A NEW TRANSONIC TEST TURBINE FACILITY

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Abstract

This paper describes the operation, performance and instrumentation capabilities of a new continuous operating transonic cold flow facility for high accuracy axial turbine tests.

Introduction

CTA Foundation was born in 1997, under the auspices of Basque Country Aeronautical Cluster and sponsored by major Spanish aeronautical companies and regional government institutions.

The aim of CTA, as a non-profit Foundation, is to be an Open World Research Institution to give services to European, Spanish and Regional Industry and Scientific community.

The institution has two facilities, the CTA-Miñano, dedicated to structural test of aeronautical components and the CTA-Zamudio.

The facility of the CTA-Zamudio was born firstly as a need of the Spanish Aero-Engine Industry, to cover the lack on fluid-dynamic testing of scaled models of turbine modules, nozzles and spoke structures, for low and medium thrust engines.

The major milestones of the FTB are the civil project and Major Work Package and Detailed Engineering finalized on 1999, the commissioning of compressor groups and wind tunnel commissioning on 2000, the upgrade of flow quality and redesign of power shaft on 2001 and the commissioning of the turbine test facility in 2002.

The commissioning has recently demonstrated its current capabilities with the test of the Rolls-Royce LP turbine DT21 rig (which is a scaled model of the RB211 Rolls Royce turbine module).

This rig was successfully tested during 40 hours. Together with the previous steady state simulation to characterize the components of the tunnel, this measurement data provided information of the operational range and the performance of the FTB. The main characteristics of the components will be described and maps based on experimental data will be presented.

FACILITY SETUP DESCRIPTION

The CTA in Zamudio is a Fluid Dynamic Test Bed (FTB) with a continuous circuit of atmospheric inlet and outlet, with continuous flow and with regulation capability of pressure/vacuum, temperature and airflow.

It consists on several integrated components (fig. 2).

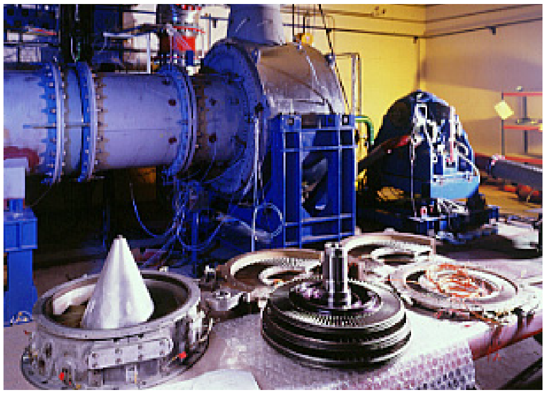

Fig 1: Assembly of the DT21 rig

<u>Compression Group</u>

The Compressor Machine, supplied by Sulzer Turbo, is composed by two stages called RT55 and RT45. The Compressor machine is specified to work as a single-stage operation by means of the RT55 or as a two-stage operation by means of TR55 and RT45 in series.

The temperature of the air supplied to the tunnel is kept constant. This is carried out via controlled bypass operation of the gas flow through the intermediate cooler and the after cooler.

The Compression Group can regulate the airflow temperature from ambient up to 550K. The pressure controller of the Compressor Group keeps the pressure of the supplied air quantity constant at a specified value at the exit. The driver is an electrical motor rotating at constant 3,000 rpm.

The maximum air mass flow is 18 kg/s at up to 450 kPa when running with both compressor stages.

The compressor and vacuum groups can work independent of each other.

The following characteristic maps (figures 3 and 4)represent the functional relationship between the three dimensionless parameters: PRs, Wc and %IGV at standard temperature. These maps are derived from experimental data obtained during the commissioning of the facility.

The corrected speed shows negligible impact on the compressor performances, since it operates with constant rotational speed and the variations of the ambient temperature does not seem a substantial effect.

