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A New Facility to Study Three Dimensional Viscous Flow and Rotor-Stator Interaction in Turbines - A Progress Report

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A description of the Axial Flow Turbine Research Facility (AFTRF) being built at the Turbomachinery Laboratory of the Pennsylvania State University is presented in this report. The purpose of the research to be performed in this facility is to obtain a better understanding of the rotor/stator interaction, three dimensional viscous flow field in nozzle and rotor blade passages, spanwise mixing and losses in these blade rows, transport of wake through the rotor passage, and unsteady aerodynamics and heat transfer of rotor blade row. The experimental results will directly feed and support the analytical and the computational tool development. This large scale low speed facility is heavily instrumented with pressure and temperature probes and has provision for flow visualization and laser doppler anemometer measurement. The facility design permits extensive use of the high frequency response instrumentation on the stationary vanes and more importantly on the rotating blades. Furthermore, it facilitates detailed nozzle wake, rotor wake and boundary layer surveys. The large size of the rig also has the advantage of operating at Reynolds numbers representative of the engine environment.

1. BRIEF OUTLINE OF RESEARCH PROGRAM

The objective of the proposed research is to gain a thorough understanding of the flow field in a turbine stage, including three dimensional inviscid and viscid effects, unsteady flow field and heat transfer in the rotor passage, three dimensional mixing in inter and intra-blade passages, tip clearance effects, effects of film and convective cooling on flow and thermal field. A brief outline of the research programs proposed for the near future is given below:

Recent investigations have shown that three dimensional effects have considerable influence on the performance, and heat transfer in turbine stages. A knowledge of the characteristics of the three dimensional flow field inside the turbine rotors, including the blade boundary layers, endwall flows and the inviscid velocities, is essential for the analysis and the design of turbines used in military and civilian aircraft. Viscous and turbulence effects play a very significant role in the study of improved design, better efficiency, cooling air requirements, mechanical reliability, flow induced vibration, and flutter of the turbine blades. Because of the complicated nature of the problem, the three dimensional viscous, turbulent, unsteady flow field inside the rotors is one of the least understood phenomena in turbines.

The Pennsylvania State University research group has recently completed a detailed experimental and computational study of the three dimensional flow field in the axial flow compressors and this has provided valuable information on the endwall flow characteristics, blade boundary layers, tip leakage flow and the inviscid flow field (including blade pressure distribution) (example Refs. 1-3). The boundary layers developing on turbines are also very complex; these are three dimensional with laminar, transitional, turbulent and separated zones. The flow field is a function of several parameters such as the solidity, incidence, camber, radial and chordwise pressure gradients, speed of rotation, blade geometry and the Mach number. Because of these complications, very few have attempted measurement of the rotor flow field. The objective of this investigation is to measure the entire flow field inside a turbine rotor and nozzle at the design condition. An additional objective is to develop analysis and computational techniques for the prediction of this flow field. The laser doppler velocimeter system (non-intrusive) is most desirable for flow measurements inside the rotor of the proposed facility. The wall and blade shear layers will be measured using hotwire sensors. The measurement will be taken at sufficient chordwise, radial, and tangential locations so as to derive a continuous variation of the flow field (including the blade and the annulus wall boundary layers) across the entire passage (hub to tip, leading to trailing edge, and pressure to suction surfaces). These measurements will provide information on the transition, turbulence properties, three dimensional flow velocities, and blade pressure distribution.

In addition, the unsteadiness into rotor inlet will be resolved through detailed measurement of nozzle wake characteristics. This will be carried out 50 and 20 percent (of nozzle chord) spacing between the nozzle and the rotor. The nozzle wake survey at several radial and axial locations, including stations close to the nozzle trailing and rotor leading edge will be carried out.

All the investigations carried out hitherto concern an independent study of steady and unsteady aerodynamics, or steady and unsteady heat transfer. These are usually from different set of facilities and operating conditions. Since heat transfer and aerodynamic phenomena are closely coupled, this approach has not led to a basic understanding of the flow and thermal field. One of the major objectives of the Penn State program is to carry out both the aerodynamic and heat transfer measurements in the same facility with identical operating conditions. The program for the measurement of steady aerodynamics was described earlier. The unsteady aerodynamics, including unsteady boundary layer properties will be measured using the hot wire techniques developed at the Pennsylvania State University. It is also planned to carry out unsteady convective heat transfer research in the Axial Flow Turbine Research Facility at a later date. The objective is to model the turbulent heat fluxes near the solid walls in complicated viscous flow zones such as the areas affected by wake passing. During the investigations, unsteady features of wall heat flux, stagnation temperature and wall temperatures will be investigated experimentally and interpreted. The vane-blade interaction phenomenon will be captured by using thin film platinum wall heat flux sensors located in the areas where the wakes from the upstream rows impinge. These sensors are excellent indicators of phenomena such as laminar to turbulent transition, separation, reattachment etc. Their time response is sufficiently high to capture the unsteady features of the vane-blade interaction process. A new method of obtaining unsteady heat transfer information from the large scale cold turbine rig is discussed in detail in ref. 4. The measurement techniques are described in refs. 5 and 6.

