SEMICONDUCTOR WEDGE PROBES FOR UNSTEADY FLOW MEASUREMENT

by

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Summary:

Two semiconductor probes for measuring unsteady pressure and flow angle fluctuations are presented. As the accuracy of the absolute pressure measurement by piezo-resistor transducers is still ambiguous a superposition of pneumatical data and time dependent flow conditions is applied.
A theoretical method to approximate the calibration characteristics for the probes has been developed with regard to Reynoldsnumber effects and the influence of isentropic coefficient. The results are compared with an evaluation of the calibration characteristics in steady flow in a closed calibration channel.

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1. Introduction

For the development of reliable highly loaded transonic and supersonic compressor stages a detailed knowledge of unsteady flow effects is required. To perform measurements of flow angle and pressure fluctuations behind a supersonic compressor rotor two probes have been designed at the "Institut für Strahlantriebe und Turboarbeitsmaschinen" /1/. Probe characteristics with respect to the influence of Reynoldsnumber and isentropic coefficient are investigated and presented in this contribution.

2. Design of semiconductor-probes

For a cranked probe stem schlierenoptical visualization showed strong interactions between the detaching stem shock and the probe head /1/. This would cause an abrupt change of the probes' characteristic especially in case of low supersonic machnumbers and big yaw angles. In addition, the influence of pitch angle on the yaw angle characteristic can not be neglected.

To avoid this, the probes have been designed as wedge type probes, fig. 1 and 2. Pneumatic pressure taps on the lateral sides of the wedge allow adjusting the probes with respect to the time averaged flow. Pressure fluctuations are measured by a Kulite XCQL - Transducer (fig. 1) or flat transducers of Kulite LQL - series (fig. 2).

In a first arrangement of the total pressure probe, the application of a transducer without protection shield in front of the pressure sensitive diaphragm was not successful. The transducer was destroyed after a few minutes measuring time behind the rotor. A design with protected transducers decreases the risk of damage. The comparison of the output signal of protected and unprotected transducers in a free jet shows that the influence of damping is negligible /2/.

3. Calibration of the probes

3.1 Static calibration

The static pressure calibration shows a remarkable influence of temperature to the offset drift. For the measurement this has no effect on the unsteady pressures because time averaged data are registered pneumatically with external transducers. As a constant voltage supply of the transducer bridge circuit was applied, a non-negligible change of transducer sensitivity was noticed. As a consequence of this, static calibration was carried out with additional regard to the temperature level. A variation of linearity due to temperature effects did not occur.

3.2 Experimental Set-Up for the flow calibration

The test facility is a closed calibration channel which can be run in air or an air/freon - mixture. For the variation of Reynoldsnumber by increasing or decreasing the pressure level an additional air-compressor and a vacuum-pump are connected to the closed loop. Subsonic Machnumbers are controlled by the supply-compressor speed, whereas supersonic Machnumbers can be generated by exchangeable Laval-nozzles. The test section is shown in fig. 3.

3.3 Determination of probes' characteristic

The determination of yaw angle characteristic was carried out with variations of pressure level and Machnumber. The results are given in fig. 4 and fig. 5, showing the voltage-difference to the adjusted position of the probe. Slight differences between right and left transducer are due to different amplifiers.
The computation of dimensionless similarity coefficients including the pressures on the lateral sides and the total pressure can not describe in a satisfactory manner the characteristic of the probe and results in angle errors up to 20 %. The variation of pressure level in these experiments means a change of Reynoldsnumber from

$2.4 \cdot 10^4$ to $8.5 \cdot 10^4$ (based on the wedge width). Obviously the dependence of the calibration on the Reynoldsnumber is not small enough to be neglected within the calibrated range. The Reynoldsnumber for the measurements behind the supersonic rotor is about $2.4 \cdot 10^5$ and cannot be realized in the calibration tunnel. An approximation including yaw angle, Machnumber and in addition Reynoldsnumber as independent variables would mean an extrapolation to the environment in the compressor, which may cause incalculable errors. Therefore, the characteristic is determined directly by a description of the supersonic flow around the wedge.

In the case of the total pressure probe for subsonic Machnumbers total pressure is registered exactly by the probe. The assumption of a normal shock in front of the wedge and the total pressure tube makes the determination of total pressure also possible for supersonic Machnumbers. A comparison of total pressure losses calculated with basic equations for the normal shock on the one hand and measured data on the other hand shows good agreement, fig. 6.

The total pressure behind the shock remains constant over a range of +-20 degree yaw angle variation.

