Paper 24

MEASUREMENT TECHNIQUES FOR 3D FLOW-FIELD IN THE NEW ROTATING AXIAL TRANSONIC COMPRESSOR TEST FACILITY

N. Sayari, S. Pahuja
Swiss Federal Institute of Technology
Switzerland

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N. Sayari, S. Pahuja
Laboratoire de Thermique appliquée et de Turbomachines (LTT)
Swiss Federal Institute of Technology
1015 Lausanne, Switzerland

INTRODUCTION

Understanding of three-dimensional flow in the rotating stages of turbomachinery is essential for developing and validating new analytical and numerical techniques which would incorporate the effects taking place in actual machines. Due to successive rotor and stator rows, the flow in turbomachines is extremely unsteady. Numerous studies (**1-3**) have shown that the flow is strongly affected by the potential as well as wake interactions, the latter being capable of influencing the flow several stages downstream. In general all programs for the performance prediction of turbomachines are based on the assumption of a steady-state uniform flow at the rotor entry, and hence don't take into account this important phenomenon. Satisfactory empirical modeling of the whole process of blade-row interaction is therefore required in order to get realistic and more comprehensive turbomachinery flow solvers.

Experiments in unsteady compressor research, conducted with modern high-response measuring techniques generate large quantities of data which, when suitably processed, can lead to important insights into the blade-row interaction process. Work has been going on at LTT to develop high-speed measurement techniques, using a compound temperature-pressure probe, in order to investigate the unsteady flow field behind the compressor rotor. The resultant pressure profiles coupled with Laser 2-Focus measurements in the rotor provide important understanding of the stator-rotor interaction process in the axial compressor stage.

EXPERIMENTAL APPARATUS

A new rotating test-rig facility has been developed at LTT (Photo.1), with supersonic relative inlet Mach numbers and closed loop operation. The rig is equipped with a section similar to the first-stage tip-section of an axial compressor, that is, an inlet guide vane row, rotor and stator. The test-rig is powered by a 70 kW motor, and rotor speeds upto 18000 rpm are achieved, with a gear-ratio of 6. In addition to air, various different test fluids can be used. The stage inlet temperature of the fluid is maintained constant by water cooling in a heat exchanger. Air in closed circuit was used as the test fluid for present investigations. The annular test section has the following dimensions:

External diameter = 240 mm
Internal diameter = 160 mm

The flow is initially directed by the inlet guide vane (IGV) row, before it passes through the rotor and the stator blades respectively. Manual displacement of the inlet guide vane row in the circumferential direction allows the probe to take downstream measurements in the pitchwise direction. The characteristic parameters for the three blade rows are given in Table T.1.

THE TOTAL-TEMPERATURE TOTAL-PRESSURE PROBE

The compound (total-temperature total-pressure) probe developed at LTT is shown in Fig. 1. The probe head diameter is 2.5 mm and contains a thermocouple and a piezoresistive pressure transducer. The thermocouple is K-type (BICC Pyrotenax, 0.5 mm dia.) and is mounted with its sensing head in the stagnation cavity on the probe head. The pressure transducer is of piezoresistive barrel-type (1.65 mm dia) with 50 psi absolute pressure range. It has an active four-arm strain gage bridge which is diffused into a sculptured silicon diaphragm. The natural frequency of the diaphragm is of the order of 400 kHz, and the unit can be temperature-compensated for any 93°C range between -54°C and +121°C. The transducer is placed in a recess 0.8 mm away from the axis of the pitot cavity. Since excitation current to the pressure transducer can cause appreciable heating leading to erroneous temperature measurements by the thermocouple, care was taken to insulate the two properly to minimize the thermal interference. The external dimensions of this probe are the same as those of conventional pneumatic and temperature probes, and hence it is compatible with all probe traverse-mechanisms on the test-rig.