2. FACILITY DESCRIPTION

A complete description of the facility and instrumentation is given in ref. 4. Only a brief summary is provided below. The Axial Flow Turbine Research Facility of the Pennsylvania State University is an open circuit facility 91.4 cm in diameter and a hub to tip radius ratio of 0.73, with advanced axial turbine blading configurations. The facility consists of a large bellmouth inlet, a turbulence generating grid section, followed by a test section with a nozzle vane row and a rotor as shown in figure 1. There are 23 nozzle guide vanes and 29 rotor blades followed by outlet guide vanes. Provisions exist for changing the vane-blade axial spacing from 20 to 50 percent of chord. The belmouth inlet is housed in an enclosure (not shown) covered with wire mesh and a thin layer of rubber foam to filter the air prior to entry to the inlet.

A variable through flow is provided by two auxiliary, adjustable pitch, axial flow fans and an aerodynamically designed throttle. This system allows accurate control of the mass flow through the experimental stage up to a maximum of 22,000 cfm. The two fans in series produce a pressure rise of 74.7 mm Hg (40" of water) with a mass flow of 10.4 m^3 per second under nominal operating conditions. The power generated by the experimental turbine rotor assembly is absorbed by an eddy-current brake which is capable of absorbing up to 90 Hp. The speed of the rotor can be varied between 175 and 1695 RPM with the "dynamatic-adjusto speed" control system and can be held constant to $\mp$ 1 RPM, with normal fluctuations in line voltage. The eddy current brake is cooled by a closed loop chilled water cooling system.

The rotor and nozzle vane passages are instrumented with high frequency response instrumentation to measure steady (time averaged) and unsteady pressures and shear stresses. The details of the instrumentation used on the nozzle vane, rotor blade, nozzle casing, rotor hub, nozzle hub will be described in the next section. Provision has been made for a laser window (item B in Fig. 1) for LDV measurement of flow field upstream of the nozzle, nozzle passage, spacing between the rotor and the nozzle, rotor passage and downstream of the rotor passage.

The facility is equipped with two traversing mechanisms. One of the probe traverse unit is mounted directly behind the rotor disk and has provisions for the radial and circumferential traverses in the rotating frame. It is driven by a stepping motor driven by a computer controlled indexer at tangential increments of 0.019 degrees/step to allow accurate measurement of the rotor wakes. The intra blade radial and tangential surveys are accomplished with the use of the L.C. Smith stationary probe traverse unit. This mechanism is also driven by a computer controlled indexer and stepping motor in 0.05 mm steps and 0.0234 degree steps in the radial and circumferential directions respectively.

The rotating to stationary interface data transmission system, attached to the rotor shaft ahead of the nose cone, is an integral part of the facility. It consists of a 150 ring mechanical (brush/coin type) slip ring unit, and a specialized ten-channel low noise/signal ratio mercury slip ring unit. A 32 channel electronic pressure scanner unit is located in the rotating drum downstream of the turbine rotor. The electrical signals carrying the pressure information is carried to the stationary frame through the slip ring assembly. The rotor frequency will be accurately determined by using an infrared emitter/receiver circuit located on the casing of the turbine rotor. This device generates the reflected infrared emissions from the tip of a selected rotor blade and directly provides the rotor frequency (once per revolution pulse-OPR).

A data processing system is built around a microcomputer with a clock rate of 10MHz. The system consists of a 16 bit computer with 1MB random access memory, a disk operating system, 40 Mb hard disk storage space, printer and plotter. All of the data from both stationary and rotating instrumentation can be processed on-line. One of the long range goals of the turbine research is to acquire unsteady heat transfer and aerodynamics data simultaneously.

A unique feature of Axial Flow Turbine Research Facility is its ability to generate the aerodynamic and unsteady heat transfer data simultaneously. This feature allows the generation of benchmark quality data to validate three dimensional viscous codes, which includes heat transfer. It is expected that this integrated approach will improve the heat transfer prediction capabilities, especially in the rotor stator interaction region.

The vane and blade design was carried out by General Electric Company's Aircraft Engine group. The aerodynamic design, while not representing any specific current or future GE product, does embody modern design philosophy. Stage loading, flow coefficient, reaction, aspect ratio, blade turning angles are all within the range of current design practice. State-of-the-art quasi three dimensional design methods are used to design airfoil shapes. The details of the design are incorporated in reference [7]. The blade geometry is shown in figure 2. Absolute Mach number at the inlet of the rotor changes from 0.30 to 0.23 from hub to tip. Exit absolute Mach number is in a range from 0.11 to 0.10 from hub to tip. Figure 3 shows a rotor blade and a nozzle guide vane after final machining.

The design features of the blading and facility are given in Table 1.