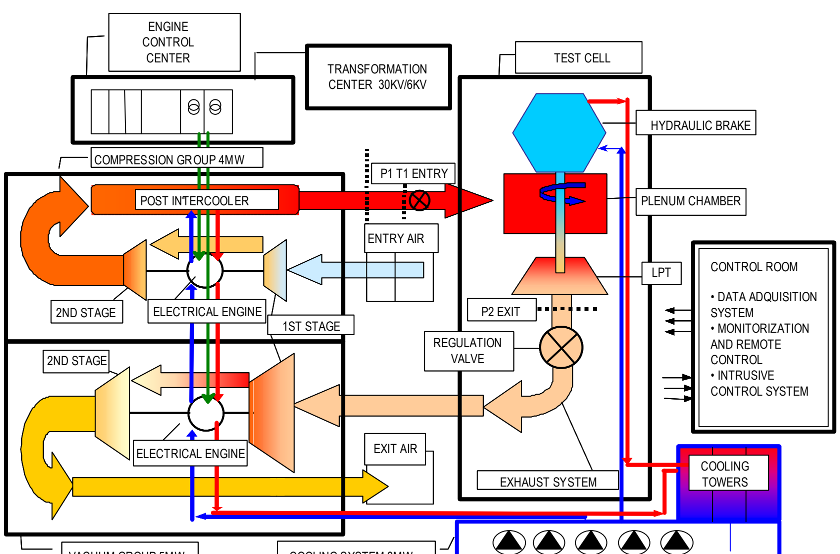

Fig 2: General layout of the FTB

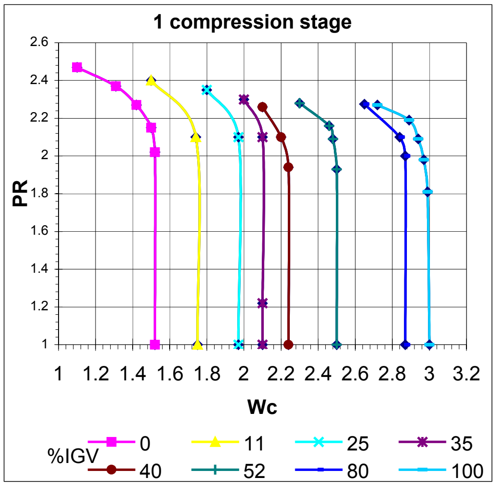

Fig 3: Performance map of 1 compressor stage

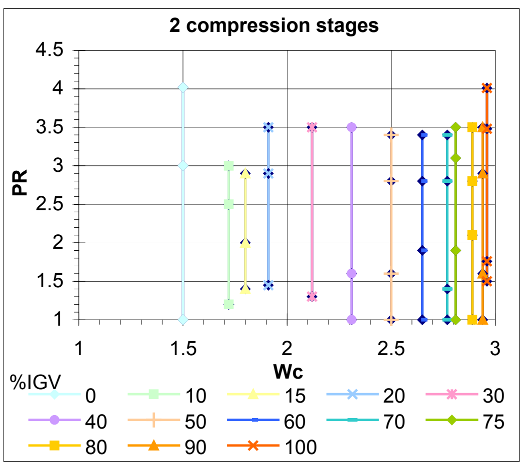

Fig 4: Performance map of 2 compressor stages

Vacuum Group

The Vacuum Machine, supplied by Sulzer Turbo, is composed by two compressor stages called RT100 and RT80. It is specified to work as a single-stage operation by means of the RT100 or as a two-stage operation by means of the RT80 and RT100 arranged in series. It keeps the pressure constant at a specified value at the vacuum group inlet.

The minimum pressure level achieved can be 12.5 kPa.

The following characteristic maps (figures 5, 6, 7 and 8) represent, again, the functional relationship between the three dimensionless parameters: PRs, Wc and %IGV. As the Vacuum Group operates also to constant rotational speed, the influence of the corrected flow on its performances is considered though the inlet temperature. Thus two representative maps have been developed at two preset inlet temperatures (300K and 370K) for both single and double stage configurations.

These maps are derived from experimental data obtained during the commissioning of the facility.