4. Calculation of the yaw angle characteristic

Depending on the direction of the flow vector several flow conditions around the wedge have to be distinguished. Assuming the flow direction behind the shock is parallel to the wedge surface the flow turning angle β is defined as follows:

left : $\beta = \beta_{wedge} + a$

right : $\beta = \beta_{wedge} - a$ (β_{wedge} = 15 deg.)

Then a division into three domains is possible (fig. 7) :

I	β	<	0		Prandtl-Meyer-Expansion
II	0	<	β	< β_{max}	attached shock
III	β_{max}	<	β	< 90 deg.	detached shock

Whereas configurations I and II can be calculated with basic equations of supersonic aerodynamics, the third domain has to be approached by considering the extreme point β = 90 degree. For β = 90 degree the assumption of a normal shock is made, i. e. the pressure registered by the transducer is interpreted as the total pressure behind a normal shock /3/.

A cubic spline interpolation based on data points from configurations I and II and the extreme point β = 90 deg. is utilized for the description of the yaw angle characteristic.

Fig.8 gives a comparison of this approach to the experimental results. The agreement is quite good, the average error in yaw angle is 0.4 degree. In general, the approach gets more accurate for higher Machnumbers.

In addition, the described procedure allows the calculation of the characteristic for another isentropic coefficient. For a mixture of air and freon (isentropic coefficient = 1.15) as it is used in the supersonic compressor, the correspondance between experimental data and the theoretical approach was investigated in the same way. The resulting error in yaw angle determination is illustrated in fig. 9 for several Machnumbers. The agreement between experiment and theory is as good as was shown for the measurements in air, so the developed approach seems suitable for the description of the wedge probes' characteristic in the flow behind the supersonic rotor.

5. Data reduction

The signals of the yaw angle probe are derived from pressure and angle fluctuations. A pressure change is registered by both transducers equally independent of the angle position. According to this an alternation of the flow angle results in opposite changes of the transducer signals. To evaluate measured data the following separation of the signal into pressure-dependent and angle-dependent components is applied:

$$U_{L,R}\,(p,\alpha) = f_{p-L,R}\,(p\,(t)) + f_{\alpha-L,R}\,(\alpha\,(t))$$

fp-l,r only depends on pressure and is given by the static pressure calibration of the transducers:

$$U = -\frac{K_0}{K_1} + \frac{1}{K_1}\, p \qquad a_{0-L,R} = -\left(\frac{K_0}{K_1}\right)_{L,R} \qquad a_{1-L,R} = \left(\frac{1}{K_1}\right)_{L,R}$$

$$f_{p-L,R}\,(\,p(t)) = a_{0-L,R} + a_{1-L,R} \cdot p\,(t)$$

fa-l,r is known by the yaw angle characteristic calculated in the described manner. To simplify the computation the angle characteristic is reduced to a linear function in the environment of the measured data point

$$f_{\alpha-L,R}\,(\alpha\,(t)) = b_{0-L,R} + b_{1-L,R} \cdot \alpha\,(t)$$

As measurements are only carried out with respect to the time mean flow, the first coefficient is equal to zero. To avoid errors due to the zero offset of the transducers, only the fluctuating parts of the voltage are registered during the measurements:

$$U_{L,R}\,(\tilde{p}, \tilde{\alpha}) = \tilde{U}_{L,R} = a_{1-L,R} \cdot \tilde{p} + b_{1-L,R} \cdot \tilde{\alpha}$$

By linear combinations

$$\tilde{U}_L \pm \tilde{U}_R = (a_{1L} \pm a_{1R})\,\tilde{p} + (b_{1L} \pm b_{1R})\,\tilde{\alpha}$$

the fluctuation quantities of static pressure and flow angle are derived:

$$\tilde{p} = \frac{b_{1L}\,\tilde{U}_R - b_{1R}\,\tilde{U}_L}{a_{1R}\,b_{1L} - a_{1L}\,b_{1R}}$$

$$\tilde{\alpha} = \frac{a_{1R}\,\tilde{U}_L - a_{1L}\,\tilde{U}_R}{a_{1R}\,b_{1L} - a_{1L}\,b_{1R}}$$

The resulting time dependent values are superimposed on the time averaged data. As the characteristics of both probes depend on the above calculated pressure and Machnumber, the procedure is carried out as an iteration until the error margin of Δ Ma $<$ 0.005, Δ P $<$ 0.001 and Δ Pt $<$ 0.001 from one iteration step to another is reached. The consideration of the isentropic coefficient which depends on the measured concentration in the closed freon cycle is included in this procedure.