TABLE 1

OVERALL PERFORMANCE PARAMETERS

Total temperature at inlet	TTO	520°R
Total pressure at inlet	PTO	14.7psia
Mass flow rate	W	24.32 lbm/s
Specific work output	ΔH	$2.36\ \frac{\text{Btu.s}}{\text{lbm}}$
Rotational speed	N	1300 rpm
Total-to-total isentropic efficiency	η_{TT}	0.8930
Total pressure ratio	PTO/PT2	1.0778
Pressure drop	PT02-PT01	30" of water (56.04 mm Hg)
Pitchline reaction	RXP	0.3820
Power	HP	81.2hp
Torque	T	328.1 lbf.ft
Stator efficiency	η_s	0.9421
Rotor efficiency	η_r	0.8815
Mean swirl angle at exit of rotor (meas. from tangential dir.)	$\bar{\alpha}_2$	29.97°
No. of stators	n_V	23
No. of rotors	n_R	29

where $\eta_s = \dfrac{\text{actual exit k.e.}}{\text{ideal exit k.e.}}$

$$\eta_r = \frac{\text{actual relative exit k.e.}}{\text{ideal relative exit k.e.}}$$

$$\text{reaction} = \frac{\text{ideal static enthalpy drop across rotor}}{\text{ideal static enthalpy drop across stage}}$$

3. FACILITY INSTRUMENTATION

The Axial Flow Turbine Research facility is equipped with large number of static pressure holes (nearly 500) at carefully selected locations on the blade, vane, casing and hub walls. Static pressure measurements in the rotating frame will be taken by a 32 channel electronic pressure scanner located in the rotor frame. The signal output, after multiplexing in the rotor frame, will be passed through a slip ring unit for processing in a computer controlled data acquisition system.

To measure the shear stress on the walls and the blades, shear stress sensors are used in the turbine rig. These are deposited thin film, (V array) "glue on dual probes" manufactured by Dantec company. The construction is similar to those used by McCroskey (Ref. 8) and is shown in Fig. 4. A total of 23 dual element sensors are mounted around the rotor blade at mid span, with close spacing near the leading edge of the blade. In addition, five sensors will be located on the hub (endwall) of the rotor blade passage. The data from these shear stress sensors will be acquired using a PSI 156 channel data acquisition system (20 KHz). Unsteady shear stresses, which are extremely important quantities in the study of vane-blade interaction, will be recorded by a Kinetic Systems (CAMAC) high speed data acquisition system (1 MHz).

The implementation of the dynamic pressure transducers in the turbine rig was driven by space limitations. The pressure transducers are inserted into chambers, which in turn are connected to the turbine airfoil surfaces through 0.5 - 0.8 mm diameter holes. The design objective is to achieve a frequency response of 40 KHz. The sensors used are Kulite model XCS-093 with a pressure range of maximum 5 psia. They are capable of measuring pressure fluctuations to an accuracy of 0.01 psia. Details of a dynamic pressure transducer used in the Turbine Facility are given in Figure 5. Sixteen Kulite transducers are located along the chord at the mid span of the rotor blade. Seven transducers will be on the pressure side and the remaining nine will be located on the suction surface of the next blade in the same passage. A schematic showing the location of dynamic pressure transducers on the blade at midspan (sixteen) and on the hub (endwall) surface (five) is shown in Fig. 6. The low level signals from the dynamic pressure transducers are amplified in the rotating frame by using miniature instrumentation amplifiers. The amplifiers will rotate in the rotor frame and provide a high level signal output before the signal reaches the slip ring unit. These amplifiers are located inside the instrumentation drum shown in Fig. 7. It is expected that this amplification may help to improve the quality of output signal from the dynamic pressure transducers. A preliminary static calibration study of an XCS-093 transducer was performed for implementation in the turbine rig.

The LDV system available in the Turbomachinery Laboratory is a two channel fringe type laser anemometer (LDA) with on-axis back scatter light collection (TSI model 9100-6). The system operates with a 4 W Lexel argon-ion laser tuned for the green line (514.5 nm). The entire system comprising the laser, the transmitting and receiving optics is mounted on a table. The table can be moved along and perpendicular to the optical axis and can also be tilted in the vertical plane. The assembly is fitted on a hydraulic bench capable of moving in the vertical direction. The three degrees of freedom with the possibility to tilt the table helps to position the bisector of the beam in the radial direction. The LDV system will be used to measure most of the flow field, except the nearwall regions.

Provision has been made for hot wire measurement in both rotating and stationary system. Both two sensor and three sensor hot wire probes will be used in a stationary frame of reference to measure the boundary layers on stationary walls (on both the casing and hub walls) and the nozzle vane surface.

The mechanism used for traversing the rotating hot wire probe consists of both the circumferential and the radial traversing units. The hot wire probe location can be incrementally changed by using 0.019 degree steps, in circumferential direction. This motion is also checked and corrected for possible errors by an angular encoder device. The planetary gearbox providing this precision motion is driven by a stepping motor having a 25000 steps per revolution. Both the radial and circumferential traversing units will be simultaneously controlled by a computer based system.