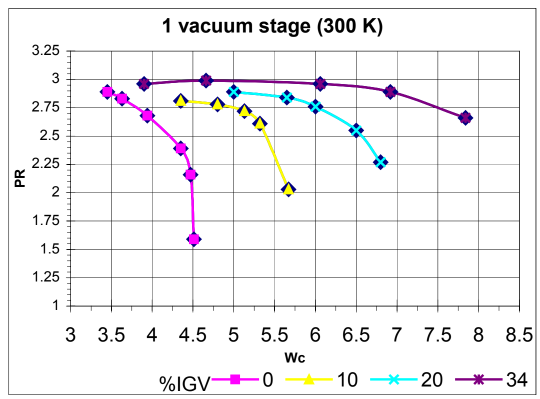

Fig 5: Performance map of 1 vacuum stage with inlet temperature of 300K

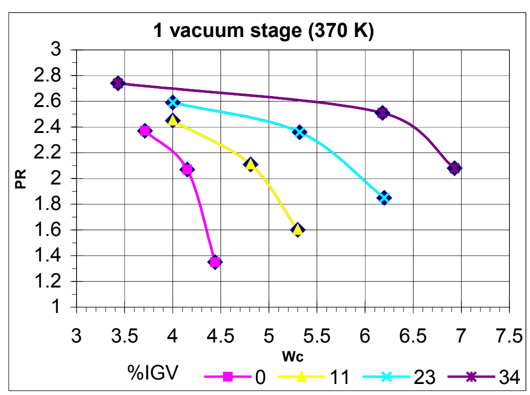

Fig 6: Performance map of 1 vacuum stage with inlet temperature of 370K

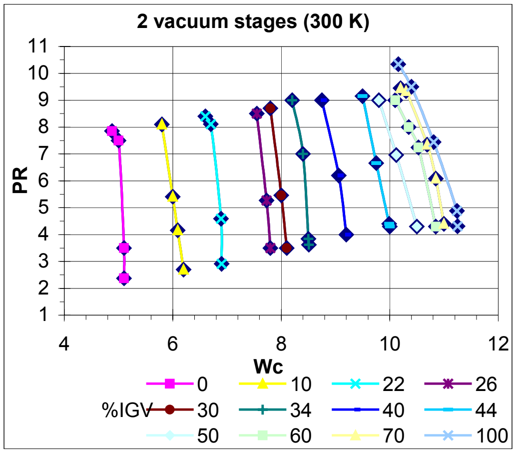

Fig 7: Performance map of 2 vacuum stages with inlet temperature of 300K

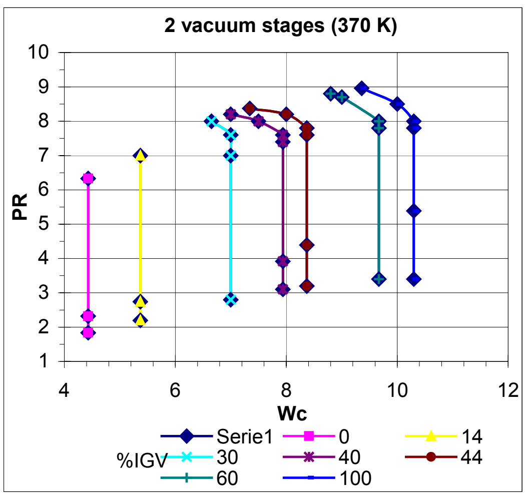

Fig 8: Performance map of 2 vacuum stages with inlet temperature of 370K

Plenum

The purpose of the plenum chamber is to improve the quality of the flow coming from the compression group, which uses to be unstable and non uniform.

This element is located just upstream the test section, the exit area is characterized by a large diameter and therefore by a low flow velocity. A flow contraction nozzle is required to achieve inlet turbine radius that depends on each application (Contraction ratios of at least 3 are suggested for rig scale factor selection).

The plenum was tailored for this specific test cell and supplies high quality airflow. The parameters that describe the achievable quality at the inlet of a characteristic turbine are detailed in Table 1 below.

Parameter	Variation
Non- Dimensional total pressure variations	<1% of mean dynamic pressure
Swirl Flow angle	<0,5°
RMS of instantaneous flow velocity	<10 similar to that a real aero-turbine sees in an actual aircraft engine
(*) Within 15% and 85% of the annulus section of plenum	

Table 1: Quality of the airflow at the inlet of a characteristic turbine, contraction ratio of 4.

It is shown below the characteristic map. It represents the functional relationship between two dimensionless parameters: PRs and Wc.