6. Results

Finally, some typical results from the measurements behind the supersonic rotor are illustrated in fig. 10. Wake effects and rotor-trailing-edge-shock and -expansion-wave systems are able to generate fluctuations up to 60 % of the time averaged value of the total pressure. In general, magnitudes of fluctuation increase remarkably with higher rotational speeds.
A detailed analysis of the obtained results is presented in /3/.

7. Conclusions

A theoretical approach for the description of wedge probes' characteristics in supersonic flow was found to consider the influence of Reynoldsnumber and isentropic coefficient. The procedure was utilized to perform measurements behind a supersonic compressor rotor.

Nomenclature

Ma	-	Machnumber
P	bar	static pressure
Pt	bar	total pressure
U	Volt	voltage
a	deg.	yaw angle
β	deg.	flow turning angle
βmax	deg.	flow angle where shock detaches

superscripts

—	time averaged value
~	fluctuating value

subscripts

L	left transducer
R	right transducer

References

/1/ Broichhausen, K.D., Kauke, G., Shi, Zhi-da — Some aspects of semiconductor-probe development, Measuring techniques for transsonic and supersonic flow in cascades and turbomachines, Aachen, 1983

/2/ N. N. — Kulite Miniature IS Silicon Diaphragm Pressure Transducer Catalog, Bulletin KS-1000 C, Kulite Semiconductor Inc.

/3/ Kauke, G. K. — Untersuchungen zur Nachlaufwechselwirkung im Tandemleitrad einer axialen Uberschall-verdichterstufe, Diss. RWTH Achen, 1986