4. DATA ACQUISITION AND PROCESSING

The Kulite, skin friction, heat transfer, hotwire and static pressure data from the rotor will be transmitted through the rotating drum to a slip ring unit (figure 1). The rotating drum consists of two probe traversing mechanisms for both the radial and the circumferential traverse, 4 constant temperature anemometers, a 32 channel electronic pressure scanner/transducer unit and a 30 channel data acquisition system for voltage inputs. The data acquisition system is shown in Fig. 8.

The slip ring unit is of brush type and has 150 channels. The slip ring unit is housed in a cowling in front of the facility (Fig. 1). The unit has a rigid one piece housing eliminating bearing alignment problems. Each ring carries four brushes made of silver graphite. The rings are made up of coin silver which withstands up to current levels of 5 Amps. The brushes are individually removable and replaceable. The contact resistance is about 5 milli.ohms maximum.

A medium speed data acquisition system with 96 channels of pressure transducers having a 20,000 samples per second capacity is available in the laboratory. The PSI model 780-B pressure measurement system is a fully integrated test instrument which offers a transducer per port for multipressure measurement applications. The present system is also capable of using an additional 60 channels which may be described as "electrical input" channels for signal types such as thermocouples, strain gauges, RTD's etc. This is a complete data acquisition system with a special emphasis on pressure measurement. Total system inaccuracy for pressure measurements including sensors is in the order of ± 0.10 percent full scale for the worst case. However, a typical value is in the order of ± 0.07 percent. The system is interfaced to an IBM compatible personal computer through an IEEE-488 (GPIB) with input output rates up to 30,000 bytes per second.

For high speed data acquisition, a 16 channel, 12 bit transient recorder with a 1 Megabyte solid state memory is planned (Kinetic Systems Int., 4022-DIA-4050-23A). This system will be built in a CAMAC crate. The acquisition system will be controlled by a parallel bus crate controller interfaced to an IBM PC-AT computer. With the current configuration the system will be able to store 500,000 measurements for a maximum duration of one second either in its own memory or in the computer storage medium. The main use of this system will be in the area of hotwire measurements, wall shear stress measurements, Kulite dynamic pressure measurements.

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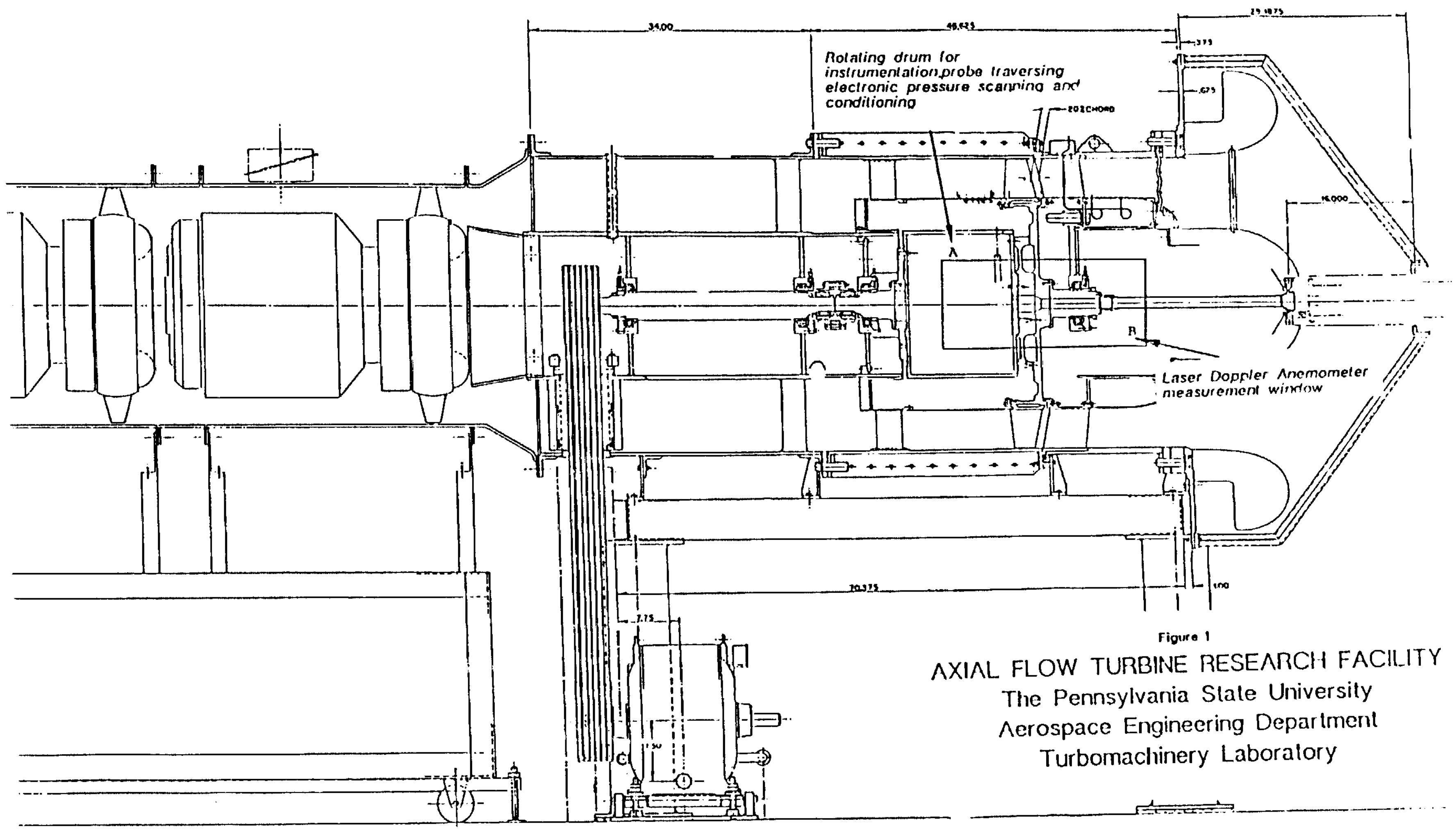

