Relative Total Pressure Measurements Downstream of a Transonic Annular Cascade

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1. INTRODUCTION

At the preceding Symposium on "Measuring Techniques in Cascades and Turbomachines" Sieverding et al. (1990) presented a high speed rotating probe system using a wide band width, (100 KhZ), high signal to noise ratio, IR (infra-red) opto-electronic data transmission system. This system has been used for measuring the relative total pressure field downstream of a transonic annular turbine guide vane in partial fulfilment of a BRITE EURAM project. These measurements were planned as a first step for guide vane performance measurements in a transonic turbine stage. The embarkment of probes onto rotor blades appears in fact to be the only way to obtain information on the stator outlet flow field without causing unacceptable flow perturbations as caused by the immersion of probes into the small interblade row space. The tests described are carried out in the VKI Compression Tube Annular Cascade Facility.

2. TUNNEL OPERATING AND TESTING CONDITIONS

A full description of the tunnel and its operating conditions is given by Sieverding and Arts (1992). The tunnel is a transient facility, in which air is compressed and thereby heated up in a long tube through a light free moving piston, and then released through the test section by a fast acting shutter valve opening a vent hole in the end plate of the compression tube. This type of facility was originally developed by Schultz et al. (1977).

Figure 1 presents the typical evolution of the inlet total pressure and temperature, P_{01} and T_{01}, and the downstream static pressure, P_2, in function of time for a typical test run. The shutter valve opens at time t $\approx$ 160 m/s. Performance data typically are taken between t=300 and 500 ms. The other flow conditions are :

• Reynolds number	$RE=10^6$
• Turbulence	$Tu\simeq 1.5\%$
• Mid-span downstream Mach number	$M_{2,is}=1.05$

3. TRAVERSING MECHANISM

The complete rotating probe traverse mechanism is depicted in Fig. 2. The probes are fixed on the disc carrying the rotatable hub endwall. The disc is fitted to a shaft driven by an airmotor. The electronics for signal amplification and transmission are placed in the central part of the shaft in between the two bearings. The right end of the shaft carries the emitting IR diodes. For each data channel the signal is transmitted via four diodes positioned at 4×90^o around the shaft. The signal is captured by one fixed diode which is in permanent contact with at least one of the emitting diodes. The system in Fig. 2 was designed for the simultaneous transmission of 4 data channels. Care has to be taken to avoid any interference between emitting and receiver diodes from different channels. The voltage supply for transducers, electronics and IR-diodes is transmitted via ordinary carbon splirings (copper rings and carbon brushes).

Figure 3 shows a photograph of the rotating hub end wall with two Kulite probe probes mounted at 180^o distance for balancing reasons. Due to the high centrifugal stresses, the probe head had to be stiffened by an additional cross bar as indicated in the figure. The pressure sensors are Kulite XCQ062-50A absolute pressure transducers with B-type screens. The transducer head is modified by an outer sleeve providing a cavity of 0.5 mm depth in front of the screen.

All tests are performed at an axial distance X/C_{ax}=0.25 downstream of the trailing edge, at mid-blade height. The first runs with the rotating probe unit were made to control the dynamic behaviour of the rotating assembly and check the noise level of the data transmission system. The tests were made without flow in the test section at a test section pressure level of ≈0.1 bar, which is the typical pressure level prior to a blow test. The acceleration tests demonstrated a save operation without any noticeable vibration problems up to the maximum rotational speed of 3500 RPM obtainable with the air motor drive.

Prior to a test the probe is speeded up to about 80% of the requested RPM. During the blow down the probe's rotational speed increases due to frictional forces acting on the rotating end wall, as demonstrated in Fig. 4. The curve presents the variation of the rotational speed over 300 ms from time t=200 ms to t=500 ms. The opening of the shutter valve for releasing the flow from the compression tube occurs at t=160 ms with a rotational speed of 2500 RPM. The high speed data acquisition system for recording the relative total pressure would starts typically at t=350 ms, i.e. after the initial strong pressure fluctuations, Fig. 1. The ensemble averaging is done in general between time t=420 and 500 ms. In the present case the rotational speed has reached 2900 RPM at t=420 ms and the total variation in RPM over the averaging period in ≈ 3.5%.

The noise of the data transmission system is controlled by recording the signal output of the rotating probe with its probe head covered up. At a rotational speed of 2500 RPM the noise band is 6.5 mbar. The noise does change little with RPM in the domain of interest i.e. from 2000 to 3500 RPM. Compared to a total relative pressure of the order of 1.2 bar during a blow down test, the noise-signal ratio is ≈0.5%.

The above test also provides information on the effect of the centrifugal forces on the transducer. This information is used to correct the relative total pressure measurements in the following tests.

4. TEMPERATURE EFFECTS ON KULITE PROBE

It is well known that Kulite transducers are very sensitive to temperature changes. However, their response time to temperature variations is relatively long. During a test run with the probe rotating at high speed, the probe is exposed (a) to a sudden temperature rize of ≈160° at the begin of the test (see Fig. 1) and (b) to much smaller high frequency temperature variations linked to the blade passing frequency. It is reasonable to assume that the probe will only respond to the overall temperature rise.

Figure 5 compares the pressure trace of the Kulite probe, in a fixed position between two blade wakes, with the upstream total pressure measured with a pneumatic probe. The comparison of the two pressure traces does provide some information on the temperature effect. Since, the pneumatic probe is insensitive to temperature effects, the overall divergence between the curves with time is an indication of the temperature effect on the Kulite pressure probe. The maximum difference in the domain of interest amounts to 0.5% of the total pressure.

5. RELATIVE TOTAL PRESSURE WAKE PROFILES

The relative total pressure measurements described here after correspond to the rotational speed curve of Fig. 4. Fig. 6 shows a typical raw data string belonging to a total data acquisition over 150 ms, i.e. between time t=350 ms and t=500 ms. At a mean rotational speed of 2900 RPM over this period and a total of 43 blades the blade passing frequency is ≈ 2.1 KHz. With a data acquisition frequency of 400 KHz the distribution of the relative total pressure over 1 pitch is defined by 192 points and the total number of periodic events over this time is 312. The determination of the exact blade passing time for the ensemble averaging is based on the accurate measurements of the rotational speed.