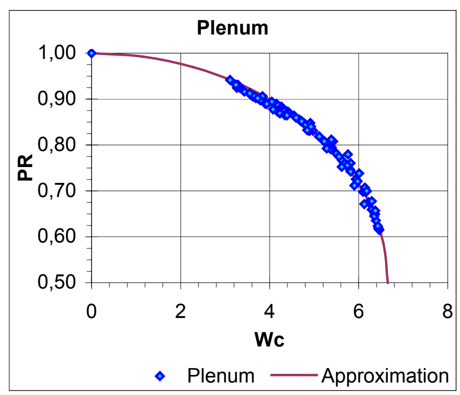

Fig 9:Experimental map of the plenum

The map has been obtained from experimental data by traversing the exit plane of the plenum chamber. In order to capture flow structures, high spatial and time resolution instrumentation was used, multi-hole miniature pneumatic probes and hot wire anemometry, respectively.

Valves and piping

Downstream the Compression Group there are two butterfly valves (DN600_1 and DN600_2).

In a section between these two valves it is placed the bypass from the atmosphere (DN300_1 and DN300_2 valves, also known as blow off valves), so when working without the Compression Group the pressure at the inlet of the test section can be controlled by means of the second valve (DN600_2).

Downstream the test section (with a diameter of 1.0 meter) is a DN1000 pipe that ends in a section where airflow is either suctioned towards the Vacuum Group passing through a DN1000 butterfly valve or it is bypassed to the atmosphere through a DN600_3 butterfly valve.

Airflow measurement

The flow is measured by means of two orifice plates located in series (the second one for duplication of measurement purposes).

The calculations are carried out following the British Standard BS-EN-ISO-5167-1:1997 formulae recommendations for orifice plates with the pressure drop being measured with 4 static pressures in each plane at D and D/2 distances. The measurement of both airflow meters is better than 1%.

Power shaft

The Turbine Prototype is assembled to a Shaft, which transmits the power delivered by the turbine to the Torquemeter. The Torquemeter is connected to the Hydraulic Dynamometer.

The Shaft has a configuration of 3+2 bearings and it is able to run up to 7800rpms with a maximum axial load up to 21000N.

The Torque meter is an ET1200HS Torquetronic model, suitable for 7,000Nm at 11,000rpms.

The uncertainty should be ±0.2% of the FSD absolute and the repeatability ±0.1%. ZTD should be repeatable to ±0.05%. Our model ET1200HS guarantees ±0.1% at nominal torque (5kNm) repeatable accuracy, which implied a ±0.16% repeatable accuracy for the worst DT21 test.

The power measurement from Torquemeter and Dynamometer should agree to ±0.5%.

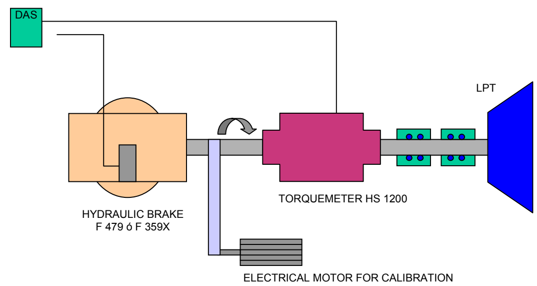

Fig 10: Torque and speed measurement and calibration of equipment

There are two Hydraulic Dynamometers, the Froude Consine F479 and F359X, which cover an envelope of 3.3kW and 13,700Nm up to 7,000rpms and 2.7kW and 3,686Nm up to 10,000rpms. The Texcell V100 Direct Digital Control System drives the turbine speed, which provides accurate speed control and dynamometer health monitoring and alarm annunciation.

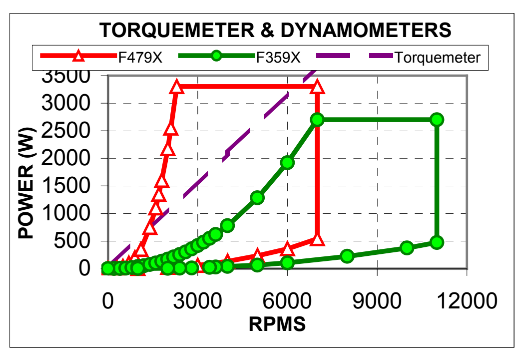

Fig 11: Capacity diagrams of the Torquemeter & Hydraulic Dynamometers

The speed control is able to keep the turbine speed within a margin of ±10rpm over extended periods of time.

Secondary flow

The efficiency of a turbofan is affected by the amount of air that needs to be extracted from the main airflow to attend many auxiliary functions. Afterwards, this air comes back into the main airflow at the turbine stages.