	IGV	Rotor	Stator
Number of Blades	18	16	20
Pitch-Chord Ratio	0.85	0.785	0.826
Aspect Ratio	0.975	0.800	1.05
Stagger Angle	15.5°	56.0°	31.0°
$\frac{\text{Tip Clearance}}{\text{Blade Height}}$	0%	0.5%	0%
$\frac{\text{Blade Thickness}}{\text{Chord Length}}$	0.095	0.03	0.10

TABLE T.1 : *Characteristic parameters of blade rows*

DATA ACQUISITION SYSTEM

The conventional 4-hole wedge probes are simultaneously used for stationary data acquisition. These probes have been designed, fabricated and calibrated for ± 15° angle range (**4**). The temperature probes carry K-type thermocouples which sense the temperature in the stagnation cavity at the probe head. The temperature probes can be oriented in the direction of the flow in order to be able to measure total temperature. The compound probe is placed downstream of the compressor rotor. All these probes are mounted on the traverse mechanisms using servo-motors, whereby the radial displacement of the probes is controlled by a FORTRAN program from an IBM PC.

The complete measurement system is shown schematically in Fig. 2. The steady-state pressures from the wedge probes are measured using a digiquartz system, and a multiplexer (scanivalve) is used to take readings of different pressures. Keithley 740 programmable thermometer is used to take temperature measurements through FORTRAN program on the PC. The steady state temperature and pressure measurements are synchronized through a probe traverse and data-acquisition program installed on the PC.

The high-frequency pressure readings from the compound probe are amplified by ENDEVCO pressure signal conditioner. The transfer characteristics feature a gain range of 10-100 which is continuously adjustable. A Signal-to-Noise Ratio of 250 is achieved for a gain of 60. This amplified signal is then fed to Keithley high-speed DAS 50 data acquisition system installed on an IBM PC The DAS 50 interface board, which forms the heart of the data acquisition system, has a 4-channel 1 MHz conversion rate and upto 1 Megaword of on-board system memory. An analog multiplexer can be programmed to accept data from the desired number of input channels. When the multiplexer changes channels, the track-and-hold amplifier maintains the status of the previous channel. This feature is important for the present application because the pressure measurements are triggered by the signal of a proximity sensor which is fed to one of the DAS-50 input channels. The A/D converter has a 12 bit resolution and a conversion rate of 1 µsecond. The data stored in the on-board memory may be read sequentially or by channel. On the completion of measurements, the raw data files are transferred to HP9000 workstation for processing and visualization.

The unsteady pressure measurements are triggered by the signal of a proximity sensor which is placed on the side wall of the test section and gives a pulse for every rotor blade which passes by. The system is set to start taking the measurements when a specified voltage is reached on the negative-going edge of the trigger signal and then to continue taking a pre-specified number of measurements. The data is read from the DAS-50 memory by the PC Bus as numerical ASCII values. These values are statically calibrated for pressure, and the calibration is carried out by putting the probe in a pressure chamber with adjustable pressure. Due to long term drift of the sensor, this calibration is done before every measure, and the calibration equation is a straight line. Repeated calibrations show that the constant in the equation varies depending upon the ambient atmospheric conditions and hence the need to calibrate before each measurement. On the contrary, the sensitivity (the multiplication factor in the calibration equation) is quite independent of these conditions. Further in order to improve the accuracy of the measurements, the unsteady pressure amplitude of the probe is superimposed on the time-mean total pressure measured by the steady-state 4-hole probe. The maximum error in calibration is less than 5 mbar, that is less than 0.5% of the measured absolute pressure value.

The rotational speed of the compressor rig and the data acquisition frequency are so matched so as to have 200 pressure measurements in a rotor blade passage. This offers a rotor blade pressure profile of good resolution, and an increase in data acquisition frequency leads to larger file sizes but without appreciable gain in resolution. Phase-locked Ensemble Averaging Technique (PLEAT) is an accepted method to process the huge amounts of raw data acquired in unsteady measurements (5). The phase-locked parameters are defined as follows:

1. Phase-lock averaged total pressure:

This is the sum of individual raw segments of data meaned over a number of rotor revolutions.

$$\tilde{P}\,(i) = \sum_{n=1}^{N} \frac{P(i,n)}{N}$$

where P(i,n) is the instantaneous pressure value, and N is the number of blade passages over which the average is carried out.