The averaging process is done using directly the row data or after filtering them numerically at 40 or 20 KHz. The signals were averaged over 50, 150, 300 events. Fig. 7 shows a comparison of the ensemble averaged signal over 300 events for both the raw signal and the signal filtered at 20 KHz. Except for small wiggles in the curve derived from the raw data, there is no significant differences between the curves. The averaging over a large number of periodic events has however the disadvantage that the rotational speed changes by a significant amount, 3.5% in the present case. This affects of course the relative flow angle and the relative total pressure via the change of the relative velocity. To reduce these variations the averaging should be done with a minimum, but sufficient, number of events. Fig. 8 compares the relative total pressure profiles averaged over 50 and 150 events after a filtering of the raw data at 20 KHz. The small differences between both traces clearly indicate, that 150 events are largely sufficient for the averaging procedure.

6. COMPARISON WITH TRAVERSE RESULTS FROM STATIONARY MEASUREMENTS

The only way to ascertain the accuracy of the relative total pressure measurements is by comparing them with the relative total pressure profile derived from measurements in the stationary frame. Fig. 9 presents the stationary flow data P_{02}/P_{01} and P_{02}/P_{01} and the derived relative total pressure ratio $P_{02,R}/P_{01}$. Fig. 10 compares the measured relative total pressure with that derived from stationary measurements. The Kulite probe measurements with the rotating probe system have been corrected for temperature effects as described in section 4.

The differences between the two curves in Fig. 10 are surprisingly large and at the first sight unexplicable. In analysing the possible reasons, it appears that the static pressure is the key problem. The stationary probe was designed with an extremely long probe head resulting in a very low probe blockage effect, while the rotating probe had to be designed with a relative short probe head and an additional cross bar to support the high centrifugal stresses (Fig. 3), leading to relatively high blockage effects, although the relative Mach number to the probe is subsonic. Obviously the differences in the probe geometry and the associated differences in the probe blockage effects outweigh the advantage of the reduced Mach number for the rotating probe.

The interpretation of the relative total pressure measurements is not an easy task. In the absolute flow the measured total pressure contains only information on the total pressure loss through the blading. In the corresponding relative flow, the measured relative total pressure depends not only on the total pressure loss but also on the static pressure and the resultant relative velocity. A change in static pressure, induced by the probe stem, will therefore have a direct impact on the relative total pressure, but affects the absolute outlet pressure only indirectly via the dependence of the total pressure losses on the exit Mach number. The sensitivity of the relative total pressure to a change in the local static pressure is also demonstrated in Fig. 11. Without changing the average downstream static pressure for the mid-span flow conditions, the local static pressure distribution is artificially modified by shifting it circumferentially by 3.65^o with respect to the absolute total pressure profile. The effect on the calculated relative total pressure is surprisingly big. The calculated value $P_{02,R}/P_{01}$ has at present nearly the same shape as the measured value $P_{02,R}/P_{01}$ except for a general shift between the two curves by $\approx 2\%$. The strong similarity between the two curves is of course purely incidental and a different shift of the static pressure distribution results in a different relative total pressure profile.

This leads of course to question the opportunity of relative total pressure measurements in a turbine rotor, because of the difficulties in the interpretation of the results. The upstream effect of the rotor blades on the guide vane exit static pressure field will indeed be even stronger than that exerted by the probe stem.

Finally, it is worth while mentioning that the rotor inlet relative total pressure profile depends strongly on the axial distance between stator and rotor. The total pressure wake of the guide vane is convected downstream following the main flow direction, while the static pressure gradients propagate in a different direction, in transonic flow often almost normal to the flow direction. Hence the wake traverses an ever changing static pressure field and thereby the relative total pressure profile will vary much stronger with axial distance that the absolute total pressure profile.

Acknowledgements

The above research project was carried out under contract for the CEC as part of the BRITE EURAM AERO CT 90-0001 Project "Investigation of the Wake Mixing Process behind Transonic Turbine Guide Vane with Trailing Edge Coolant Flow Ejection". The authors wish to acknowledge this financial support as will as the contributions by ALFA AVIO, MTU and SNECMA who made this research possible.

References

Sieverding, C.H.; Vanhaeverbeek, C.; Schulze, G.; Angeli, T.: Development of a high speed rotating probe traverse system using opto-electronic data transmission.
Proc. of the 10th Symp. on Measuring Techniques for Transonic and Supersonic Flow in Cascade and Turbomachines, VKI, Sept 1990.

Sieverding, C.H. & Arts, T.: The VKI Compression Tube Annular Cascade Facility CT-3. ASME Paper 92-GT-336.

Schultz, D.L.; Jones, T.V.; Oldfield, M.L.G.; Daniels, L.C.: A new transient cascade facility for the measurement of heat transfer rates.
AGARD CP 229 "High Temperature Problems in Gas Turbine Engines", 1977.