To account for this effect the FTB can simulate the injection of secondary airflow into the turbine flow.

This injection is simulated by feeding atmospheric air through a circuit with adequate pressure conditions into the turbine rig.

The secondary mass flow is measured at the entry of the system. The amount of air is controlled by a valve allowing a maximum flow of around 300g/s.

WIND TUNNEL OPERATION

When testing a specimen, it is possible to fix the stagnation Pressure and Temperature at the entry test section, the Pressure at the exit test section and the rotating speed of the rotor by means of the dyno controller. There are three ways to handle the wind tunnel operation:

- Compression Group only. In this situation the DN1000 remains fully closed. The pressure at the rig exit it is controlled by the DN600_3.
- Vacuum Group only. The DN600_1 remains fully closed while DN300_1 and DN300_2 valves are fully open.
- Vacuum and Compression Groups.

Whereas the IGVs of Compression and Vacuum groups are used for a coarse control of the inlet and outlet pressure respectively, the upstream (DN600_1 and DN600_2) and downstream valves (DN1000 or DN600_3) allow the final accurate fitting.

The compressor, again, controls the mass flow and the element controls the exit pressure.

The plant is able to keep the following constant conditions (up to 1 hour):

Supply and Vacuum pressure is maintained better than ±1kPa.

Temperature supply is maintained better than ±0.5ºC.

Rotating speed of the rotor is maintained better than ±10rpm.

Operating the facility

The FTB is operated remotely from a Control Room and its state is continuously controlled and monitored for alarms or emergency conditions that might occur during a test session.

The plant is controlled with a PLC from Allen-Bradley that monitors the plant state.

The control system is arranged in a control network of dedicated controllers and transducers around the plant.

Pre-alarms, alarms and emergencies of the PLC are supervised during the test. In case of emergency shutdown, valves DN600_2 and DN_1000 are fully closed in less than 1.5 sec to prevent the air from flowing through the wind tunnel.

Simulation tool

A simulation tool has been developed to predict the valve apertures and IGV openings to reach a given condition in the airflow at the test section.

In the same way it can be used to calculate the conditions at the test section that result from a given set of valve, IGV openings.

The model has been developed using the commercial EcosimPro software. Each one of the facility elements is modeled with the dimensionless parameter maps generated during the facility characterization.

DESCRIPTION OF THE INSTRUMENTATION IN THE FTB

The CTA is equipped with the following instrumentation and equipment:

- Two channels hot wire anemometry with probes of 1 and 2 wires. (55P11, 55P14, 55P61, 55P62…).
- Tip clearance, electro mechanical system.
- Traversing system that is constituted by the following Intrusive remote actuators: four radial ROTADATA RT290, two ROTADATA RT190 actuators and two area Traverse circumferential actuators.
- Pneumatic Probes with compressible calibration.
- A subsonic tunnel for calibration purposes.
- Noise measurements equipment for aeronautical components.

The selection of such equipment was a balance between the limited experience on LPT measurement techniques and the advantages of such systems.

The instrumentation available is mostly intrusive. A description of such instrumentation is detailed below.

Pressure sensing equipment

In the facility, there are a wide variety of pneumatic probes:

- Three hole miniature cobra probes (tip size 1.5 mm),for total pressure, static pressure and yaw angle of airflow. There are 4 units, 2 with "L" shape and other two with straight shape..
- Five hole miniature probes with 90º conical tip (< 2 mm) for total and static pressure measurement capable of sensing yaw and pitch angle of airflow.

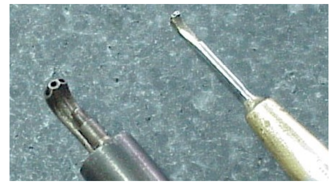

Fig 3: Conventional (left) and miniature(right) Pitot probes

The miniature multi hole probes offer very high spatial resolution and therefore low flow distortion. All of them have been individually calibrated at the Whittle Laboratory (University of Cambridge) to account for Mach number, flow angles and Reynolds No. variations. To improve the time response of these probes, the pressure tubings have been characterised to enhance the maximum frequency achievable.

