Session 1 - Cascade Testing

AERODYNAMIC MEASUREMENTS IN TURBINE CASCADES AT HIGH MACH NUMBER

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ABSTRACT

The paper presents the measurement technique developed at C.N.P.M. for testing supersonic turbine cascades. These cascades are characterized by high Mach numbers ($M = 2.0$-2.5) both in the inlet and in the outlet section.

The main features of the experimental apparatus used in the investigation, i.e. the probe, the calibration facility, the wind tunnel and the data acquisition system, are described.

The most relevant problems that had to be solved for carrying out these tests are discussed. Particular attention is payed to the problem of the measurements in high gradient field.

INTRODUCTION

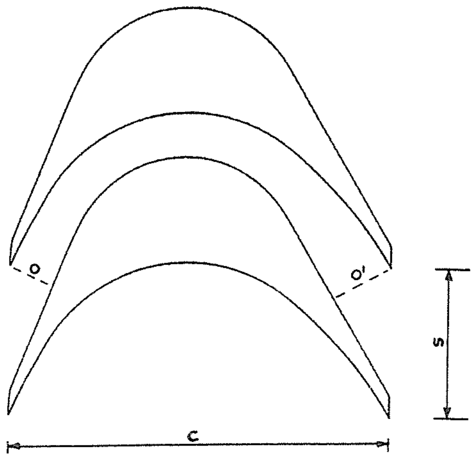
In the last years the demand of experimental investigation in cascade wind tunnel is moving towards Mach numbers which are more and more extending in the supersonic range. Indeed highly loaded transonic bladings are now usually employed in gas turbine engines, and supersonic blades with Mach numbers over 1.6 are used in low pressure overexpanded stages of large steam turbines. Even more severe supersonic regimes are required in space application turbines. With regards to the measuring technique, this last case is a very severe challenge.

In liquid fuel engine rockets, supersonic turbines are usually employed for driving the feed pumps for fuel and oxidizer. The requirement of limiting the overall mass leads the optimal solution towards single or two stage highly loaded turbines [1]. As a consequence in these turbines both absolute and relative Mach numbers are very high and result often to be larger then 2.0 .

The design of supersonic nozzles is not a very difficult job, as the viscous phenomena in general are not dominating; anyway a lot of information on the achievable efficiency is available in the open literature [2] [3]. On the other hand the performance of supersonic rotor cascades cannot be easily predicted with sufficient accuracy, as large viscous effects take place. Indeed the large deflection of supersonic flow implies high blade loading, which joined to shock wave boundary layer interactions, makes the boundary layer on most of the suction side prone to separate. Moreover additional uncertainties come from the supersonic entry, which requires the determination of the unique incidence angle.

In order to investigate the flow field in various rotor cascades with different geometries, and operating conditions, a research program has been undertaken at C.N.P.M. (Istituto per Ricerche sulla Propulsione e l' Energetica) in Milano, under a contract sponsored by Fiat Avio s.p.a.. An example of these cascades, togheter with the design operating conditions is provided in Fig.1. It has to be noticed that the Mach number is very high, not only at the exit ($M_{2is} = 2.39$) but also at the inlet ($M_{is} = 2.19$). Further details on the turbine stage, togheter with the results of the investigation can be found in [4].

For these tests the usual measuring technique has been improved to overcome several problems, which are mainly connected with the high Mach numbers. In particular they consisted in :



Solidity	$s/c = 0.385$	Inlet geometric angle	$asin\ (o/s) = 25.3$
Aspect ratio	$h/c = 0.96$	Outlet geometric angle	$asin\ (o'/s) = 30.0$
Inlet Mach number	$M_1 = 2.19$	Inlet flow angle	$\beta_1 = 17.5$ deg
Outlet Mach number	$M_{2is} = 2.39$	Outlet flow angle	$\beta_2 = 30.0$ deg

Fig. 1 Supersonic rotor cascade.

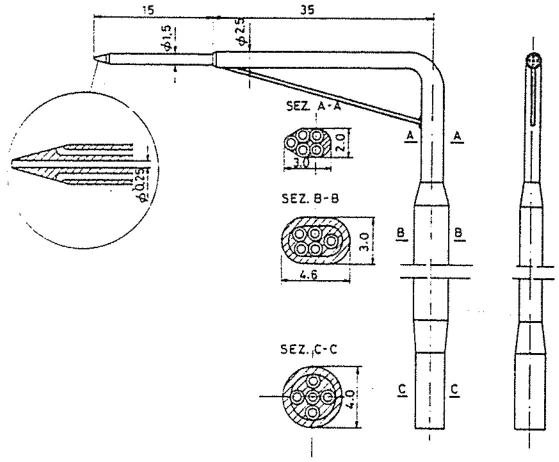


Fig. 2 Miniature 5 hole probe.

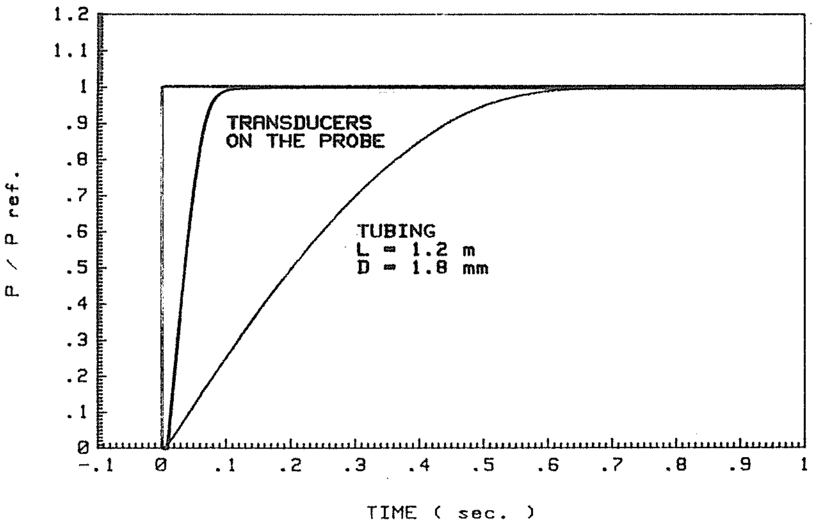


Fig. 3 Response time of the probe tubing transducer system.