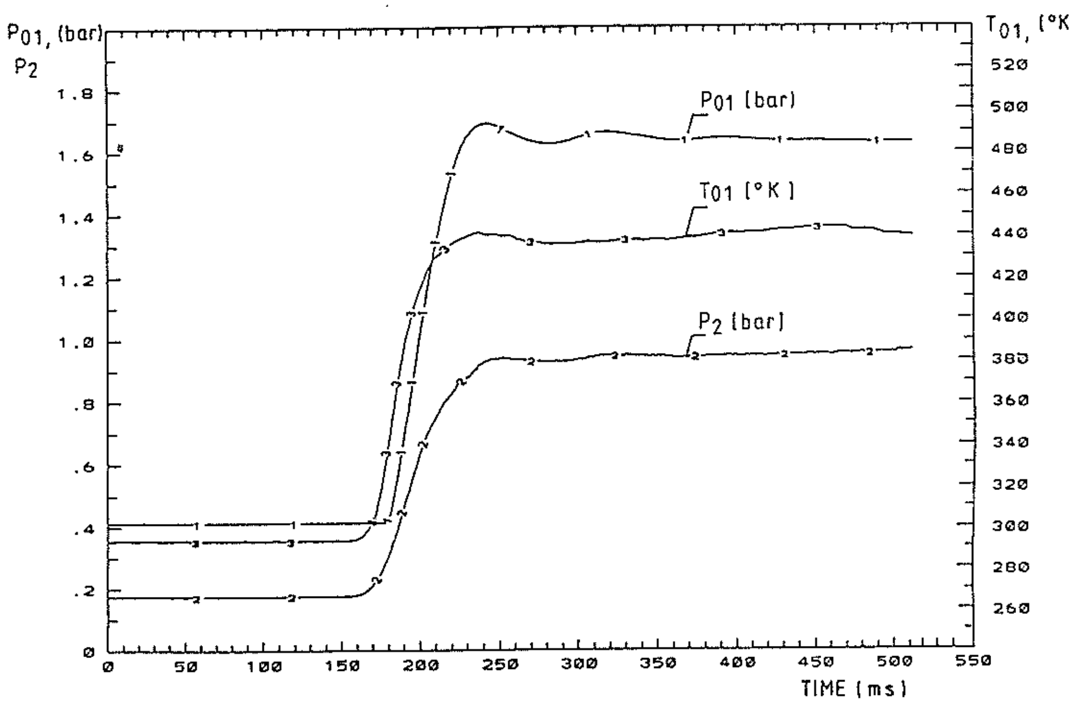

Fig. 1 – Evolution of overall cascade flow conditions over one typical test run

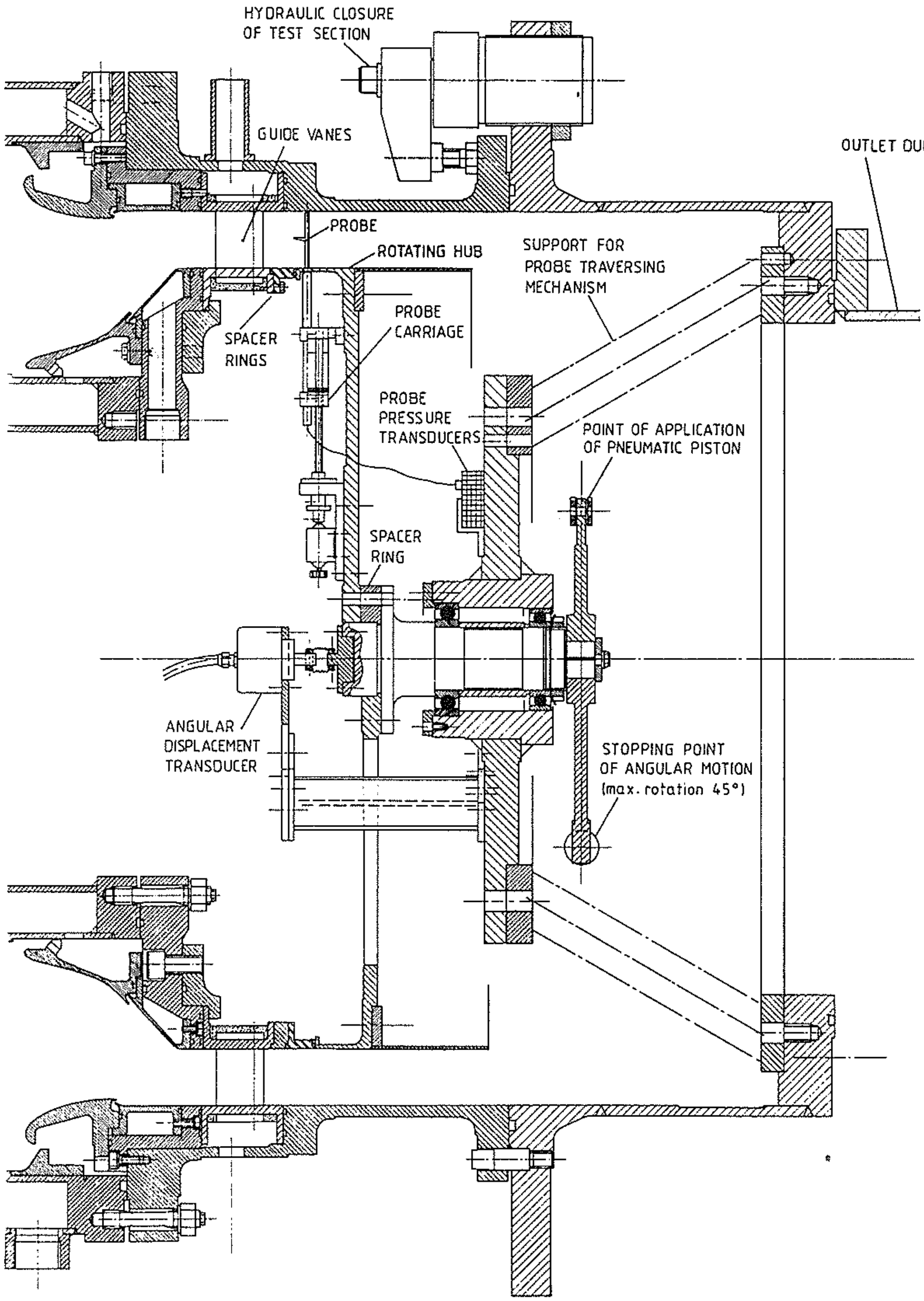

Fig. 2 - Rotating probe traversing mechanism in the VKI Compression Tube to Annular Cascade Facility