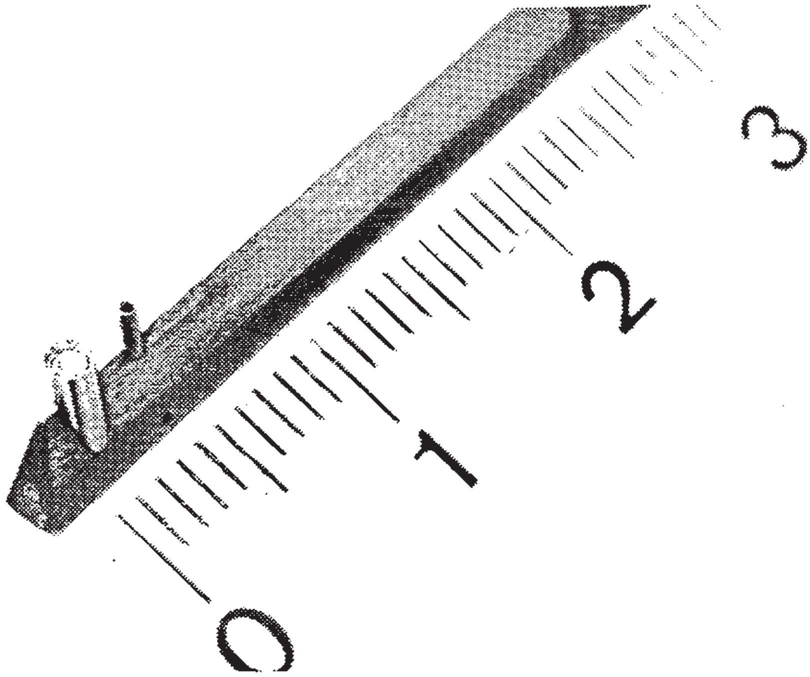

fig. 1 : total pressure wedge probe

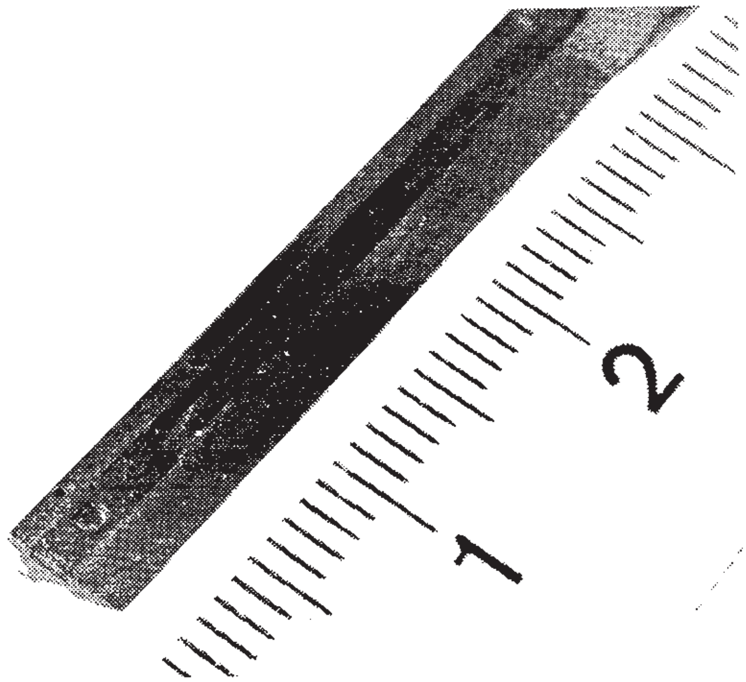

fig. 2 : wedge probe for static pressure and yaw angle measurement