2. The Phase-locked Periodic Turbulence Parameter:

This is the square of the phase-locked average.

$$T_p^2\,(i) = \tilde{P}^2\,(i)$$

3. The Phase-locked Random Turbulence Parameter:

This is the root-mean-squared difference between the raw data and the phase-lock averaged trace.

$$T_r^2(i) = \sum_{n=1}^{N} \frac{\left(P(i,n)-\tilde{P}(i)\right)^2}{N}$$

The distribution of Random Turbulence Parameter helps in the identification of the wakes of stator and rotor blades downstream of the rotor. Since this parameter is a time-averaged mean square of random fluctuations, it reveals the wake pattern in the absolute frame for a stationary measuring location.

LASER 2-FOCUS ARRANGEMENTS

In order to understand the flow in the interior of the rotor passage, the rig has been adapted to carry out Laser 2-Focus measurements. The details of L2F measurement procedure are to be found in (**6**). This is made possible by a 60 mm long, 8 mm thick trapezoidal glass window, whose internal surface is made flush with the rotor wall casing so as to avoid disturbing the flow. Measurements can thus be made in rotor blades as well as in sections upto 15 mm upstream and downstream of the rotor.

Two proximity sensors, one placed on the shaft and the other on the casing, allow the synchronization of L2F measurements in the rotating system. Particle seeding is achieved using an injection system with a flexible head which can be oriented in the flow to obtain optimum seeding. Polyamide particles (1 micron dia.) are injected 250 mm upstream of the test-section. In order to avoid the contamination of the test fluid with the gas used for particle injection, a bypass system with a turbo-pump has been constructed.

EXPERIMENTAL RESULTS

Experiments were conducted on the test rig while fixing the rpm constant and varying the flow coefficient, to achieve various points on the compressor performance characteristics. For each operation point, the probes are traversed radially with the aid of probe traverse mechanisms and the measurements are taken at five sections, at 10%, 30%, 50%, 70% and 90% of the canal height respectively. The experiments are conducted once with and once without the inlet guide vane raw, so as to investigate the interaction phenomena as they manifest in the rotor blade stage. Thus the overall performance of the stage can be predicted from the steady-state measurements using the standard methods, but the emphasis here is laid upon the technique to study the unsteady phenomena associated with the rotor-stator interaction. Firstly, the wake of the inlet guide vane is located by traversing the steady pressure probe upstream of the rotor. The velocity profiles at this station are presented in Fig. 3, which show the strong 3-D nature of the flow upstream of the rotor. As expected, the velocity decreases in the wake, accompanied with significant total pressure loss. The wake is more widespread towards the casing, which is due to the influence of the wall boundary layer. Further, it is displaced tangentially towards the suction side, as one moves away from hub. The flow angle distribution in the wake follows an S-shape and the Mach number varies by as much as 30% across the wake, both of which put into question the validity of the assumption of a homogenous and steady rotor inlet flow, on which most of the calculation procedures are based.

The relative Mach number distribution in the rotor passage as measured by Laser 2-Focus Velocimeter is presented in Fig. 4. The shown profile is for the stream surface at midspan. The measured velocities are found to be consistently higher than the values predicted by a 3-D viscous code, due to the effect of wake. Wake propagation into the rotor increases the incidence and hence leads to loss in total pressure. The total effect manifests itself as a lower overall pressure-ratio for the compressor stage. Further, the rotor passage is marked with a high degree of turbulence, which makes the L2F measurements difficult, especially towards the trailing edge. Another problem arises from the fact that two (or more, depending on the blade thickness) data windows out of the total of 16 have to be closed, in order to avoid the saturation of L2F photomultipliers by strong reflection from the blade surface passing through the probe volume. This leads to an uncertainty of 2.8° in the angular position of the blade, which actually serves as the reference location for all the measurement points.

Measurements from high-frequency pressure probe are carried out downstream of the rotor. All unstationary data is analyzed using phase-locked averaging, thus revealing the periodic characteristics of the measurement, which are otherwise obscured by the random fluctuations in the raw data. The phase-lock averaged profiles are very sensitive to the precision in determination of the periodicity of the signal, and lack of precision may lead to suppression of vital periodic features of the signal. It is therefore necessary to ensure perfect synchronization between the signal and the triggering function. The number of blade passages required in order to obtain a stable phase-lock averaged profile can serve as an indicator of this precision. In the course of the present experiment, it was observed that the averaged parameters stabilize after 40 rotor revolutions approximately. Further, all profiles are sampled over 8 blade passages. This has been done in order to have an integral number of stator wakes in the rotor sample profile. As shown in Table T.1, the IGV/Rotor blade ratio is 9/8, and hence the choice of 8 blade passages as the average sample.