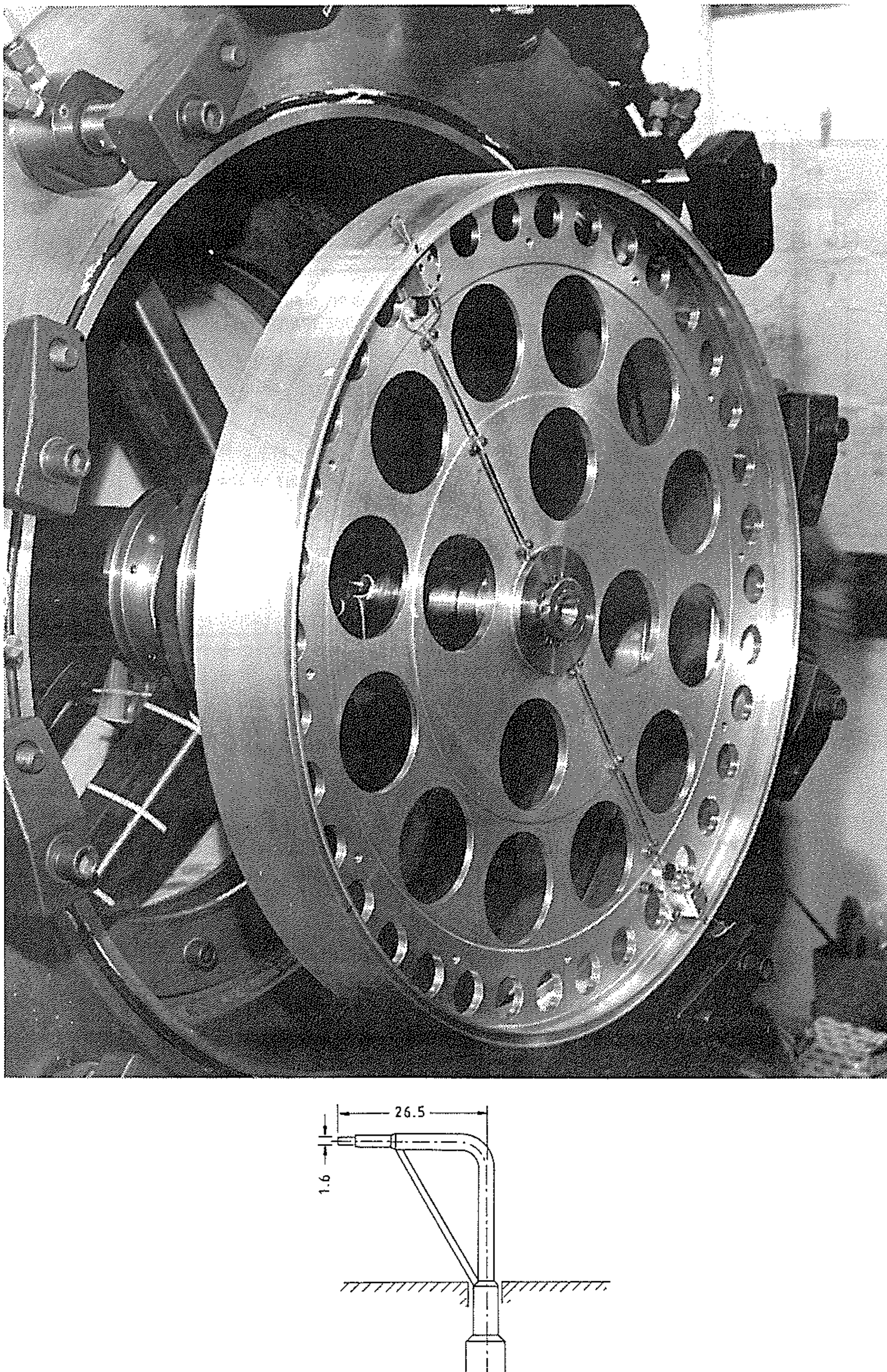

Fig. 3 – Photograph of rotating hub end wall with Kulite pressure probes

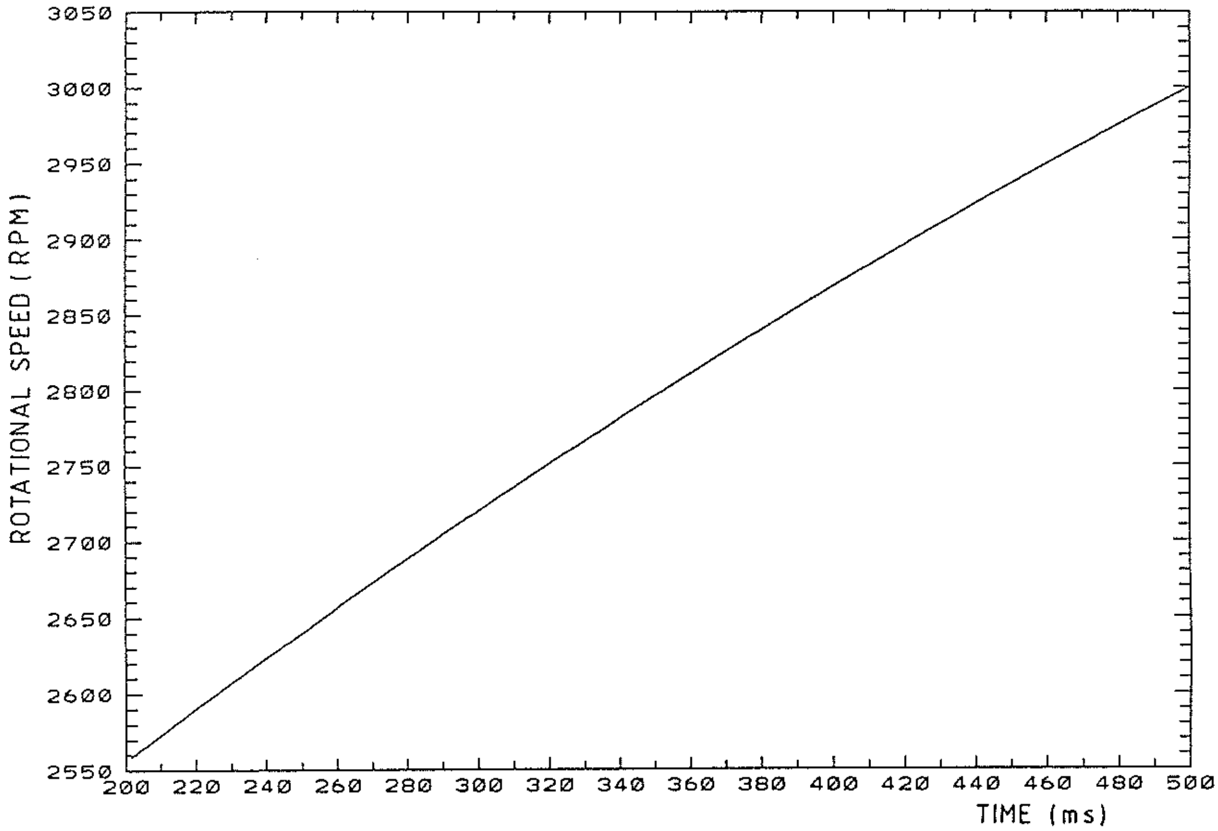

Fig. 4 – Variation of rotational speed