- developing a miniature probe, and calibrating it up to high Mach numbers, i.e. $M = 2.90$,
- speeding up the data acquisition, to limit the huge air consumption connected to these high velocity flows,
- getting a satisfactory periodicity of the inlet supersonic flow,
- doing measurements in high gradient field.

PROBE CHARACTERISTICS

The probe used in this investigation is presented in Fig. 2. It is a miniature 5 hole probe, with a head diameter of only 1.5 mm, and an internal tubing diameter of 0.25 mm. The probe head is displaced 50 mm ahead of the probe stem, and a thin wire is set to avoid spanwise vibrations of the needle. These characteristics were selected to reduce at minimum the disturbances induced on the flow field, and particularly the blockage effect in the transonic regime.

An important point, related to the use of this probe, is the response time. If the probe is connected with the transducers by a standard tubing, the response time results too large for the use in blow-down tunnels. Therefore 5 miniature Kulite transducers were fitted just on the probe stem, to reduce at minimum the capacity of the probe-tubing-transducer system; in this way the response time of the system after a pressure step has been reduced from 0.6 s down to 80 ms (Fig. 3).

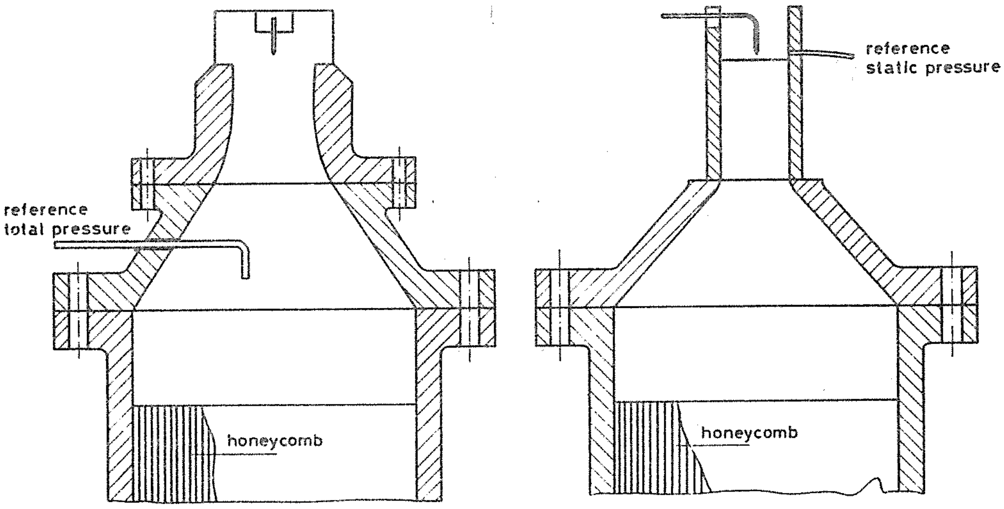


Fig. 4 Calibration facility configuration.

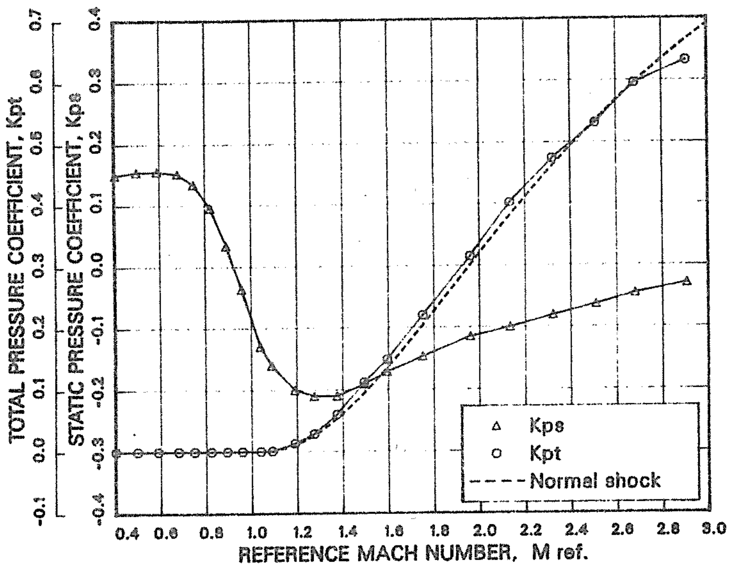


Fig. 5 Static and total pressure coefficients at zero yaw and pitch angles.

PROBE CALIBRATION

The calibration configuration is presented in Fig. 4. The probe head is located 4 mm downstream of calibrated 2-D nozzles, which provide uniform flow at the desired Mach number. A semiconfined nozzle configuration has been selected, as it has been found to be the best solution, in comparison to other geometries, like as for example, completely confined, sudden enlargement, or free jet [5]. Indeed, as far as it concerns the blockage effect, semiconfined nozzles provide flow conditions more similar to those taking place in the wind tunnel, as the nozzle height is the same one of the wind tunnel.