Fig. 5 shows the averaged total pressure profile at midspan behind the rotor at 50% vane opening (the corresponding flow coefficient is 30.1), with and without inlet guide vane stage. In the absence of inlet guide vanes, the blade passages are clearly defined by the total pressure loss due to the passing rotor wake, and the subsequent well- defined peaks in the blade passage. In contrast, the profiles for the case with inlet guide vanes show the complex interaction of rotor blade wakes with the wakes convected downstream from the inlet guide vane stage. The total pressure profile in the blade passage is now marked with strong variations. The number of stator wakes present in one rotor blade passage is given by:

$$n_w = \frac{r\, n_s\, c_r}{v_x} = 3.26$$

where r is the number of rotor revolutions per second, n_s is the number of blades in the upstream stator row, c_r is axial chord length for rotor blade and v_x is the axial velocity. Hence about three stator wakes are simultaneously present in each rotor passage.

Fig. 6 shows the variation of Random Turbulence parameter over 8 blade passing periods, for the cases with and without the inlet guide vane stage. The shown profiles are at 30% of the canal height (measured from hub). It is seen that with the inlet guide vanes, the region marked with high turbulence is more widespread in the blade passage than in the flow without the guide vanes. This indicates that the rotor exit flow is infested with wakes to a large extent. Further, the degree of turbulence (as indicated by the magnitude of Random Turbulence Parameter) is also higher due to the interaction between the stages.

It is also noticed that for increased throttling, that is with decreasing flow coefficients, the depth and width of the wakes grow considerably, which can be inferred from the Random Turbulence Parameter profiles at the same location (70% canal height) for different flow coefficients (Fig. 7). The throttling is leading to increasing incidence angles, with the above mentioned effect. This is corroborated by the results of other experimental studies (**3**).

CONCLUSION

The compound probe and the measurement system developed for the study of unsteady phenomena in turbomachinery proves to be promising. The high-frequency pressure measurements coupled with L2F measured velocity profiles in the rotor passage provide important information about the wake effects on the rotor exit flow.

Future measurements using this technique are envisaged to investigate how the variation of axial gap between blade rows affects the rotor-stator interaction phenomena.

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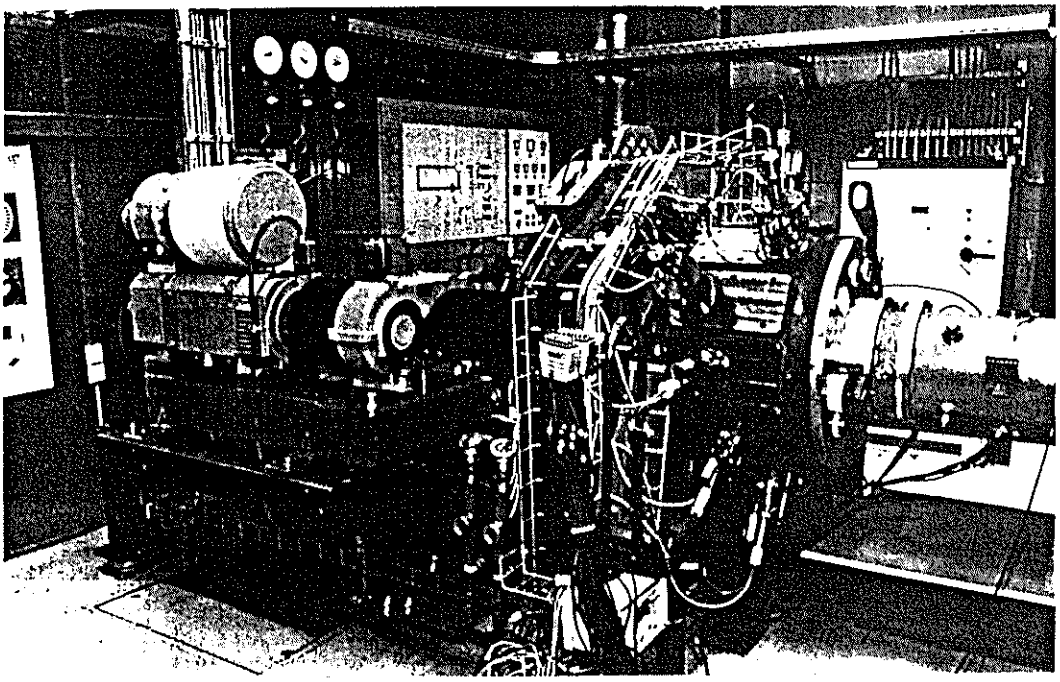