of the probe during a test run

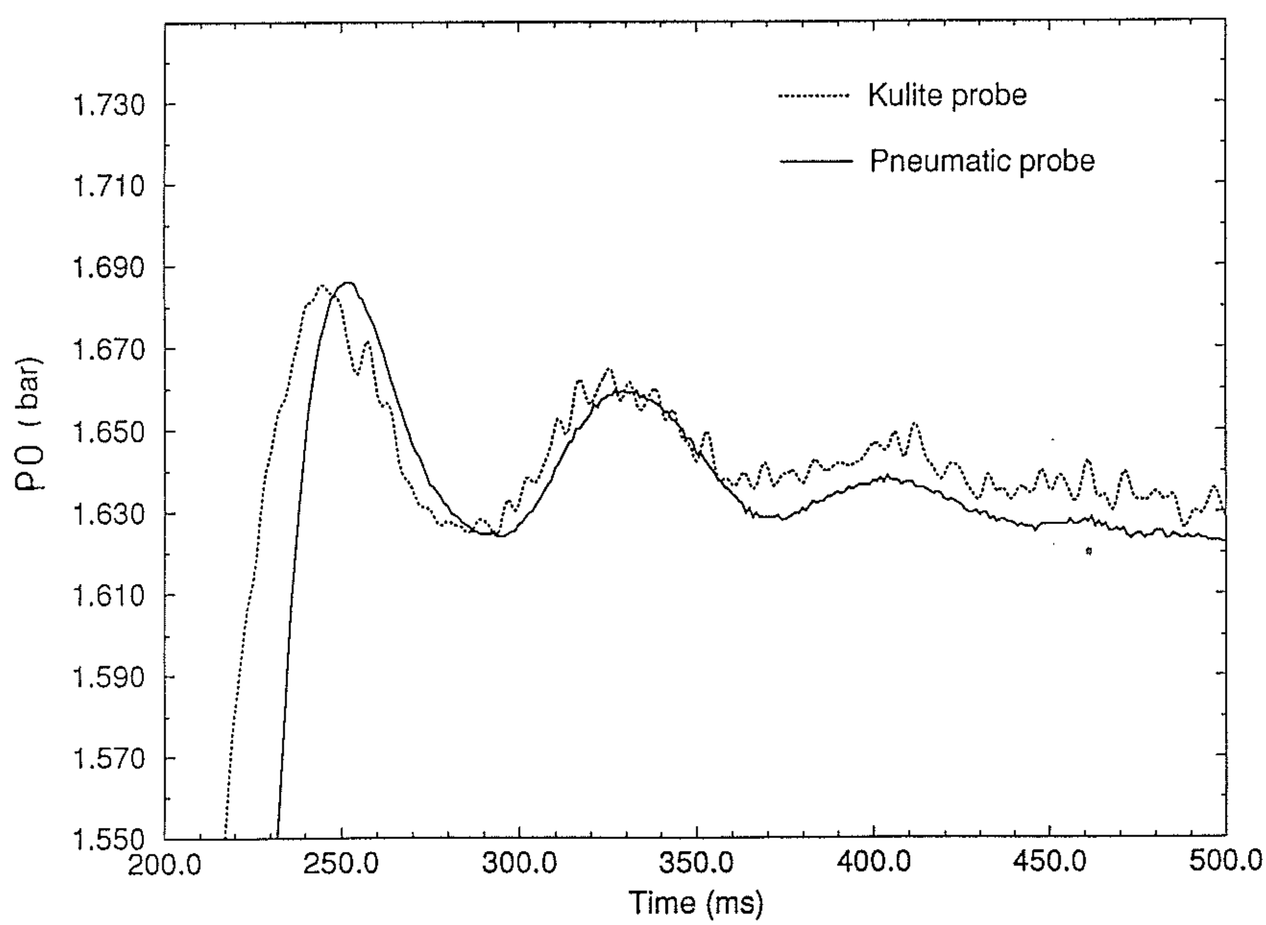

Fig. 5 – Time-pressure traces of Kulite and pneumatic pressure probes

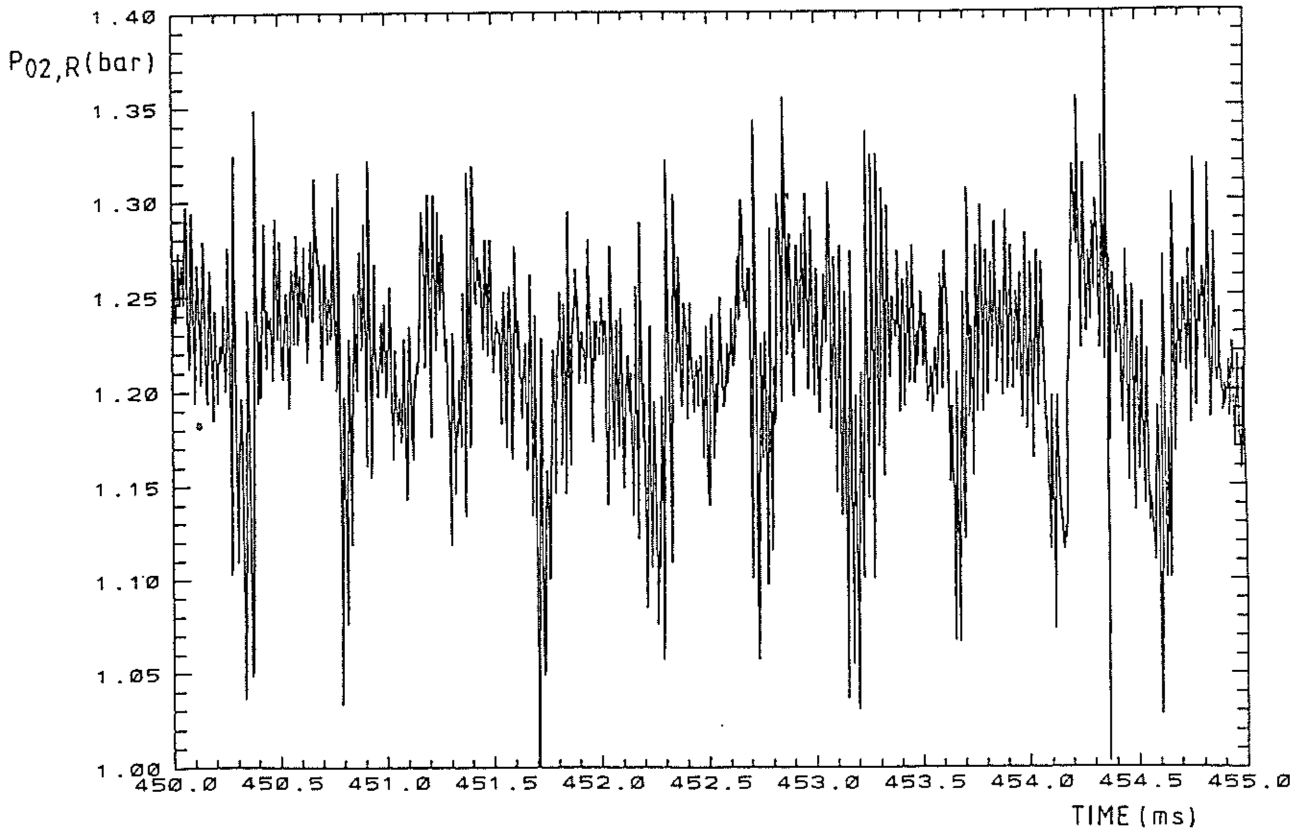