Figure 1

AXIAL FLOW TURBINE RESEARCH FACILITY
The Pennsylvania State University
Aerospace Engineering Department
Turbomachinery Laboratory

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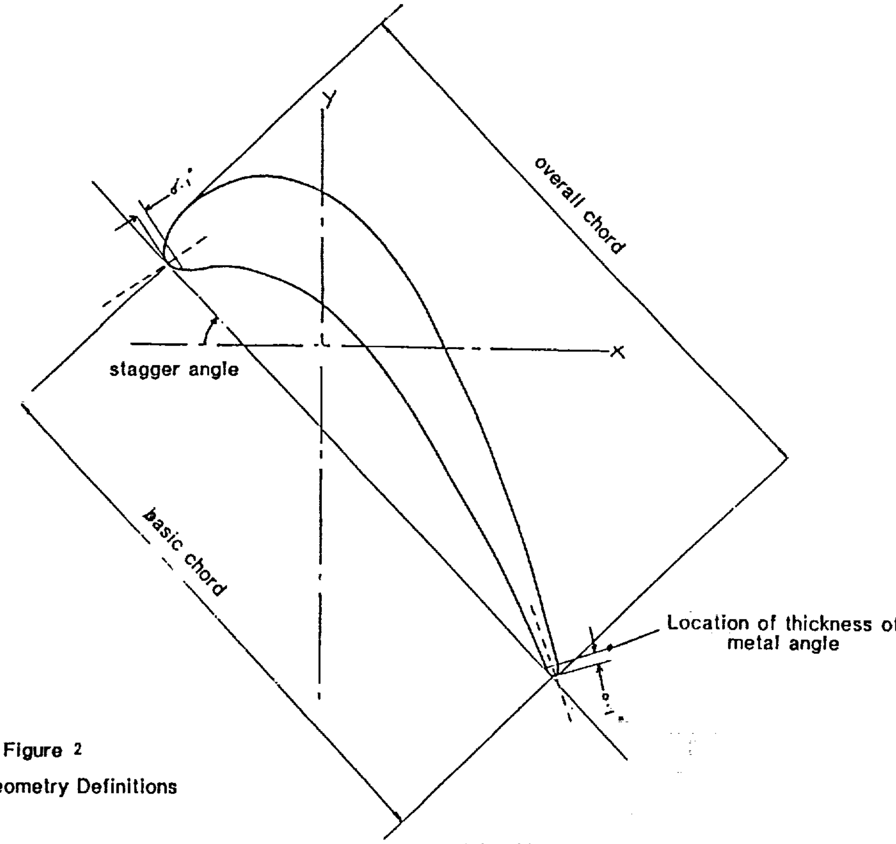