Photo 1. : Measurement chamber of the axial compressor test rig

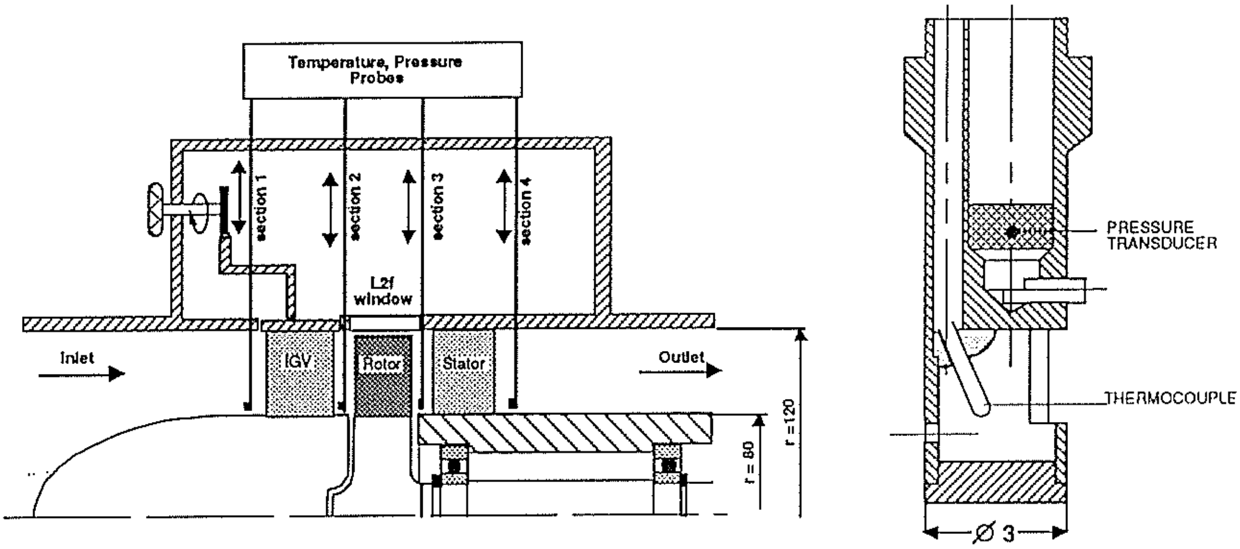


FIG 1. : Schematic view of the axial compressor test rig with the instrumentation; right side the head of the instationary total pressure-temperature probe downstream of the rotor