Fig. 6 – Raw data string recorded by Kulite pressure probe

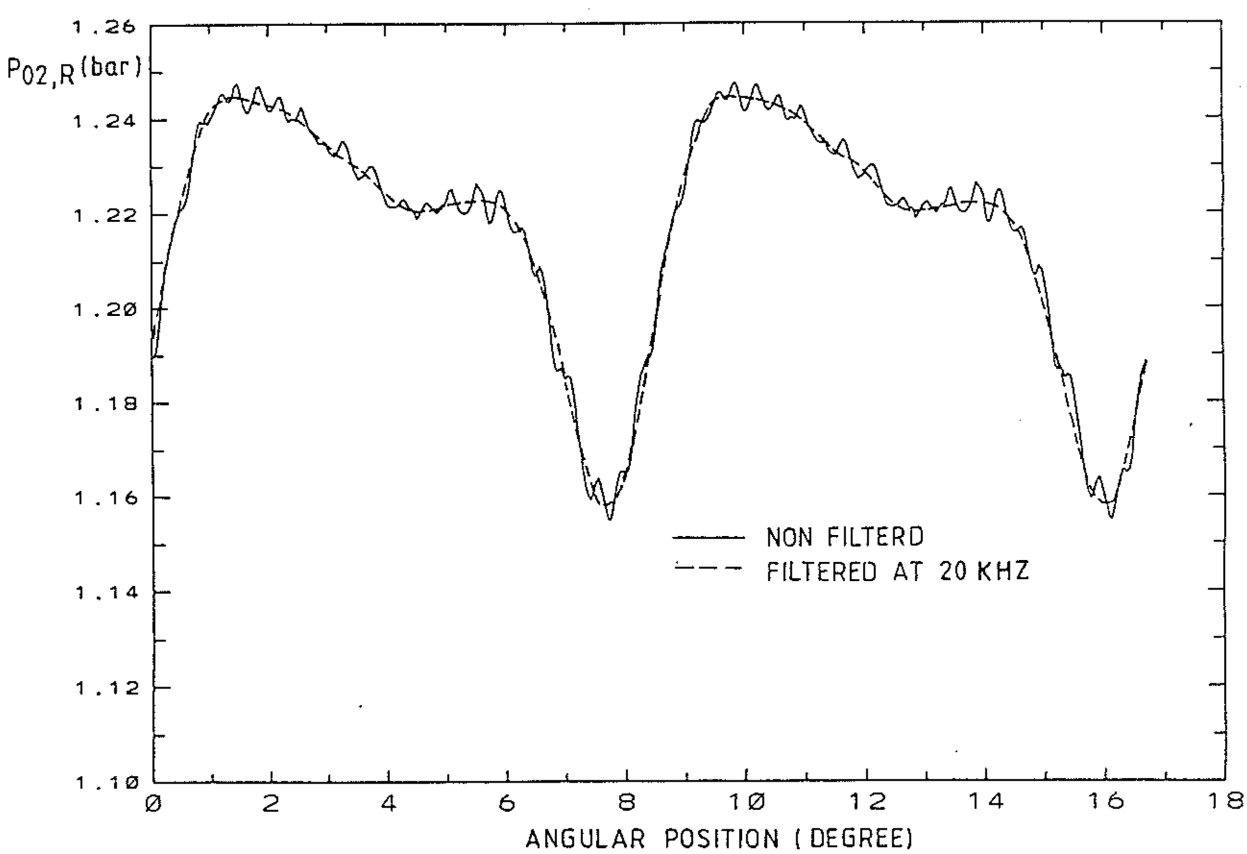

Fig. 7 – Ensemble averaged signal over 300 events

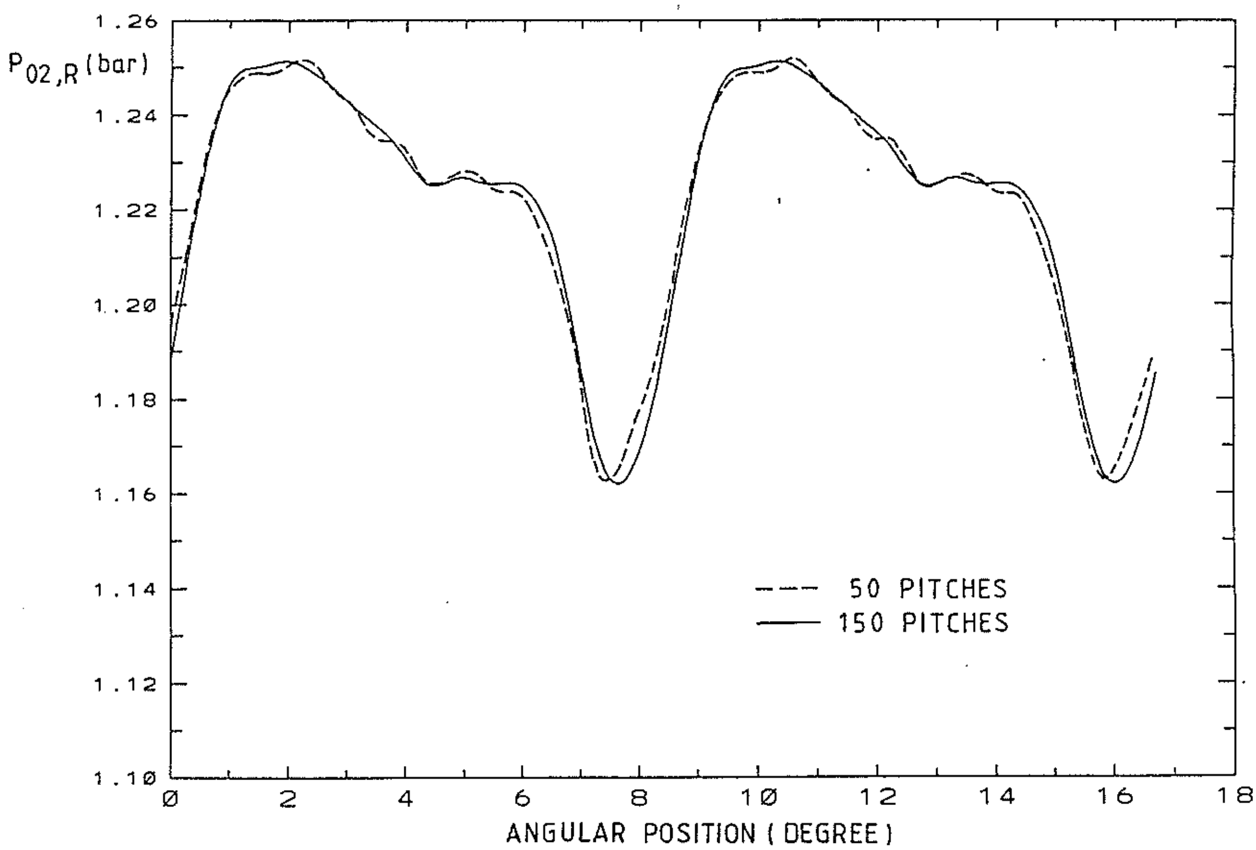