- Boundary layer pitot probes designed for traversing boundary layers as thin as 1 mm and revolving the flow direction in regions of strong pressure gradients. Probes incorporate an electrical circuit to detect the contact of the probe tip with the wet surface of the casing and to measure the boundary layer as close as possible of the turbine walls. In particular, the diameter of the boundary layer probe depicted in Fig 4 below is ∅0.2mm.

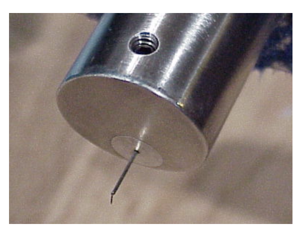

Fig 4: Special micro-Pitot probe used to characterize boundary layers

Hot-wire anemometry

Single and double hot wire anemometry can be employed in the FTB to measure airflow velocity and turbulence.

The system is an integrated measuring system based on Constant Temperature Anemometer, supplied by Dantec. It consists of a Frame inclusive of an Ambient Temperature Transducer and a Null Modem cable for serial communication and two CTA modules with conditioning system controlled by the StreamWare Application software package. There can be up to 2 velocity or turbulence channels measured simultaneously with sampling frequency of up to 1200KHz to be shared by the number of channels.

The system incorporates a Calibration System. It consist of a Calibration Module Unit 90H01 to be placed in the Frame and a portable Flow Unit 90H02 connected to the Calibration Module. There are four nozzles (20, 60, 120 & 140mm2) covering velocities from 0,02m/s up to Mach 1.

Tip clearance

The tip clearance measuring system is a data acquisition system to measure the gap between the rotor of a gas turbine and its casing. She system mounted in the facility consists on several elements:

- A probe
- An electro mechanical actuator
- A rack mounted controller

The tip clearance measuring system has a resolution of 0.01mm and a repeatability of ±0.01mm. The equipment can measure clearances of the longest rotor blade from rotor speeds of 0rpm up to 50,000rpm.

There are three tip clearance actuators available in CTA.

Traversing system

The traverse system positions an aerodynamic probe within the flow path. The traversing system comprises an engine mounted actuator, to which the aerodynamic probe is attached, as well as an electronic controller and the communication cables. The following actuators are available:

- Four radial RT290 and two RT190 actuators. This actuators move the probes in two axes: radial displacement of 290mm or 190mm depending on the RT model and yaw angle rotation of +/-127 degrees. The radial resolution is 0.01mm and the radial accuracy is ±0.05mm. The yaw resolution 0.1 degrees with an accuracy of ±0.25degrees.
- Two Circumferential basis for Area Traverse of ±7º circumferential actuators. Two radial actuators can be mounted on top of the carriage block spaced by 14 degrees, giving a total measure window of 28 degrees.

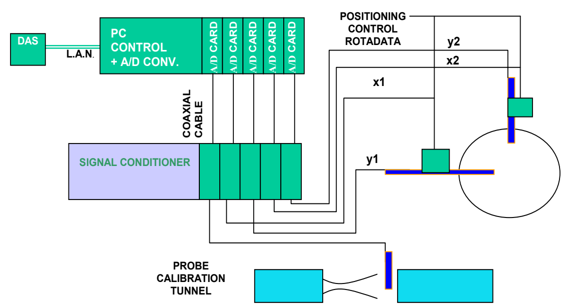

Fig 5: Rotadata positioning control (RT290 and RT190)

The current FTB installation is able to control 8 actuators simultaneously.

Description of the probe Calibration tunnel

Besides the main wind tunnel there is additional smaller tunnel for compressible probe calibration and for setting the null angle of the traversing pneumatic probes once installed on a traversing actuator. The tunnel is an open circuit with ambient pressure discharge. It can move a mass flow of almost 6 Kg/s and it is able to achieve a maximum Mach No. of 0.6.

To enhance the yaw resolution that can be obtained for the calibration, the tunnel has been equipped with a differential pressure sensor Rosemount with a range of -500 Pa to +500 Pa and an accuracy of 0.025% FS.

MEASURING SYSTEM

Data Acquisition Software

Central Engineering's Real-time Executive System (Ceres) is a group of computer programs that allow operators to perform computerized test on engines.

The Pilot software is the portion of CERES that runs during an engine test. Pilot enables an operator to open a test, store performance point data, generate reports and close a test.

CERES software is interfaced with the acquisition hardware and with the PLC, which controls the facility.