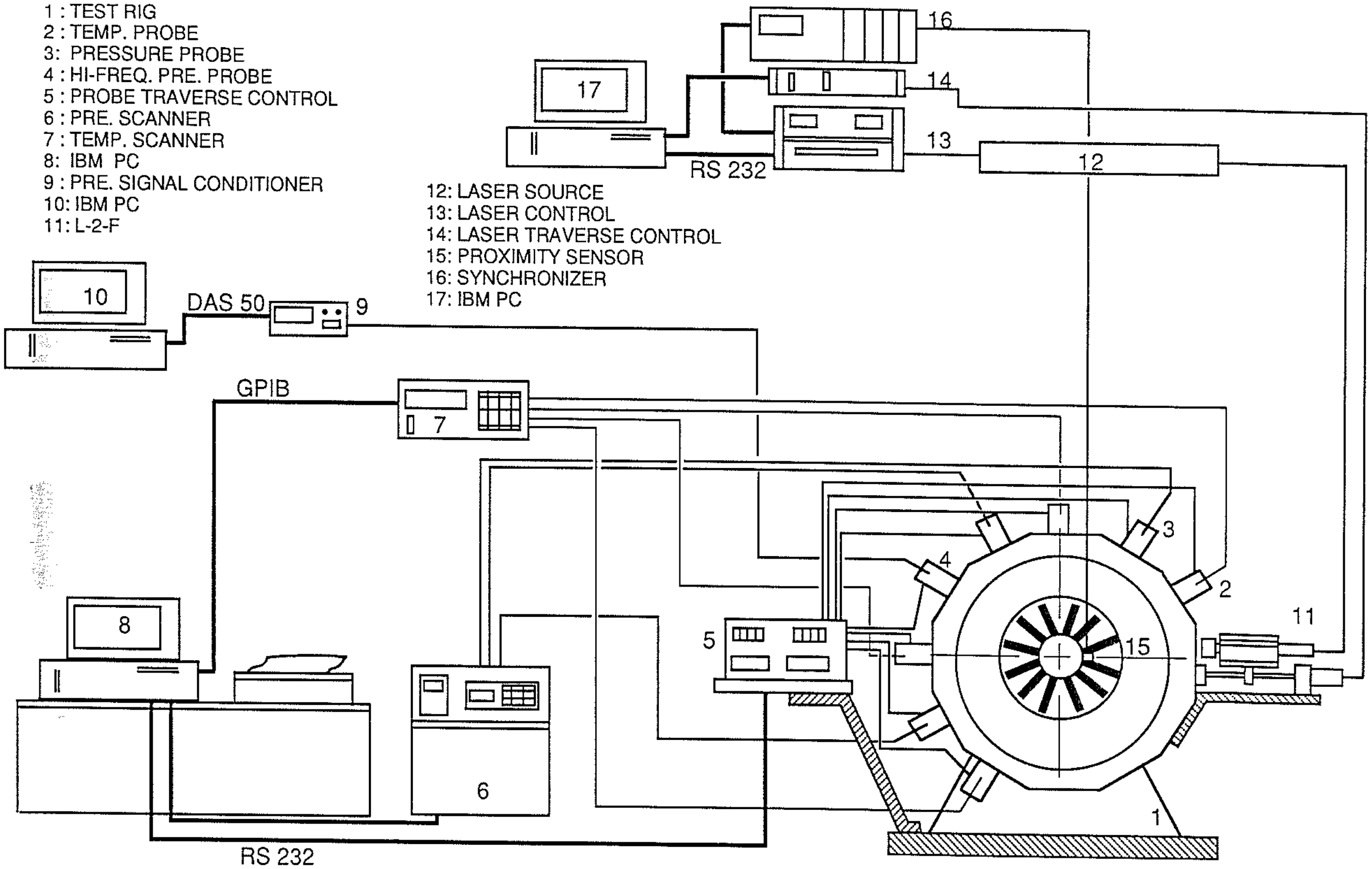


FIG. 2 : MEASUREMENT AND DATA ACQUISITION SYSTEM

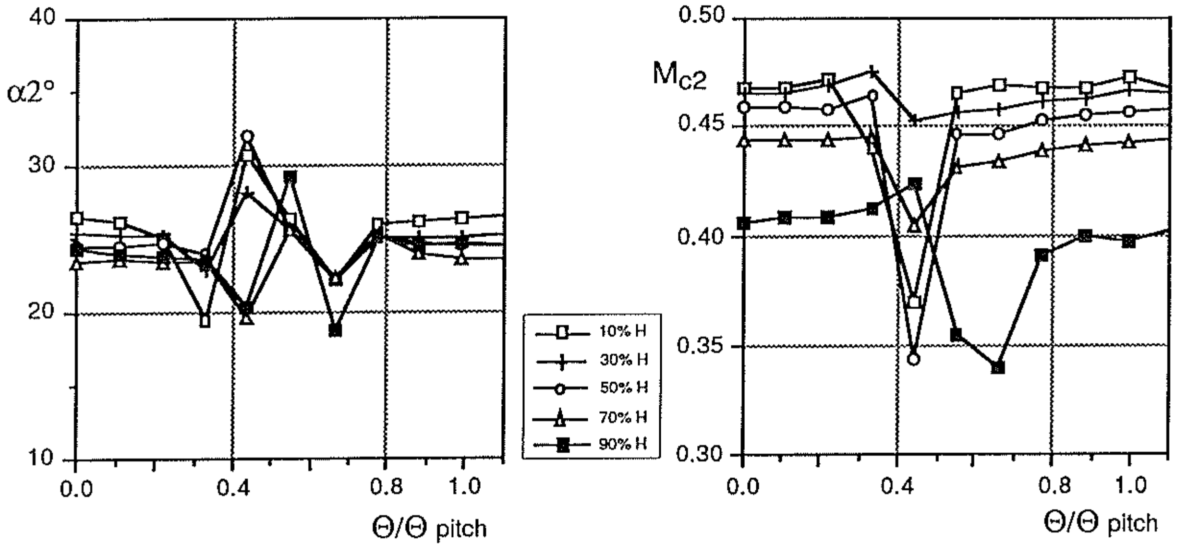


FIG. 3: Measured Flow Angle and Absolute Mach number Profiles in the Wake of Inlet Guide Vane

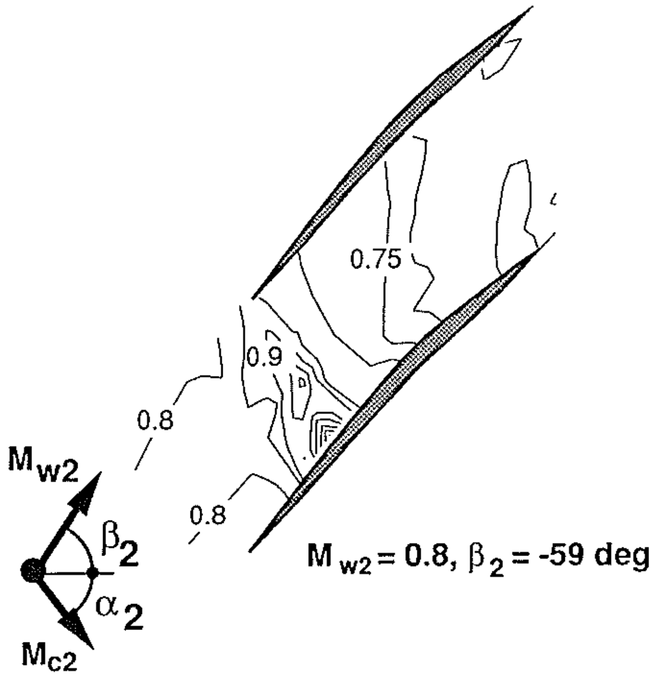