Fig. 8 – Ensemble averaged signal for 50 and 150 events

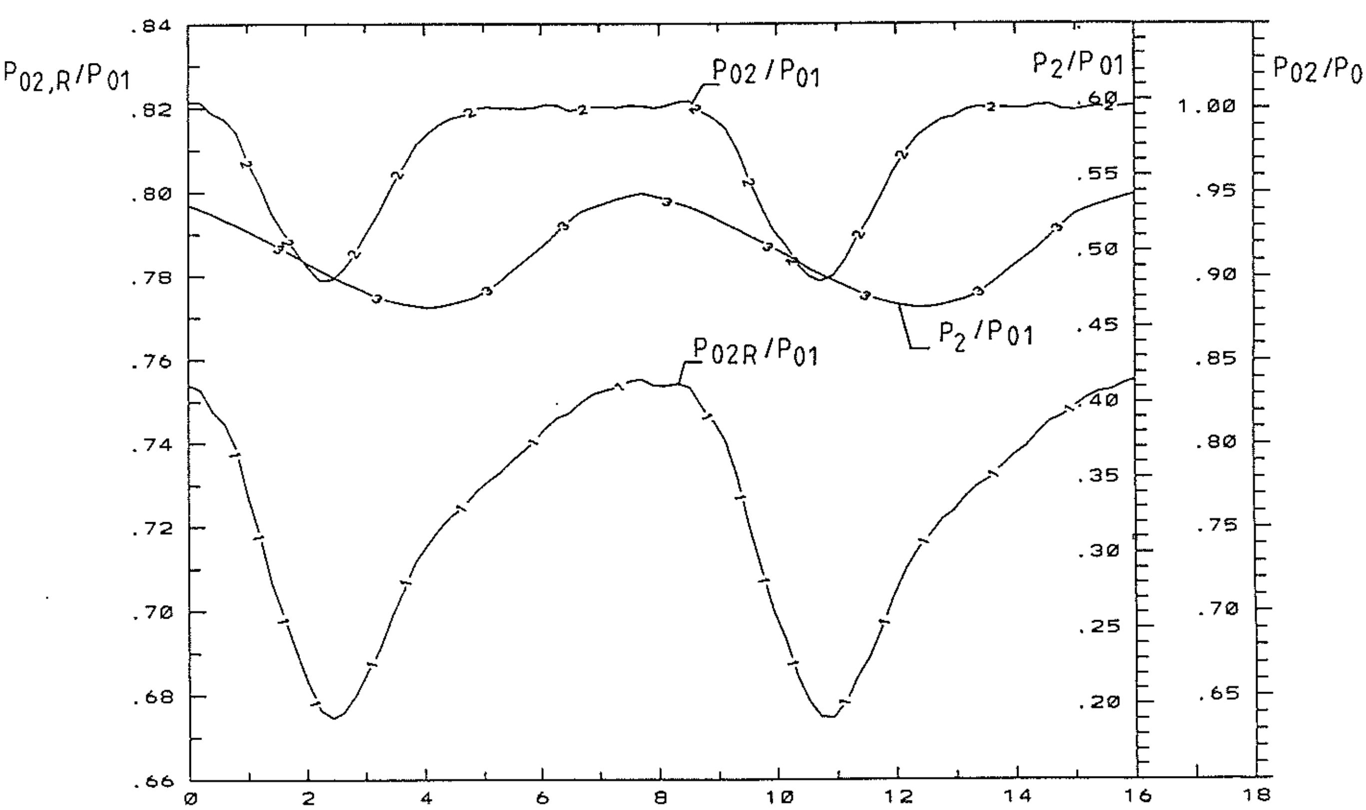

Fig. 9 – Theoretical relative total pressure ratio profile derived from stationnary flow measurements