The reference total pressure is measured upstream of the nozzle troath, while the static pressure is measured by a wall static pressure tapping. The probe can be rotated for yaw and pitch angles, leaving the probe head in the same point i.e. at the center of the nozzle outlet.

The probe calibration is carried out in a fully automatic way; the probe positioning, for yaw and pitch angles, is performed by stepping motors driven by the computer of the data aquisition system. By using this system, a typical calibration at a defined Mach number, for yaw and pitch angles ranging from -24 deg. up to +24 deg. in 2 deg. steps, takes about 290 s.

Static and total pressure coefficients, K_{pt} and K_{ps}, at zero yaw and pitch angle are presented in Fig. 5, together with the curve of the total pressure coefficient K_{ptNS}, based on the normal shock relationship. The lower values of K_{pt} with respect to K_{ptNS} found at $M_{ref} = 2.9$ can be explained by

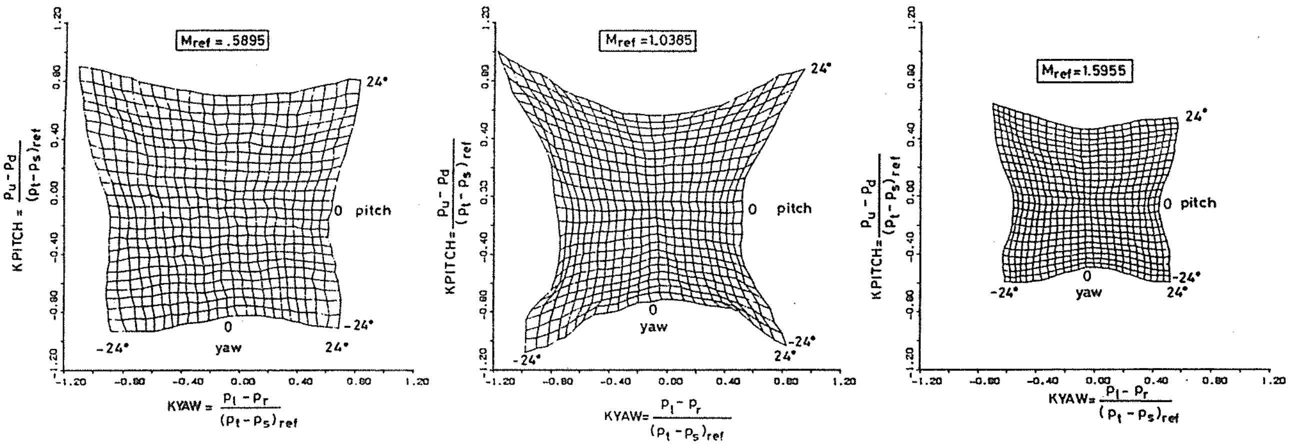
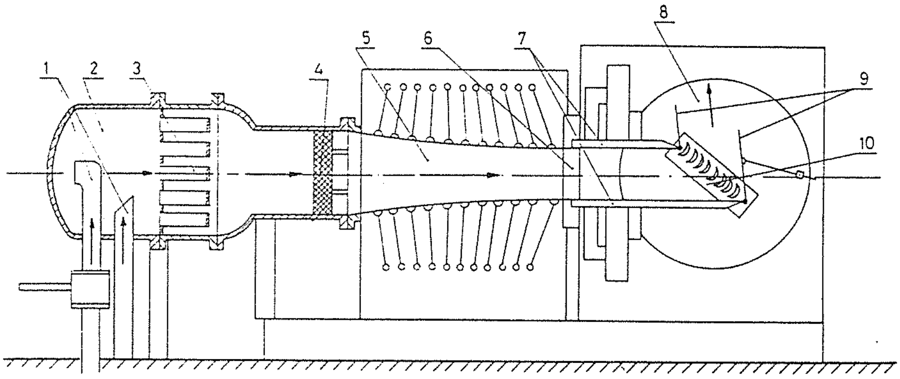


Fig. 6 Constant yaw and pitch angles vs. K_{yaw} and K_{pitch} coefficients.



1 Air supply
2 Settling chamber
3 Filtering section
4 Honeycomb
5 Moveable wall section
6 Boundary layer suction
7 Moveable walls
8 Rotating disk
9 Motor driven tailboards
10 Test section

Fig. 7 C.N.P.M. transonic wind tunnel.

the occurrence of a weaker oblique shock in front of the probe head. It is not clear the reason why K_{pt} results slightly higher than K_{ptNS} for $1.4 < M < 2.4$: this means that in front of the probe there is a shock that is stronger than the normal shock, which is obviously unphisical. Otherwise it could be supposed an error either on the reference static pressure or on the reference total pressure. Notwithstanding a careful investigation has been done, it was not possible to eliminate this supposed error. This inconsistency appears to be strictly related to the so called "overpressure" phenomenon, which at high Mach numbers is responsible for an underestimation of the cascade losses.

The maps of constant yaw and pitch angles versus K_{yaw} and K_{pitch} coefficients are presented in Fig. 6; they show how compressibility influences the calibration results.

WIND TUNNEL ARRANGEMENT

The C.N.P.M. wind tunnel, shown in Fig. 7, is a blow-down facility with an air storage capacity of 3000 kg at 200 bar. For high Mach number tests, i.e. for M_{2is} = 2.0-2.4, it allows for a maximum running time of about 4 minutes; this is a heavy limitation in carrying out 3-D investigations downstream of the cascade.