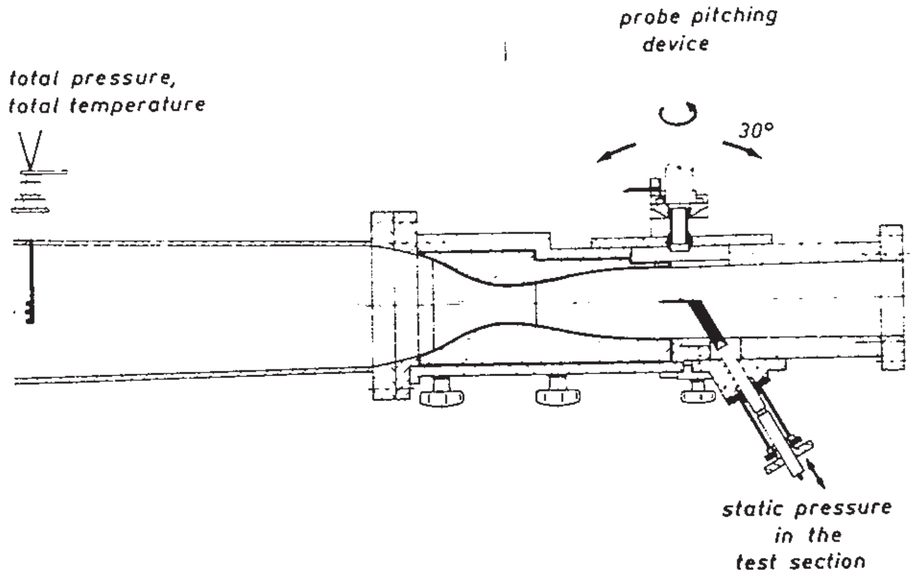

fig. 3 : test section of the closed-loop calibration channel

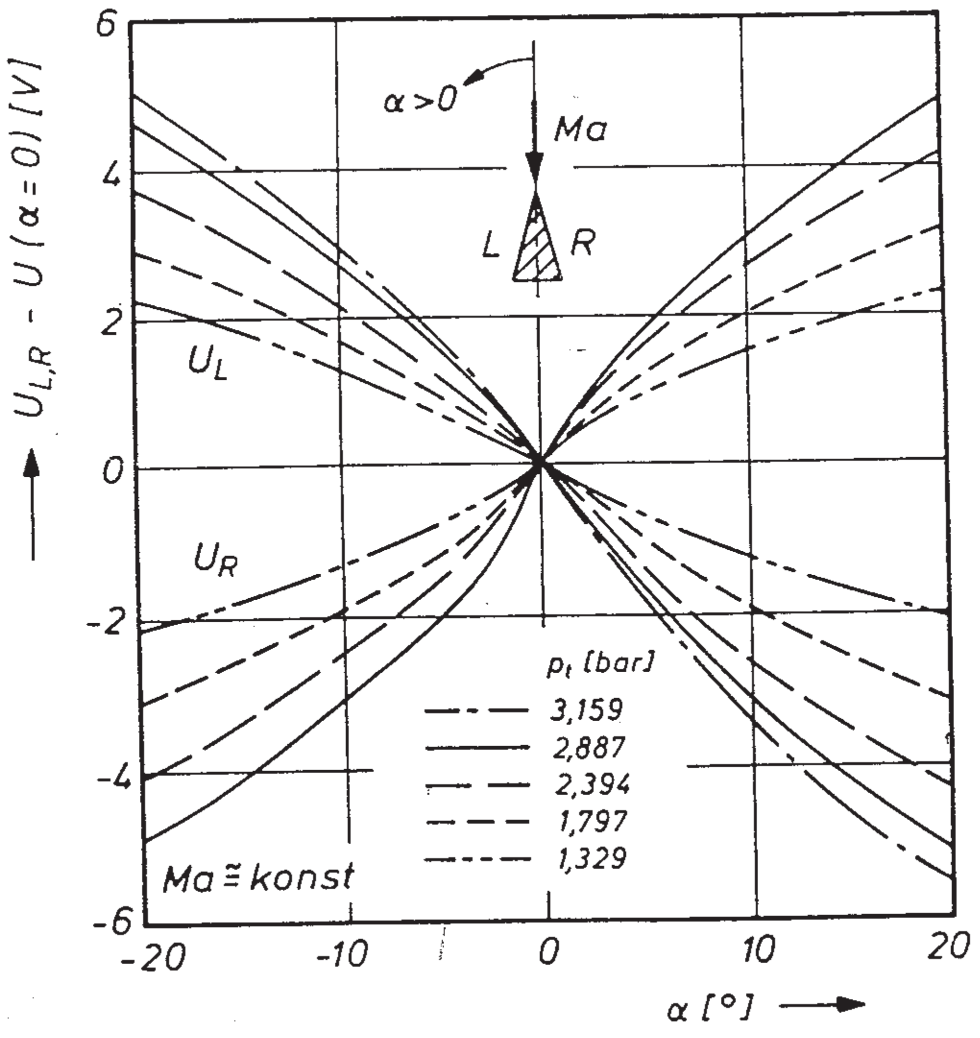

fig. 4 : yaw angle characteristic with variation of total pressure