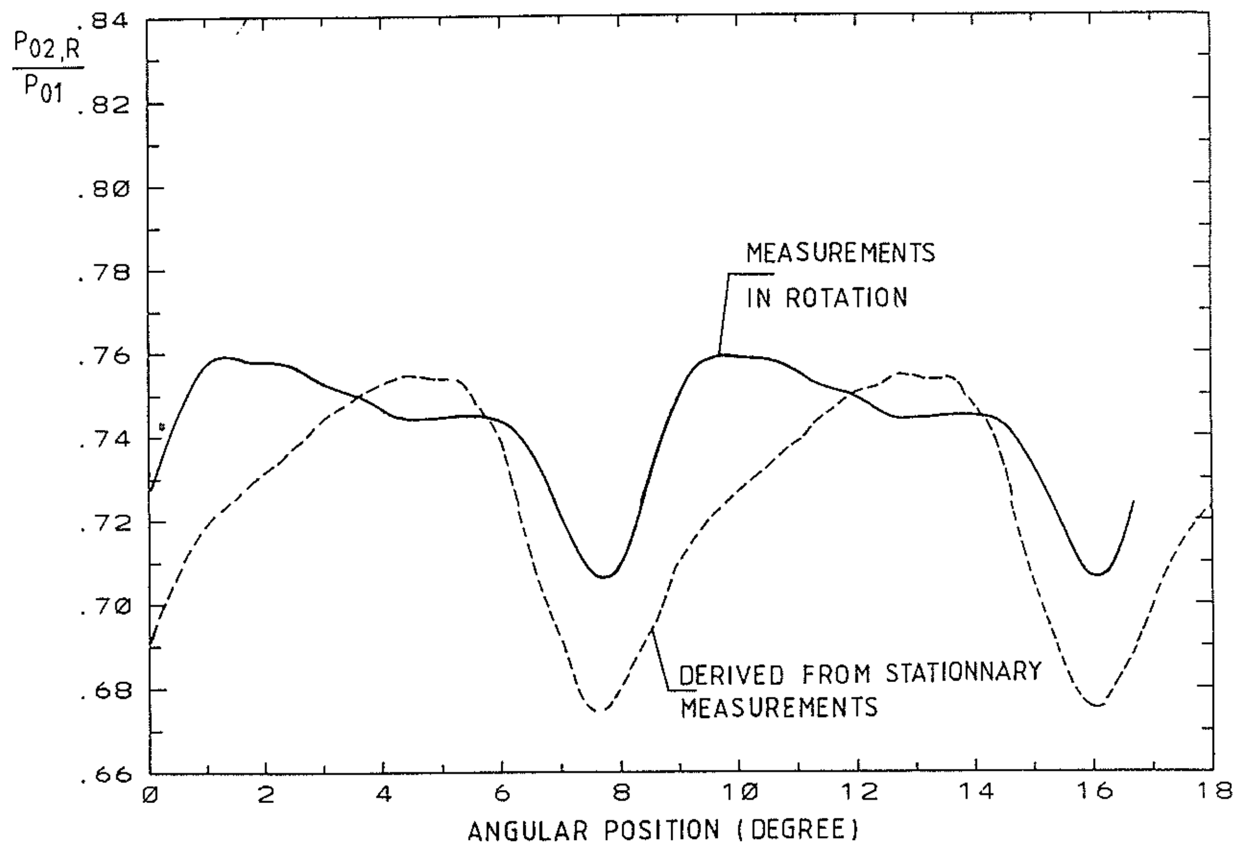

Fig. 10 – Comparison of measured and theoretical (derived from stationnary measurements) relative total pressure ratio profiles

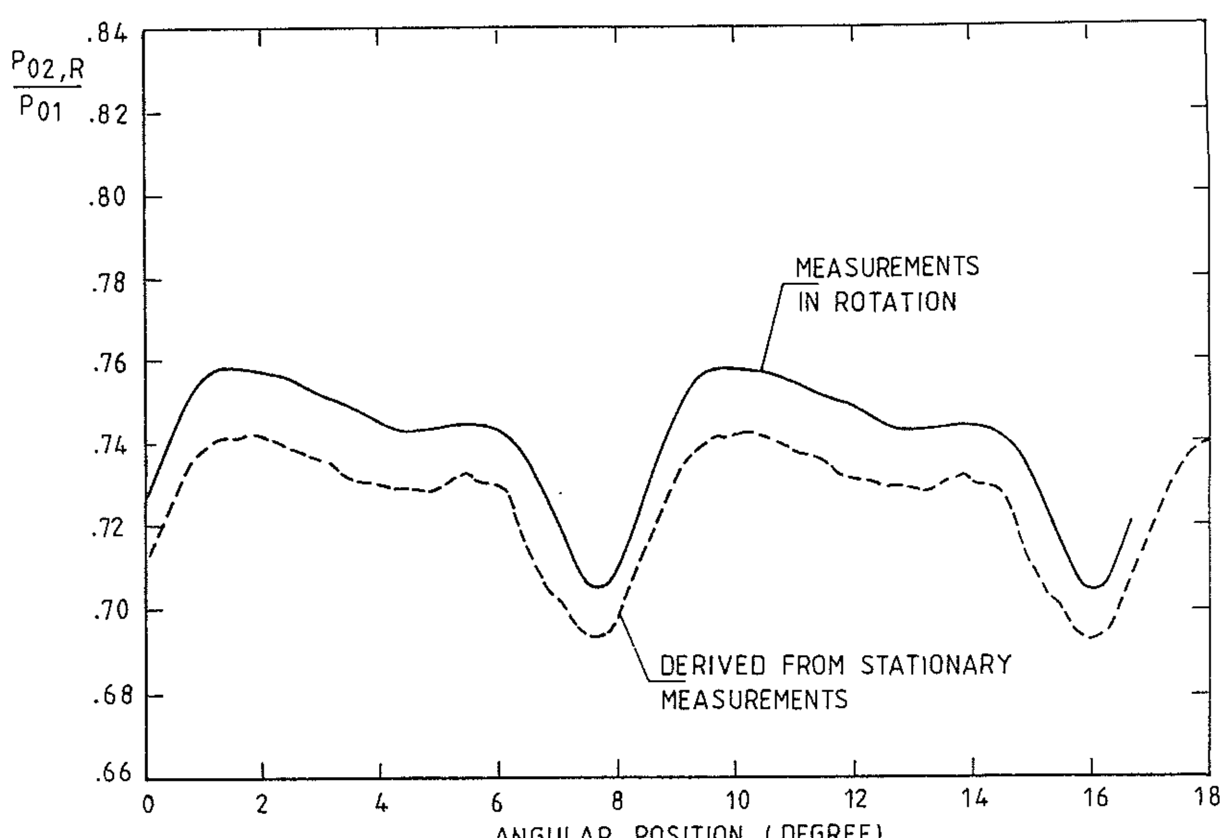

Fig. 11 – Comparison of measured and modified theoretical relative total pressure profiles (modification obtained through circumferential shift of static pressure profile in Fig. 9)