The test section, fitted on a rotating disk, is 400 mm width and 50 mm high, and can accept a rather large number of blades (18 in this cascade).

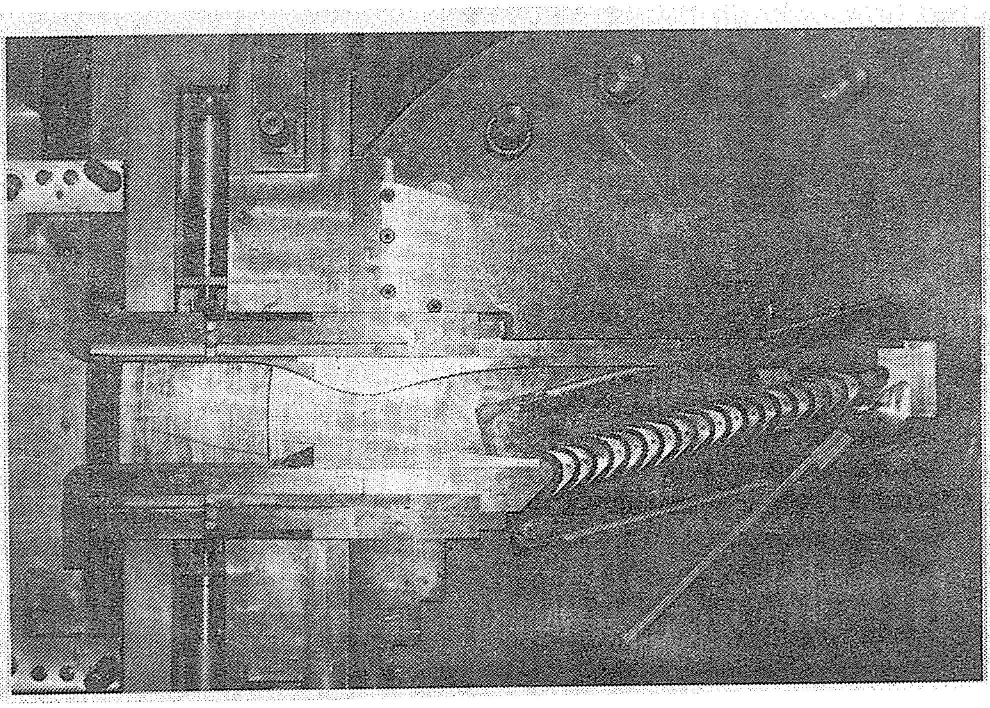


Fig. 8 Wind tunnel configuration for supersonic entry and test section.

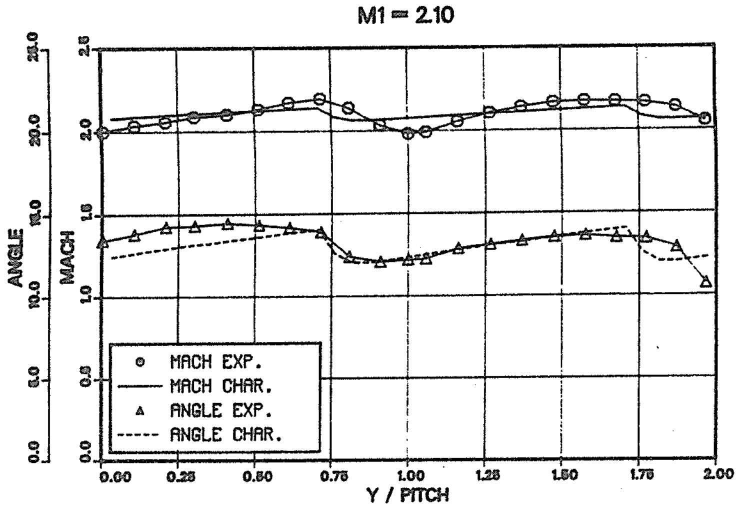


Fig. 9 Upstream traverse results.

Supersonic entry

Due to the high supersonic inlet Mach number, the usual tunnel set up has been modified as shown in Fig. 8. To ensure the desired inlet Mach number, a calibrated nozzle, designed for a uniform exit flow, has been installed just ahead the cascade inlet. The nozzle design Mach number has been assumed larger than the one at the cascade inlet, just to compensate the Mach number decrease due to the first shock generated at the leading edge of the first blade. The actual nozzle Mach number can be slightly adjusted, to get the design test conditions, by translating the upper wall with respect to the lower one, i.e. through a small variation of the area ratio.

An important problem in this tests is to get periodic flow conditions, not only at outlet, but also at inlet; indeed, according to the unique incidence theory, for a defined inlet Mach number, only one direction of the incoming flow produces periodic flow conditions in front of the blades. If the cascade is not set with the right angle with respect to the inlet flow, i.e. if the angle of attack is not the right one, an oblique shock wave, starting from the first blade, deflects the flow just to make it to assume the direction of the unique incidence. In this case a periodic flow might be obtained too, but for a Mach number lower than the design one, due to the presence of the shock wave.

Several runs of the tunnel have been done at different inlet angles, in order to determine that one producing satisfactory periodicity conditions at the design Mach number. An example of the upstream traverse results is given in Fig. 9.

