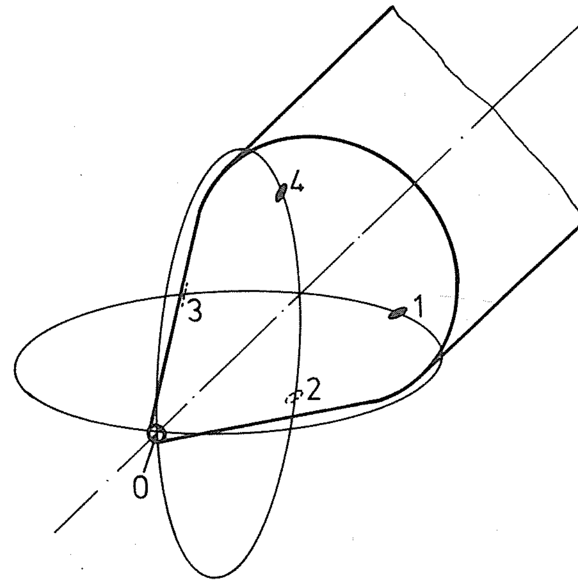
figure 8



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Perpendicular Circles through Pressure Holes

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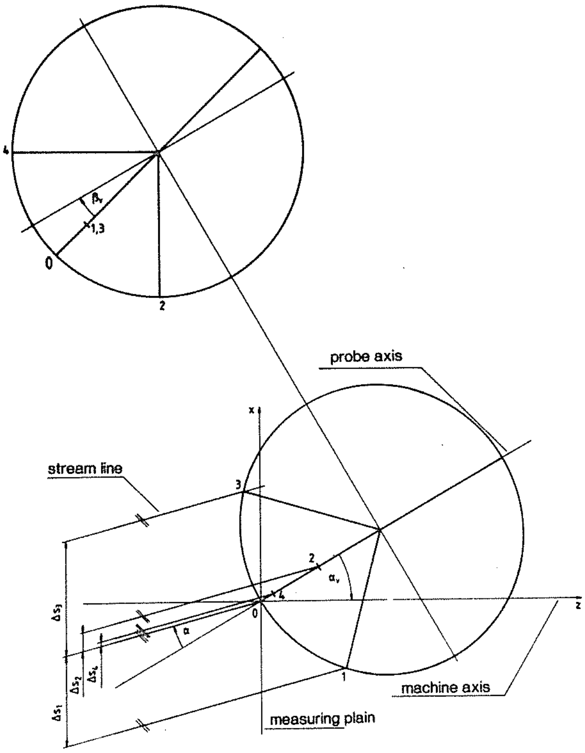
figure 9



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Circumferential Displacement

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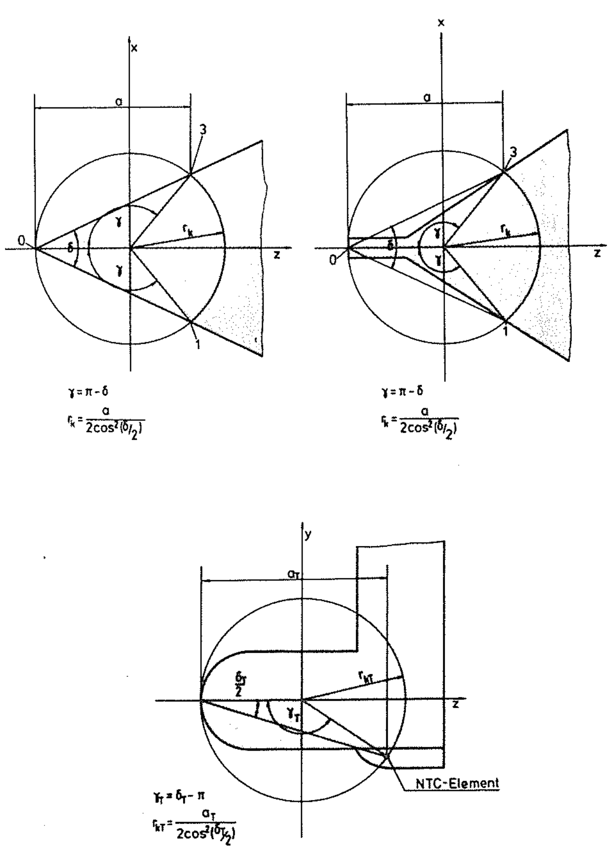
figure 10



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Probe Heads with Angles of Pressure Holes