FIG. 4 : L2F Measured Relative Mach Number Distribution in the Rotor Passage with Inlet Guide Vanes Upstream

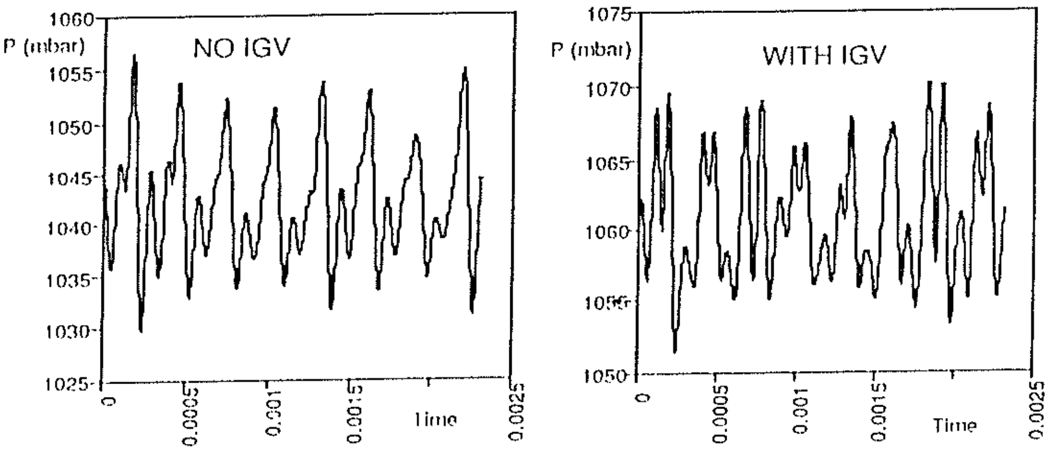


FIG. 5: Effect of Inlet Guide Vanes on Averaged Total Pressure Profiles
Rotor Exit, 50% Span