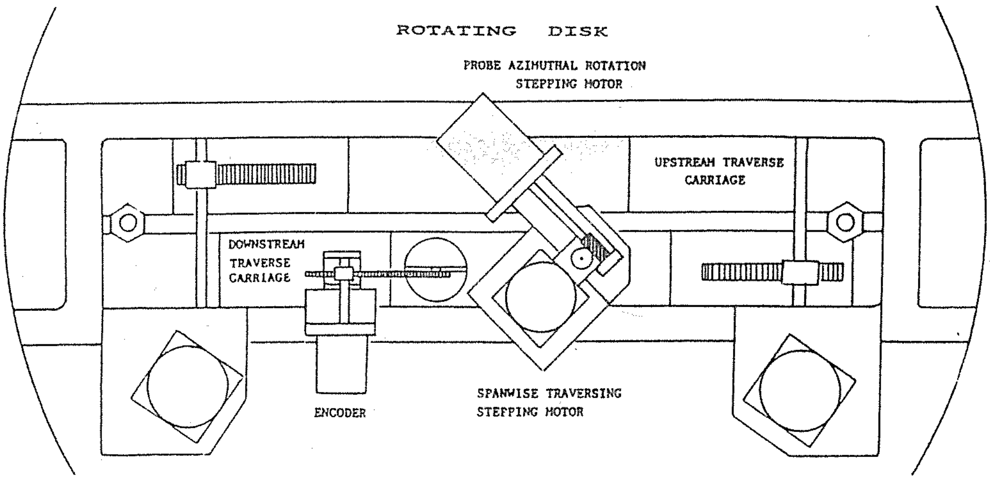


Fig 10. Probe traversing mechanism.

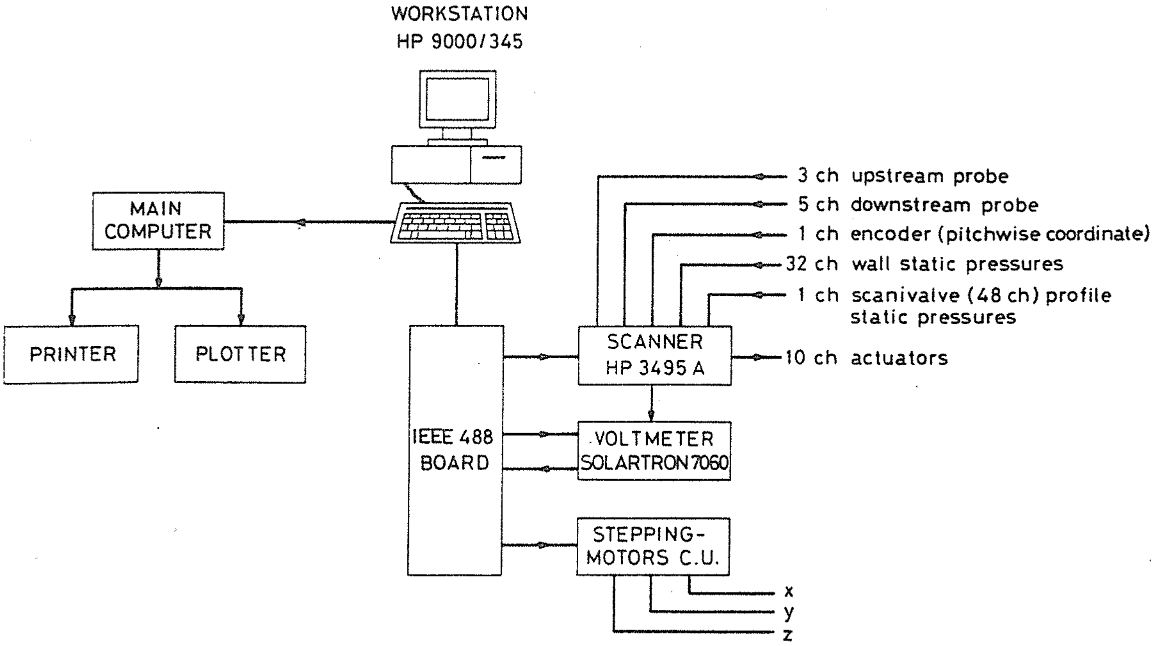


Fig. 11 Data acquisition system.

The variation of the static-to-static expansion ratio accross the cascade is obtained by changing the pressure level at the cascade outlet; this is achieved by an adjustable tailboard fitted at the trailing edge of the last blade (Fig. 8); the angular position of the tailboard determines the degree of after-expansion at the blade exit, and consequently the outlet flow angle. Moreover the use of the tailboard contributes to improve the flow periodicity downstream of the cascade.

Traversing system

In Fig. 10 it is shown the traversing system fitted on the rotating disk. There are two stepping motors driving respectively the upstream and the downstream traversing carriages. The pitchwise position of the probe is given by an encoder. An additional stepping motor operates the spanwise traversing of the probe. It can be noticed also the presence of a fourth stepping motor, which is used in case of hot wire measurements, to rotate the probe about its axis. All the stepping motors are controlled by the computer of the data acquisition system, that is a HP 9000 / 345 workstation. The configuration of the data acquisition system is shown in Fig. 11.