CERES performs two test types depending upon the different uses of the acquired data.

- Continuous Recording System (CRS): It stores the value of all the test variables at up to 10 samples/second.
- Steady state tests: The measures taken in CRS are averaged to filter the high frequency components of the signal , which usually are caused by electrical noise rather than pressure fluctuations that are eliminated by the pneumatic tubing.

Acquisition hardware for analogue signals

5 A/D E1419A cards of 64 channels each and a tachometer counter all based on VXI to do the process of acquiring the different signals. These produce a digital stream of data from analogue signals coming from temperature sensors, valve position actuators and rotating speed sensors of the torque meter and the hydraulic dynamometer.

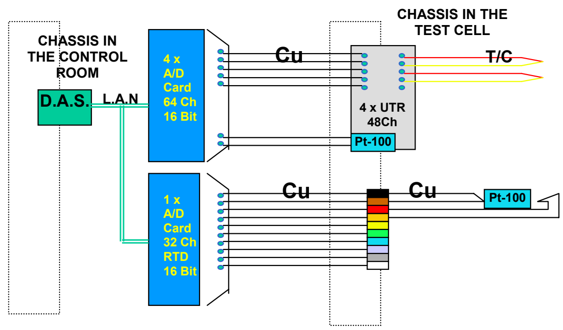

Fig 15: Capture of analogue signals

There are 200 channels of temperature with ±0.080K accuracy, 20 rotating speed and 28 vibration analogue signals available.

The capturing cards are self-calibrated once a test session starts. In order to improve the temperature channel performances even more, the cards have been thermally isolated and cooled to avoid the overheats. Moreover an individually calibration of each channel has offered a precision uncertainties of about 25 mK after a thermal drift correction [3].

Acquisition of digital signals

The pressure is measured by means of pressure transducers grouped in several channels or "bricks". The readings are already obtained as digital data from a network of bricks by the DAS.

The bricks are DSA 3017 (Digital Sensor Array) type from Scanivalve Corp. and measure differential pressure between a reference and each one of the probes or tapings.

The reference can be set to pressures below ambient.

These arrays of pressure transducers convert the pressures in each of its channels into a stream of data to an Ethernet network to which the D.A.S. is connected retrieving data from every brick of the installation.

There are 350kPa, 100kPa and 35kPa full-scale differential pressure transducers with an on-line calibration capability virtually eliminates thermal sensor errors achieving static accuracy of ± 0.05% FS.

There are also other types of differential pressure measuring bricks that measure differences between pairs of measure-reference.

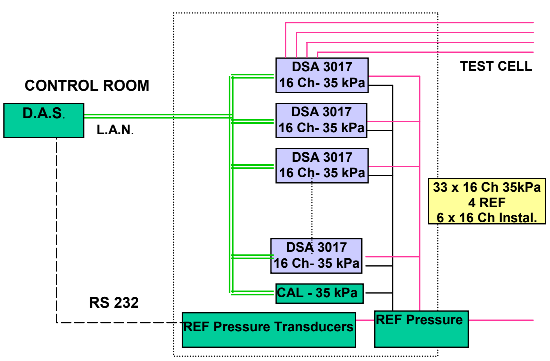

Fig 6: Capture of digital signals (Scanivalve, DSA and SCP pressure transducers)

The reference pressures are measured by the SPC 3000 (Servo Pressure Calibrator) type from Scanivalve Corp. which are calibrated by a traceable external calibration authority.

There are up to 800 pressure channels measured simultaneously.

Acquisition of the rpm signal from the rotor

The VXI chassis is also equipped with a tachometer and signal conditioner card with 8 input channels that generates a digital output of the rotor speed when it is fed with electrical pulses derived from the rotation of the rotor.

Each input of the tachometer card is fed by two redundant measures of the rotor speed. One comes from the torque meter, and the other from the dynamometer.

Vibration sensing equipment

The vibrations during a test session are monitored for unacceptable levels of vibration by accelerometers located on the compressors (due to surge conditions or any other malfunction), on the turbine rig, the torque meter and the dynamometer that may render the test unsafe to be continued.

When vibrations are unacceptable for a test to be continued safely an alarm is triggered and an automated decision of shutting down the test is taken.