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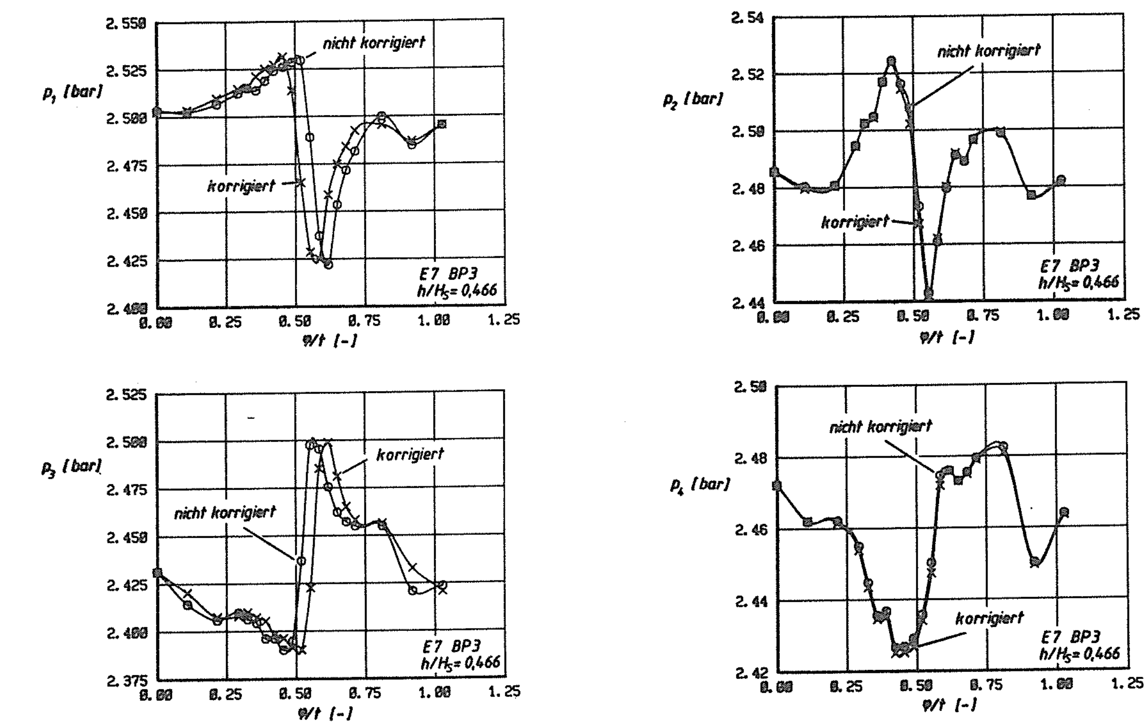
figure 11



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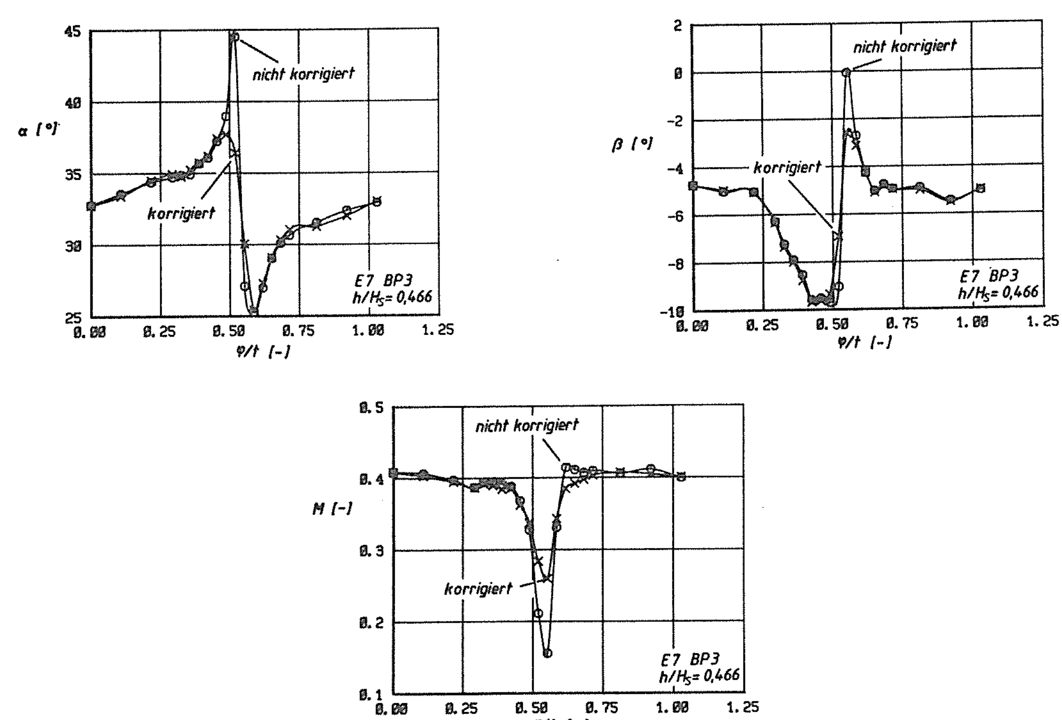

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