The traversing procedure and the data acquisition have been carefully optimized in order to reduce at minimum the overall time required for a single test, and therefore to limit the air consumption. By this way, a typical secondary flow test, including 20 measuring stations in pitchwise direction, and 10 along the span, for a total number of 1800 data, is performed within 150 s. Two

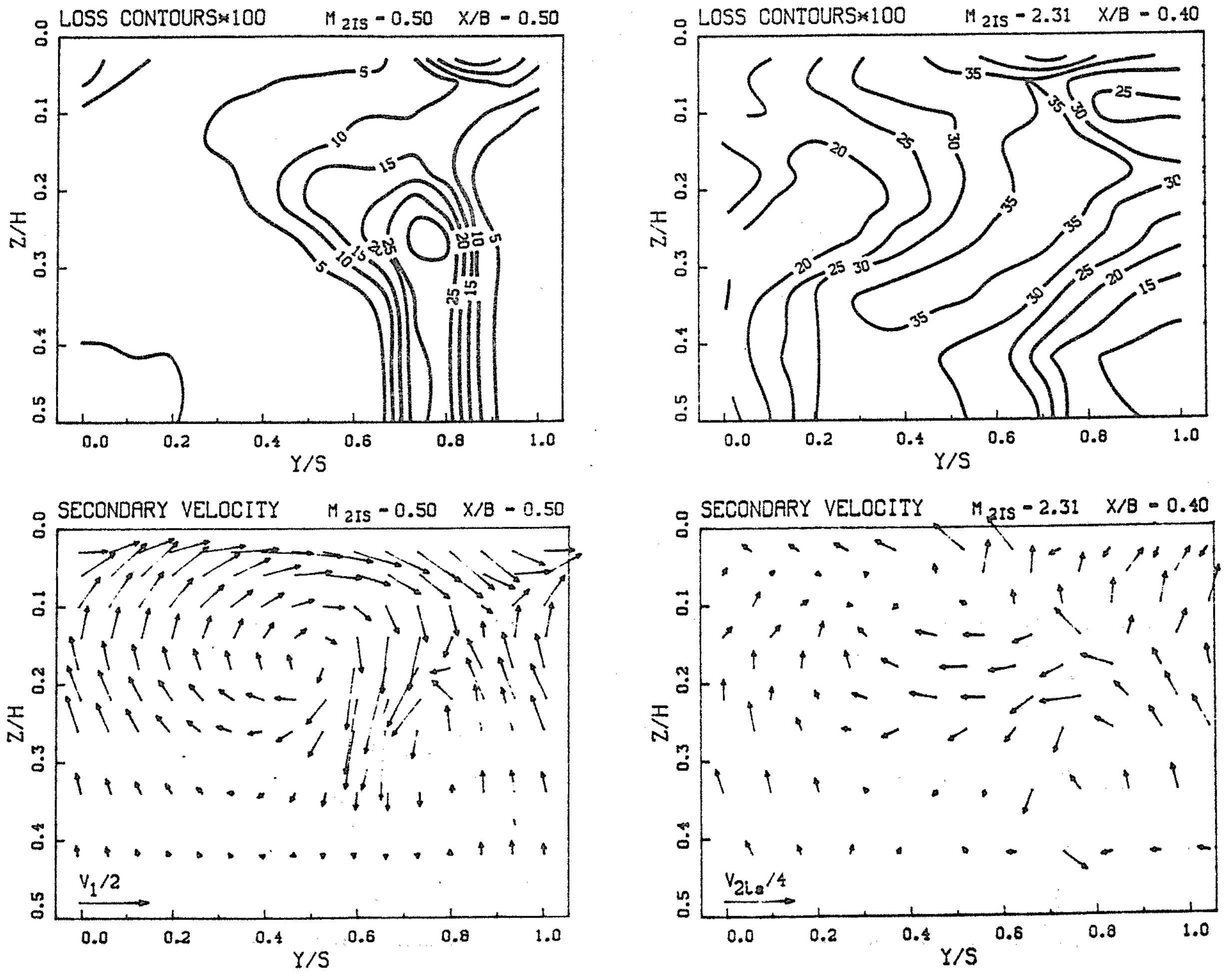


Fig. 12 Secondary flow results.

examples of secondary flow test results are shown in Fig. 12; the first, at M_{2is} = 0.50, refers to the cascade of Fig. 14, while the other one at M_{2is} = 2.31 refers to the supersonic rotor cascade of Fig. 1.

MEASUREMENTS IN HIGH GRADIENT FIELD

As well known, in transonic and supersonic flows, different kinds of high gradients are present, e.g. shock waves, expansion waves, and wakes. Pressure probe measurements may therefore be affected by significant errors: indeed the pressure measurements are actually taken in different points, because of the finite thickness of the probe head.

In pure 2-D flows the best solution should be to use probes similar to the so called "cone probe" developed at VKI [6], but with a smaller hole diameter; in these probes all the pressures are actually measured at the same pitchwise position, but the static pressure hole is taken on the cone head of a separate needle. The major disadvantage of such probes is that the static pressure is measured at a different spanwise position with respect to the other ones. Therefore even small variations of the flow properties along the span produce significant measurements errors. An attempt has been made to overcome this limitation, by using the three hole probe of Fig. 13; the static pressure P_s was assumed to be the average value of P_{left} and P_{right}. This attempt failed because of the scarce sensitivity of the probe for Mach numbers larger than 1.3; indeed, due to the shock in front of the probe head, P_s is actually too close to P_t.

In case of 3-D flow measurements, the only possible solution is to use a 5 hole probe; but, even if the probe head is very small, substantial errors are generally made, due to the finite distance between the 5 holes.

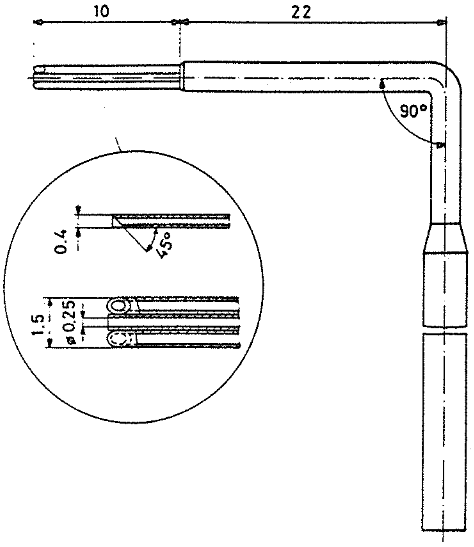


Fig. 13 Three hole probe.