Figure 2

Blade Geometry Definitions

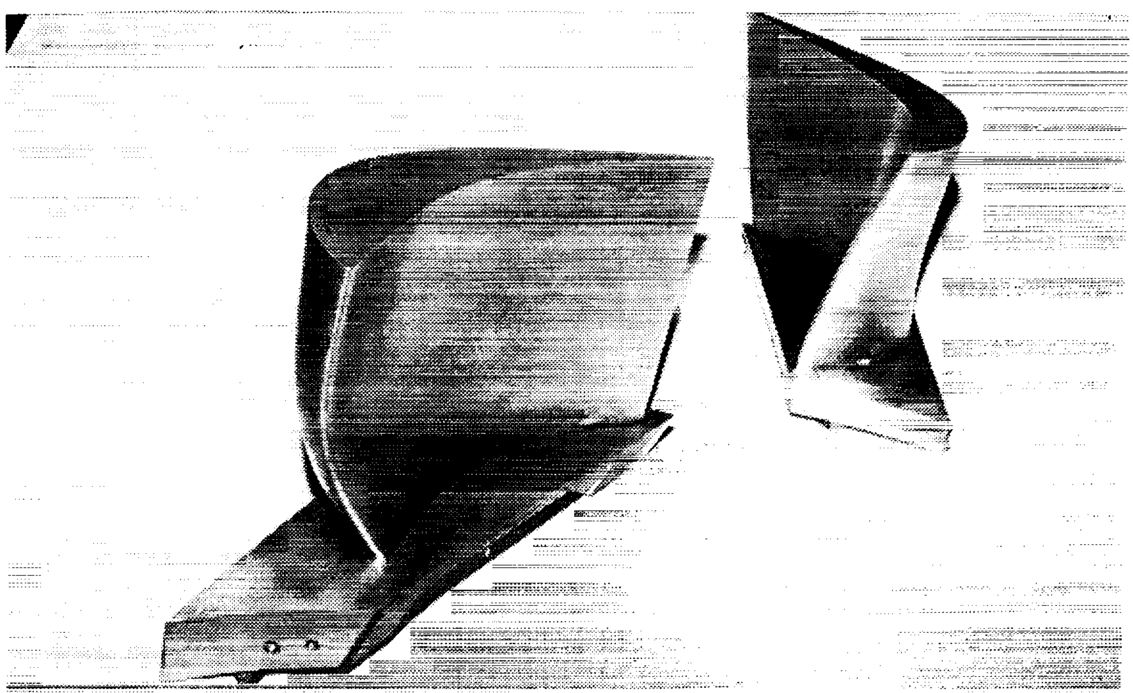

Figure 3

A Nozzle Guide Vane and a Rotor Blade
After Final Machining

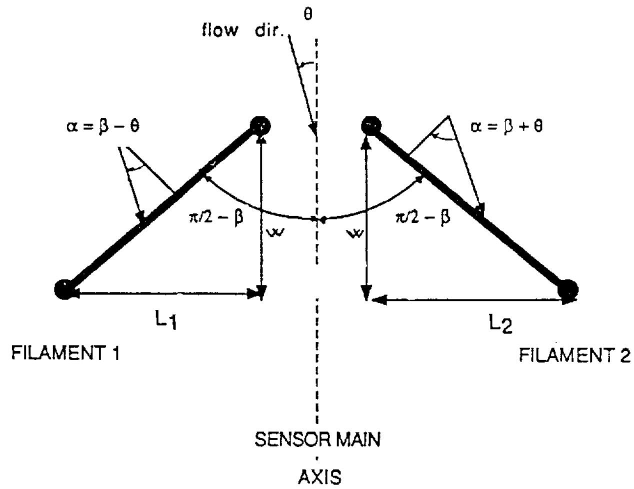

Figure 4

Geometry of a Twin Element, V configuration
Shear Stress Gauge