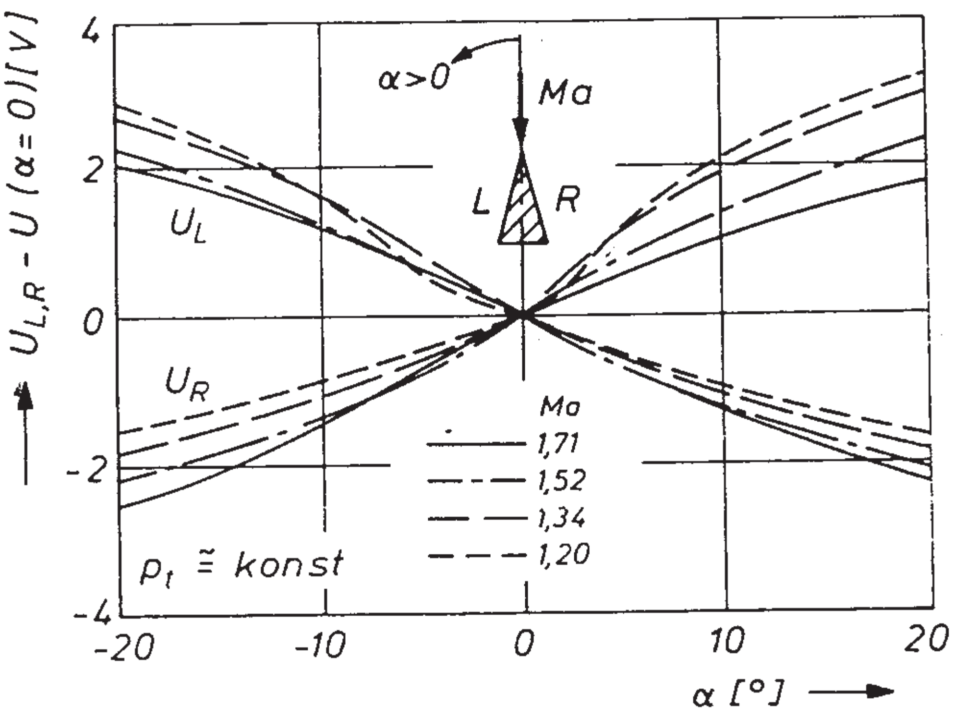

fig. 5 : yaw angle characteristic with variation of Machnumber

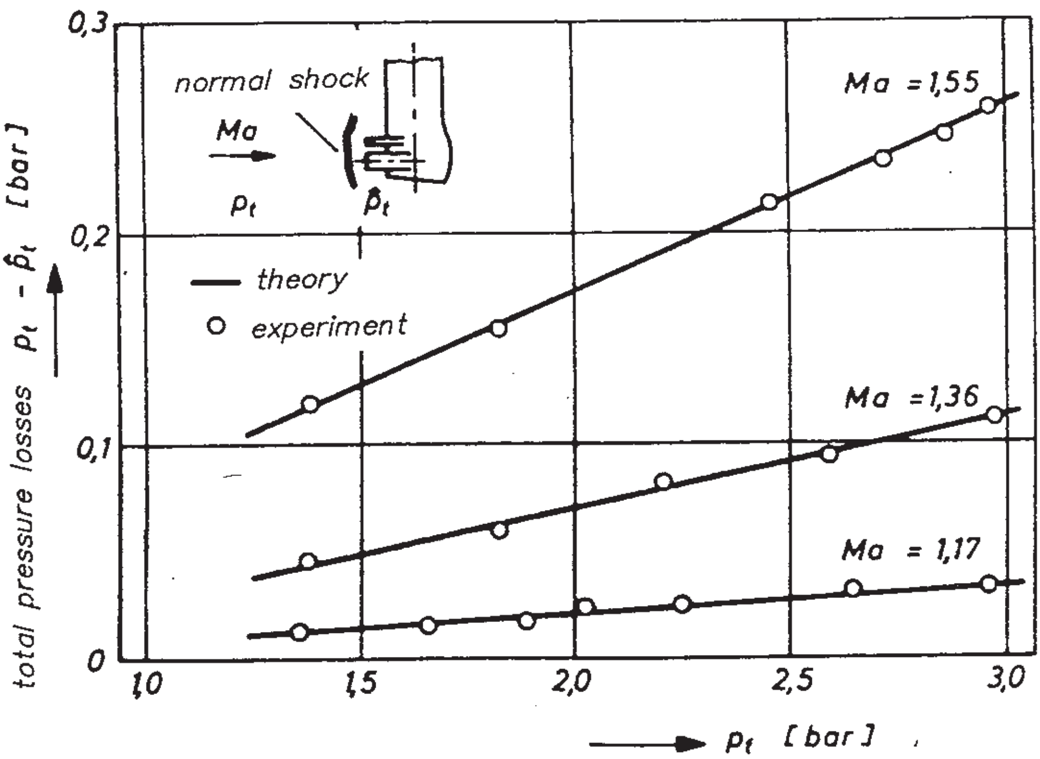

fig. 6 : comparison of total pressure losses