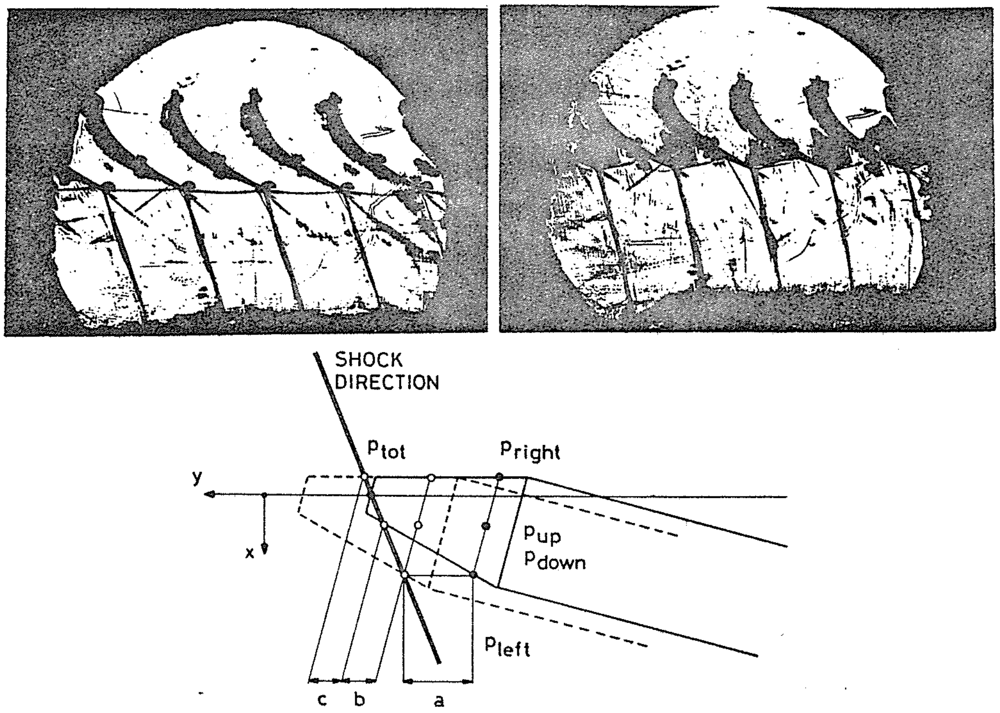


Fig. 14 Schlieren pictures and scheme of the shifted probe traversing procedure

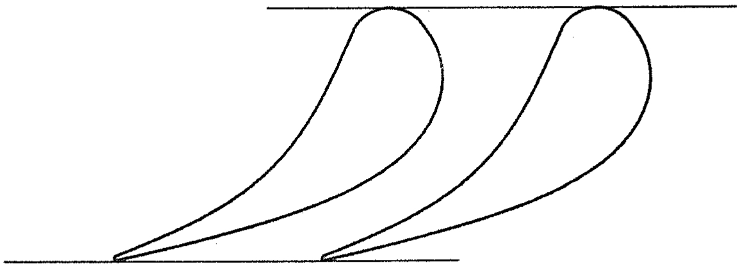


Fig. 15 Nozzle cascade geometry.