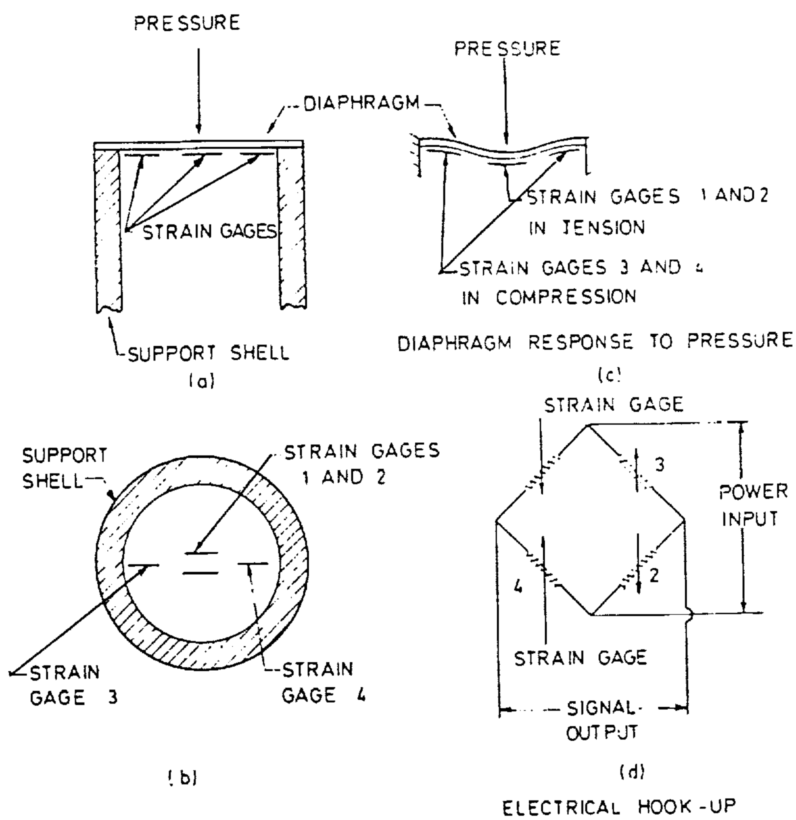

Figure 5

Silicon Based Semiconductor Strain Gauge
Pressure Transducer

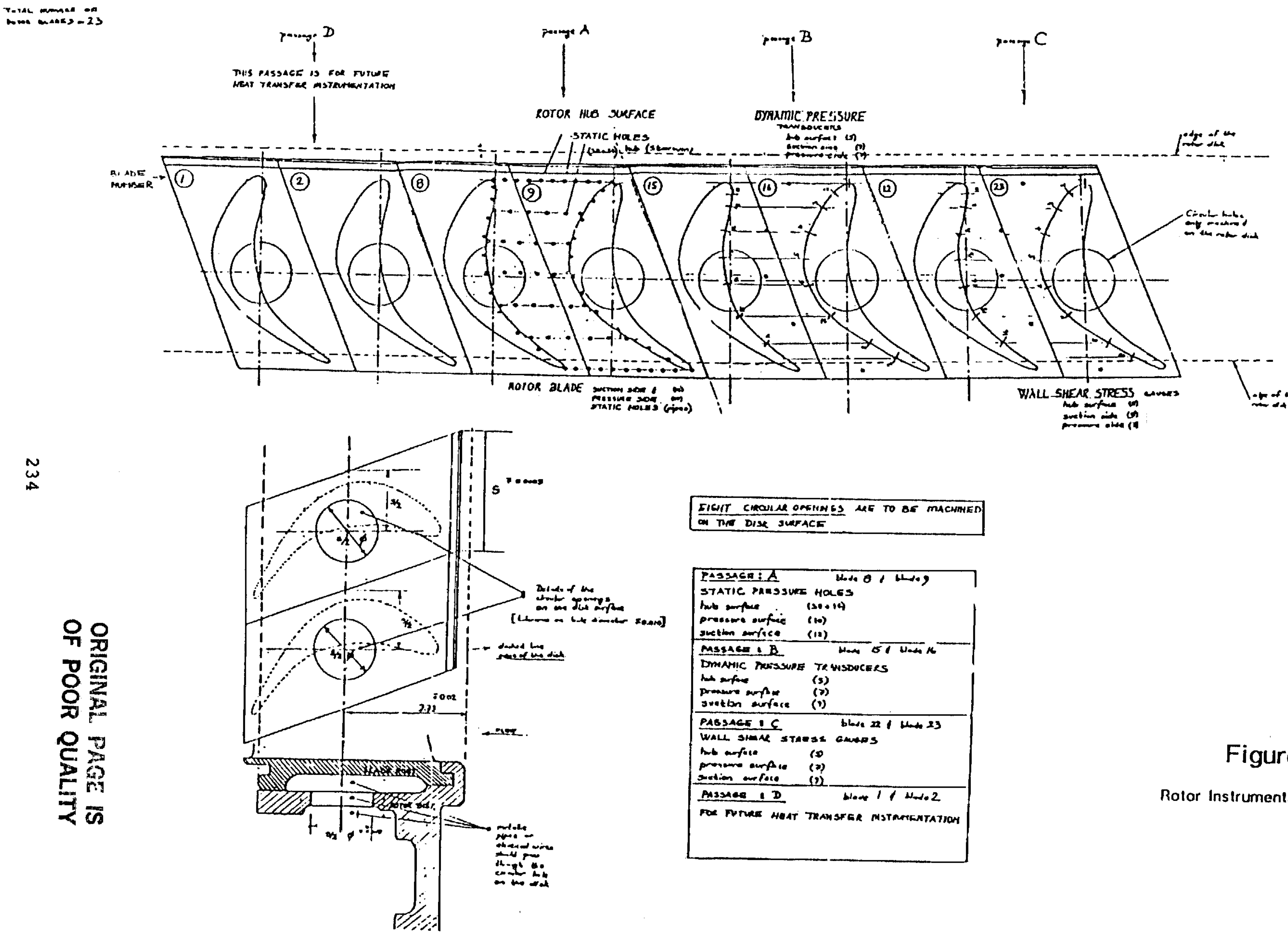

Figure 6

Rotor Instrumentation Details

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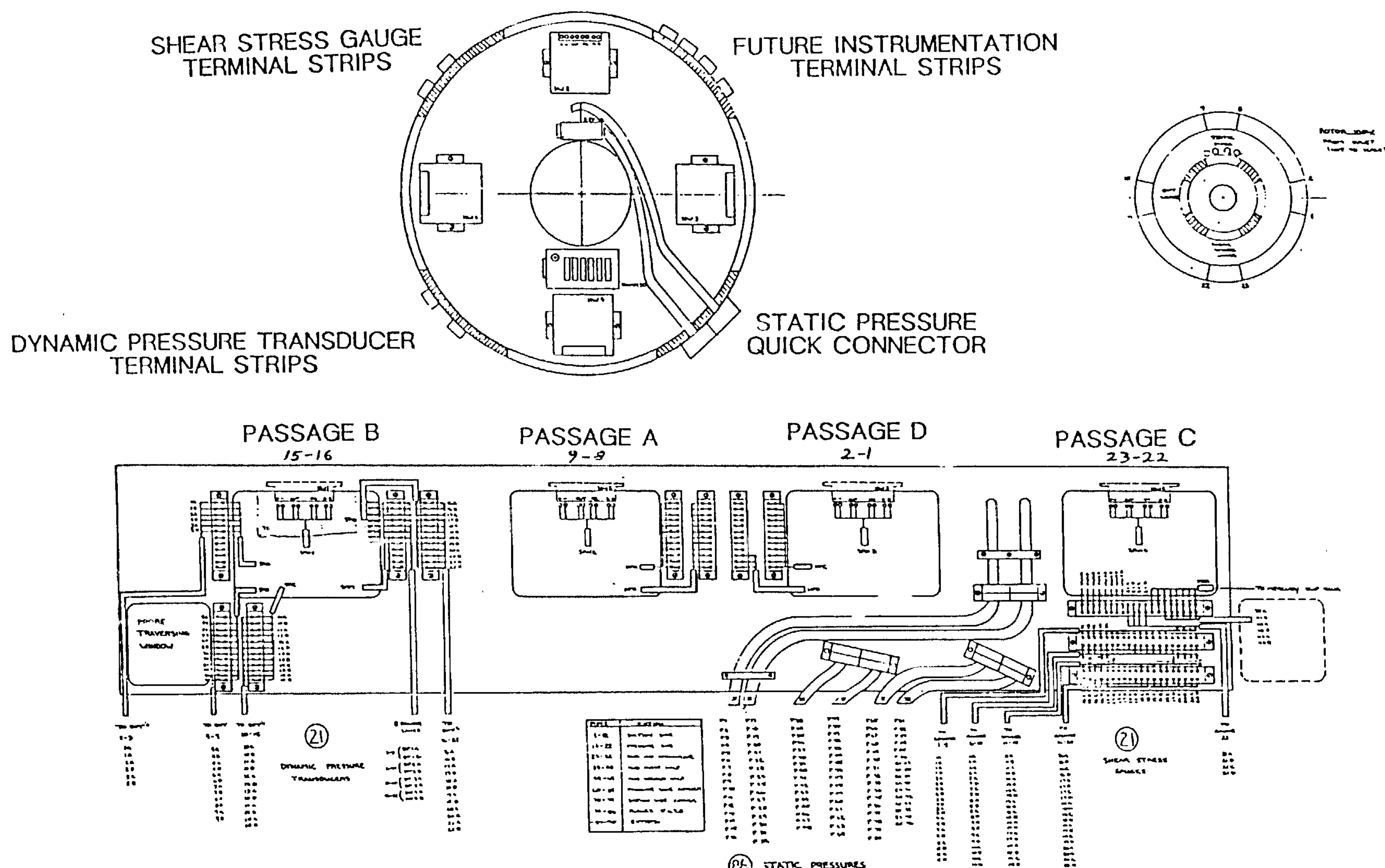