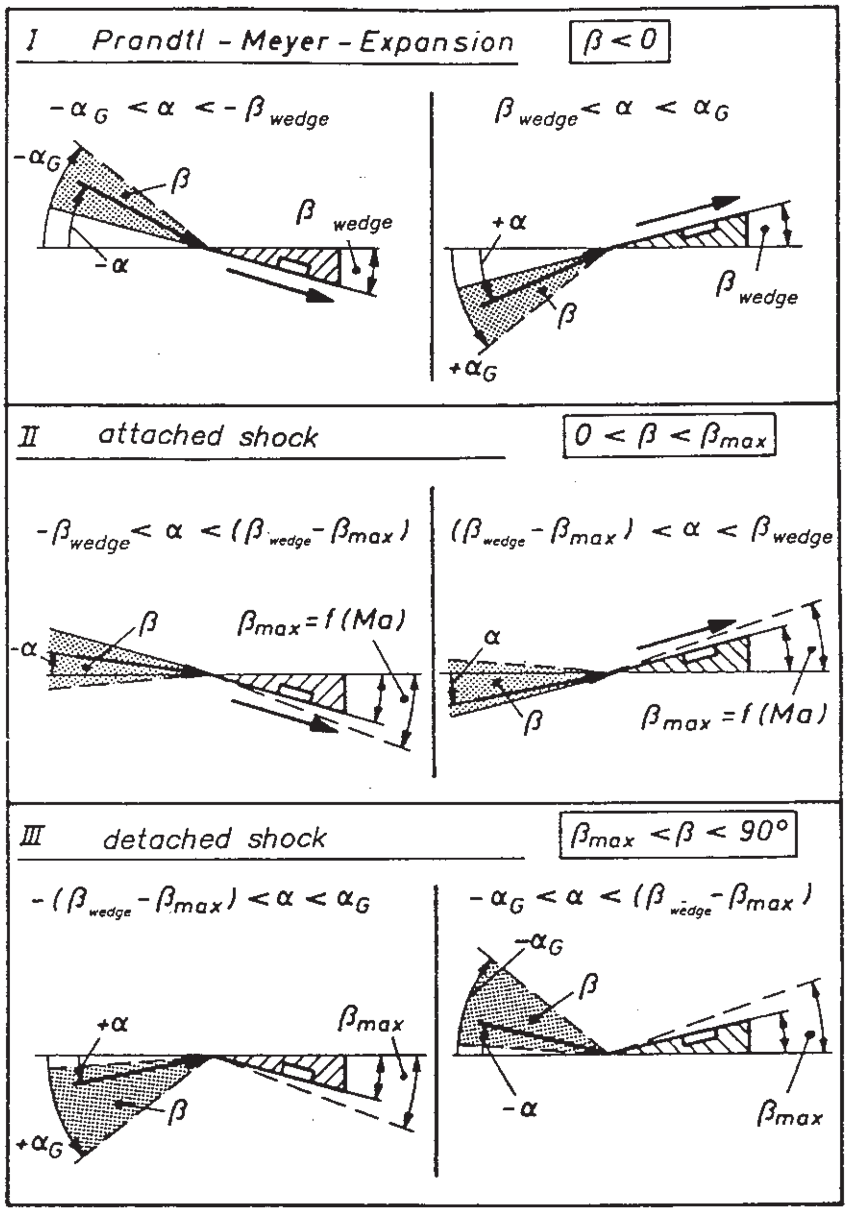

fig. 7 : flow conditions around the wedge

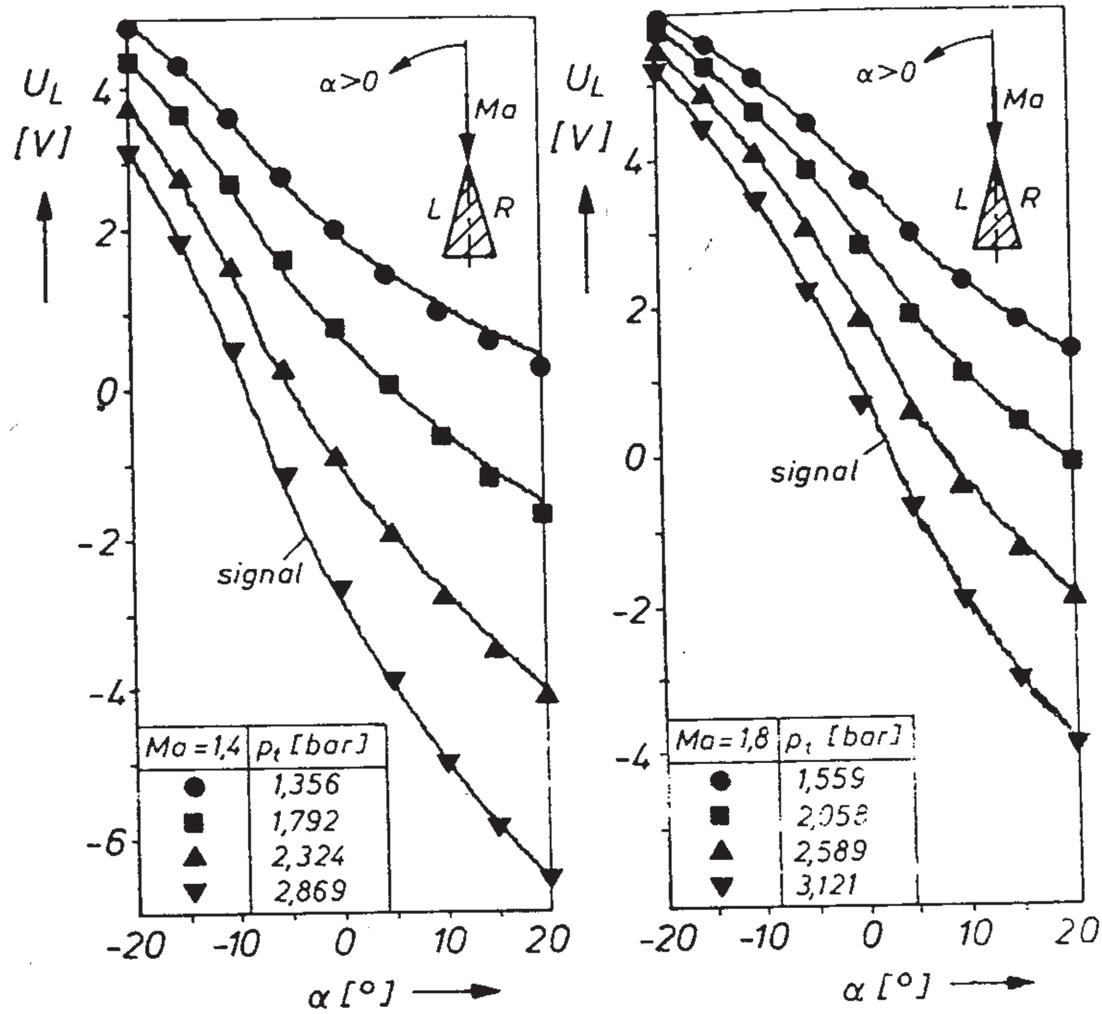

fig. 8 : comparison of experimental data and theoretical approach (air)