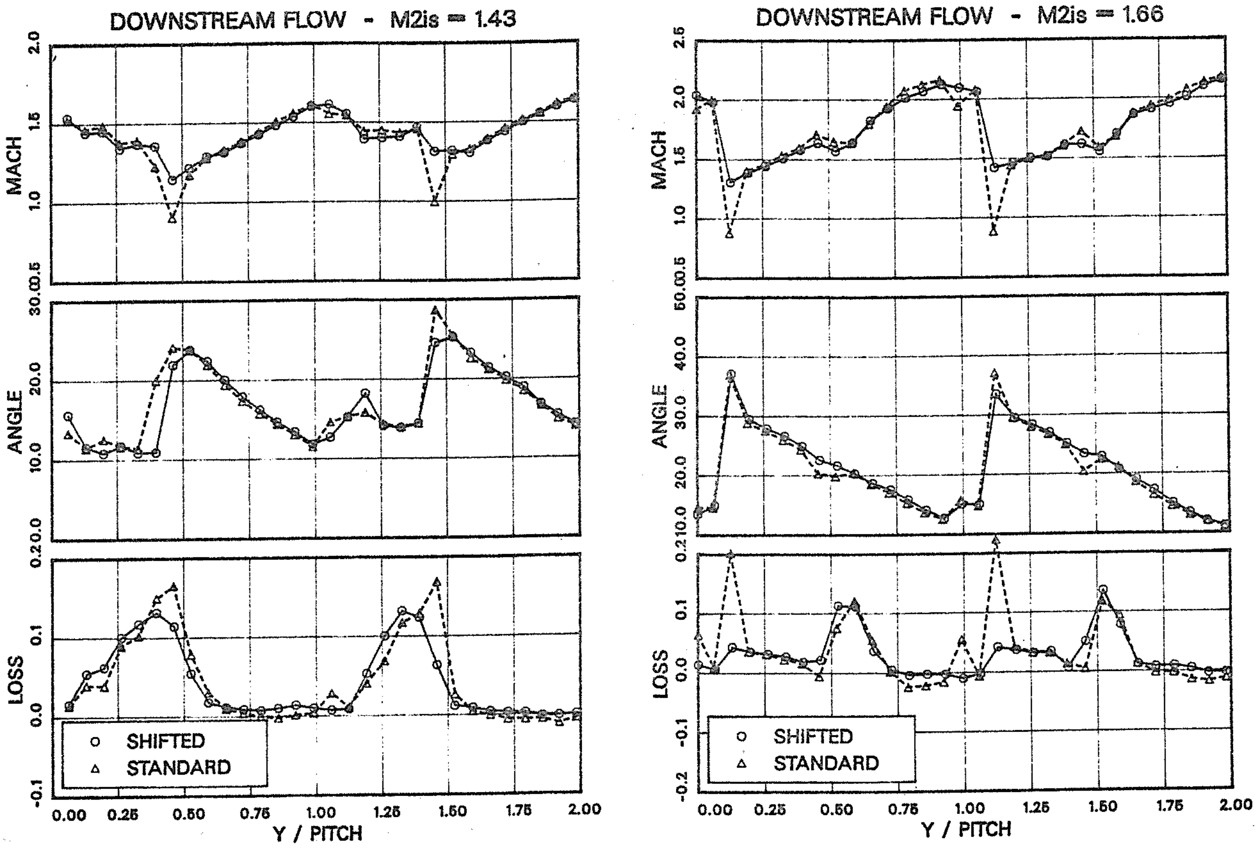


Fig. 16 Results for shifted and standard traversing techniques.

In order to reduce at minimum these errors, the following traversing procedure has been developed. Assuming that the highest gradients are those related to the shock waves, and that the direction of the strongest shocks is roughly always the same, (as shown by the Schlieren pictures in Fig. 14), the traverse is performed paying attention not to do measurements with the probe head across the shock. In practice for each measuring point, the total pressure is firstly measured; then the probe is displaced the distance a (see Fig.14), to align the P_{left} hole with the assumed shock direction, and the P_{left} is measured. Then the other readings P_{up} and P_{down} and subsequently P_{right} are done after displacing the probe respectively the distances b and c, so to align the probe holes with the assumed shock direction. In this way the probability to get erroneous measurements owing to the shocks is significantly reduced.

The results for a nozzle cascade (Fig. 15), obtained by this shifted probe technique are compared in Fig. 16 to those of the standard traversing. It appears very clearly that large errors are made by using the standard mode of operation: at the shock location there is a heavy underestimation of the Mach number and an overestimation of the loss coefficient, while in the expansion fan region one gets negative losses. These errors practically disappear by using the shifted probe procedure. With this technique an improvement can be observed also in the wake region.

As far as it concerns the pitch-averaged results, it is shown in Fig. 17 that the standard traversing procedure produces a significant overestimation of the loss coefficient, all over the considered Mach number range. It is about 1-1.5% for the mass-average results, and about 2-3% for the mixed out flow results. Therefore it is proved that in traversing high Mach number flows by means of 5 hole probes, it is important to perform measurements by respecting the flow domains separated by shock waves, otherwise not negligeable errors can be made. It has been shown that this leads to a substantial loss overestimation.

CONCLUSIONS

Testing supersonic cascades in blow-down wind tunnel requires a good experimental efficiency in order to limit the huge air consumption requested by high Mach number tests. This has been

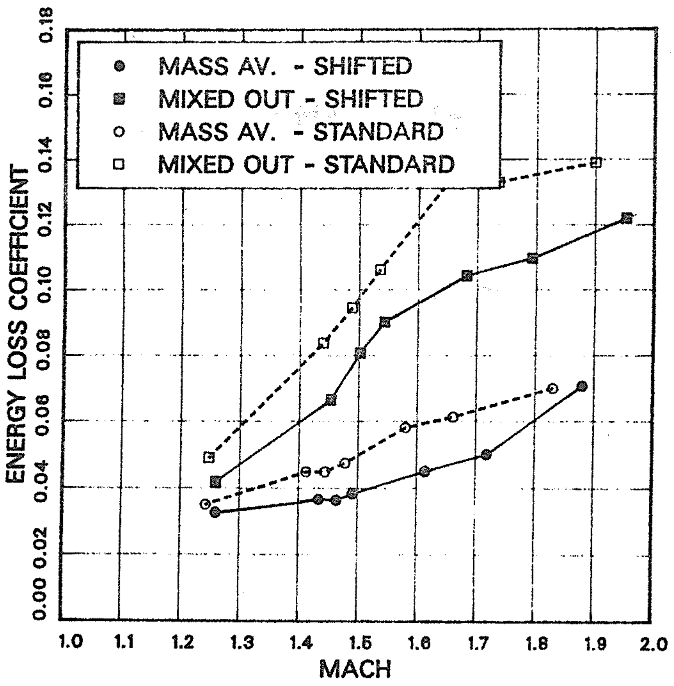


Fig. 17 Losses for the two traversing techniques.

mainly achieved by reducing at minimum the response time of probe-tubing-transducer system, and speeding up both the data acquisition and pitchwise/spanwise probe positioning; in this way the overall testing time has been significantly reduced, so as to make possible to do secondary flow investigations in high velocity flows.

With regards to the measurements in high gradient field, it has been found that in 2-D flows three hole probes are not usable for Mach number over 1.3, owing to a sensitivity shortcoming. In case of 3-D flows it has been shown that traversing a miniature 5 hole probe by the "shifted probe" procedure, i.e. avoiding to do measurements with shocks across the probe head, allows to reduce significantly the errors of the loss estimation.

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