Figure 7

Details of the Rotating Instrumentation Drum

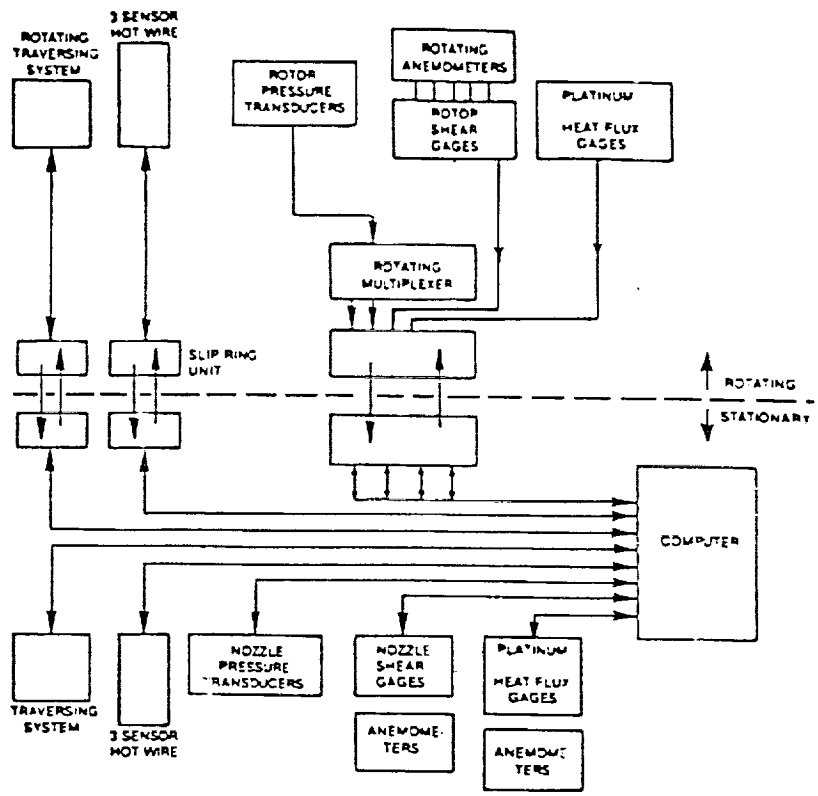

Figure 8

Measurement Chain and Data Acquisition System
in the Stationary and Rotor Frame of the
Pennsylvania State University AFTRF

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