The vibration monitoring and acquiring hardware consists on the following elements:

- Piezometric accelerometers (Endevco 7254A-100 and 7221A piezoelectric)
- Endevco model 6634B Signal conditioners
- E1419A A/D boards
- VXI chassis connected to the D.A.S. by means of an Ethernet network.

Post-processing of the information stored in the D.A.S.

The huge information that is made available to the DAS network is stored in a database in a Unix environment that can later be accessed and exported to easily human readable text files for further post-processing.

Acquisition of noise from aeronautical components

The facility was also intended to acoustic tests for the characterisation of materials and induct turbo machinery noise measurements.

It has been equipped with capturing hardware and software for noise acquisition. The equipment comprises:

- Kulite relative pressure transducers of 5psi full-scale
- Endevco signal amplifiers
- PXI standard chassis for capturing boards
- National Instruments NI-PXI-4472 capturing boards with a total of 16 channels with 24bit precision and 100kHz sampling rate
- National Instruments LabVIEW software for data acquisition and analysis of the captured signal

CHARACTERISATION AND TESTING

The DT21 Rig Test

The objective of this test was to evaluate the installation of CTA Zamudio (FTB) by means of the comparison of the results of this test with those obtained at RR Derby in 1986 with the same LP turbine rig, DT21.

The turbine rig to be tested was DT21 build 13. This configuration was prepared to measure with traverse actuation the conditions at the exit of IGV and behind the exhaust cone. For measuring the traverse at exit of the turbine rig a parallel duct was manufactured.

DT21 test required 109 pressure channels; 77 of those were meant for static pressures and 32 for total pressures.

Most of the pressure channels were read by 100Kpa differential transducers with ambient reference pressure instead of probe differential pressures measured by 35Kpa transducers.

There were only 20 temperature channels required for the test of the DT21. All the channels used N type thermocouples and conventional electronic UTRs.

The test of the DT21 required two radial actuators provided by CTA which hold a RR Wedge Probe WRT213 and a three hole miniature cobra probe, to measure flow velocity, flow angles and total temperature via a thermocouple placed in the probe tip.

The actuators were placed at the inlet of the turbine, upstream the IGV, and at the exit of the turbine, in the jet pipe traverse plane.

The actuators worked in auto-yaw mode. This means of orientation in the direction of the flow was made by means of the auto-yaw controller from ROTADATA.

The flow characteristics of the turbine were experimentally obtained and successfully compared with previous RR data. The trend of the turbine characteristics were properly captured and a reasonable efficiency reference was established between the CTA tunnel and the RR Derby turbine facilities.

CONCLUSIONS

As it has been described in this paper, the new transonic tunnel at CTA is capable of:

- Installing a LP turbine test rig of a diameter as big as one meter.
- Supplying 18kg/s of dry air to the test section at 450kPa absolute pressure.
- Suctioning at 12.5kPa absolute pressure from the test section.
- Supplying high quality airflow to the rig.
- Controlling speed up to 7,800rpm and torque on the shaft of the turbine rig up to a power dissipation of 3.3MW.

- Place probes to measure airflow pressures, temperatures, etc. in different sections of the turbine by several traversing techniques.
- Measure a high number of channels of pressure, temperature, velocity and turbulence with very high precision.

REFERENCES

[1] British Standard: "Measurement of fluid flow by means of pressure differential devices. Part 1: Orifice plates, nozzles and Venturi tubes inserted in circular cross-section conduits running full," BS EN ISO 5167-1:1997.
[2] British Standard: "Measurement of fluid flow in closed conduits. Part 1: Pressure differential devices. Section 1.5 Guide to the effect of departure from the conditions specified in BS EN ISO 5167-1," BS 1042: section 1.5:1997.
[3] Vázquez , R., Sánchez, J.M.: "Temperature Measurement System for Low Pressure Ratio Turbine Testing," ASME paper No. GT-2003-38685, June 2003.
[4] Rotadata Ltd. Mini Tip Clearance Actuators and RCMS4 Controllers. Version 4. Dec. 1999
[5] HP E1586A Rack Mount Terminal Panel. Part Number E1586-90001. 1996.
[6] Eight-Channel Current Source Signal Conditioning Plug-on. HP E1505. Part Number: E1505-90002. April 1997.
[7] DSA Digital Sensor Array manual. 1996.
[8] CERES Easifit Modifications Manual. April, 1999.