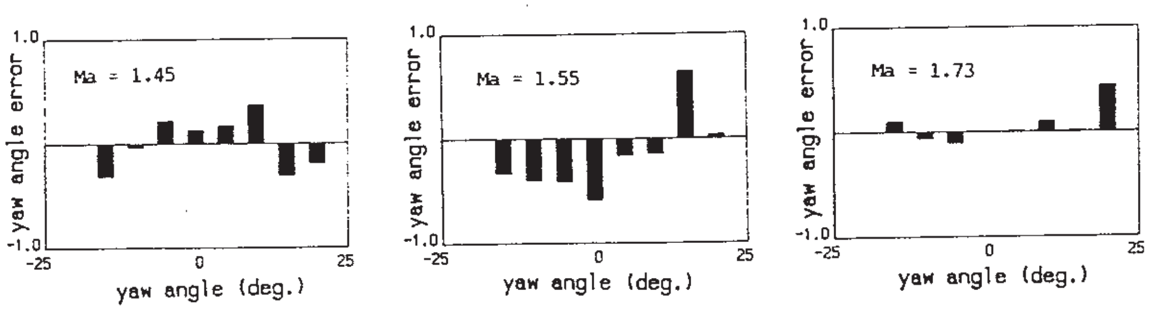

fig. 9 : yaw angle error for approach (air-freon-mixture)

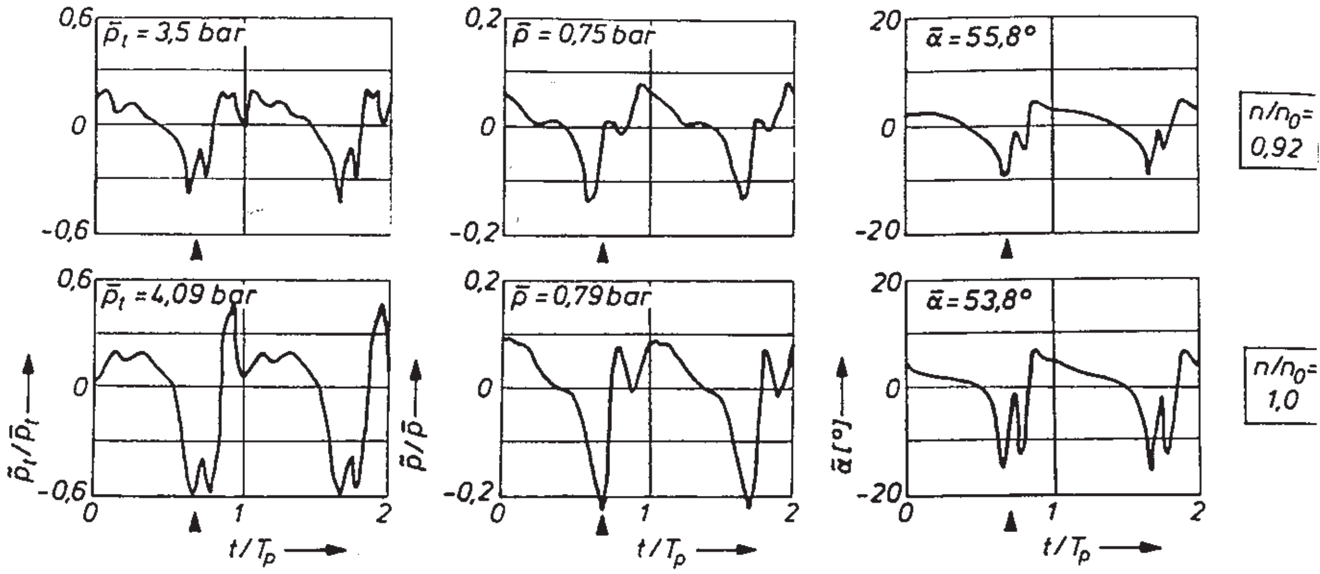

fig. 10 : results of unsteady measurements behind the supersonic rotor