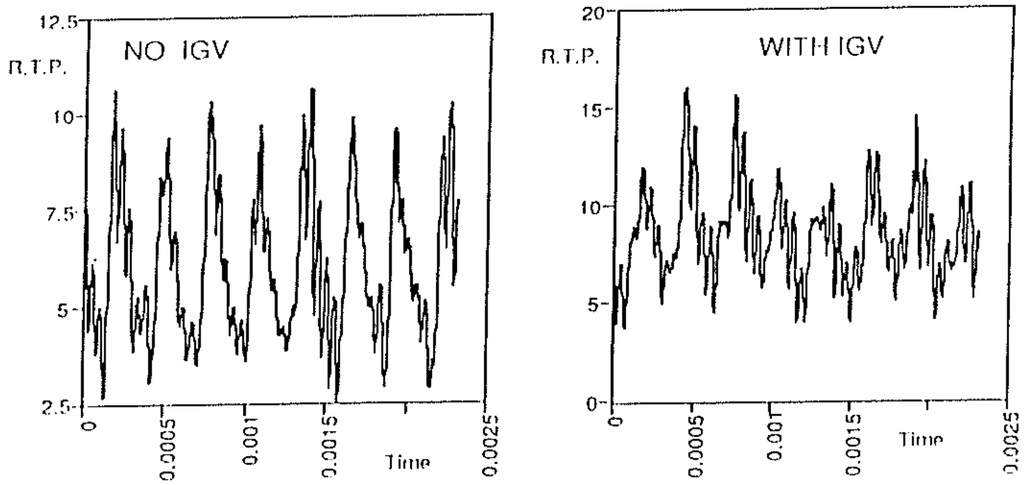
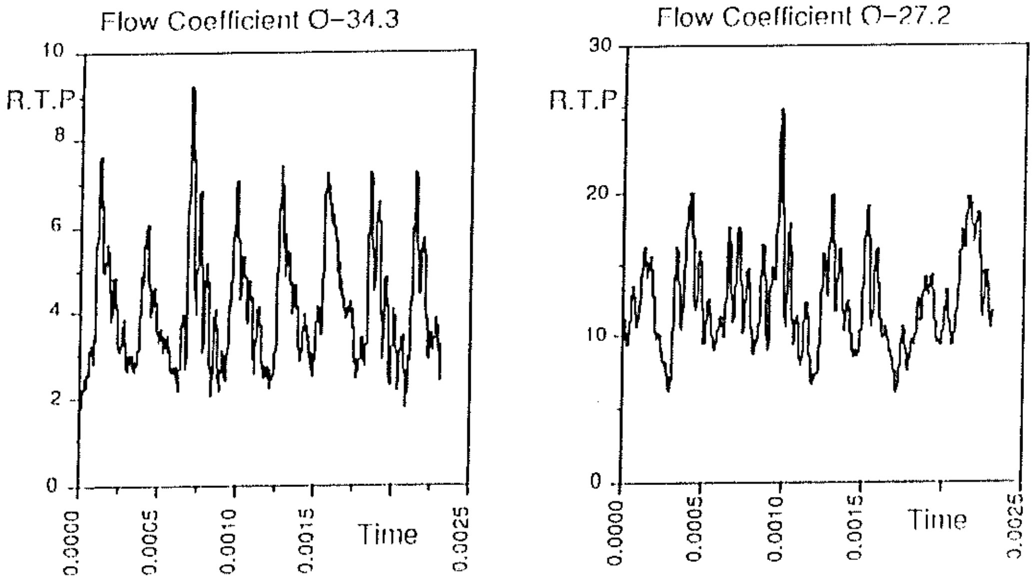


FIG. 6: Effect of Inlet Guide Vanes on Random Turbulence Parameter
Rotor Exit, 50% Span


Flow Coefficient Ø-34.3

Flow Coefficient Ø-27.2

FIG. 7 : Effect of Throttling on Random Turbulence Parameter
Rotor Exit, 70% Span