DEVELOPMENT IN TURBINE TESTING AT ONERA

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In 1996, ONERA, the French National Establishment for Aerospace Research, decided to build a new test rig specially designed to study the characteristics of the aerodynamic flow across the different parts of multistage and co or contra-rotating turbines. This new device has been recently commissioned and the first tests were performed on a full scale turbine. The general arrangement of the rig, its capabilities, proved performances and some typical experimental results are presented.

Nomenclature

HPT = *High Pressure Turbine*
LPT = *Low Pressure Turbine*
NGV = *Nozzle Guide Vane (i.e. Turbine stator)*
N/RT = reduced rotation speed
$\Delta H/T$ = reduced enthalpy drop
DRT/P = reduced mass flow

INTRODUCTION

In the present context of energy saving, raising interest for improved engine efficiency points out need for better understanding of the complex aerodynamic phenomena existing in the different parts of turbo-engines. These problems are not only limited to the aerospace background, but are also of high interest in all transports or energy production systems.

Following the engine manufacturers and universities wishes, it was decided some years ago to build in France a new test rig enabling detailed

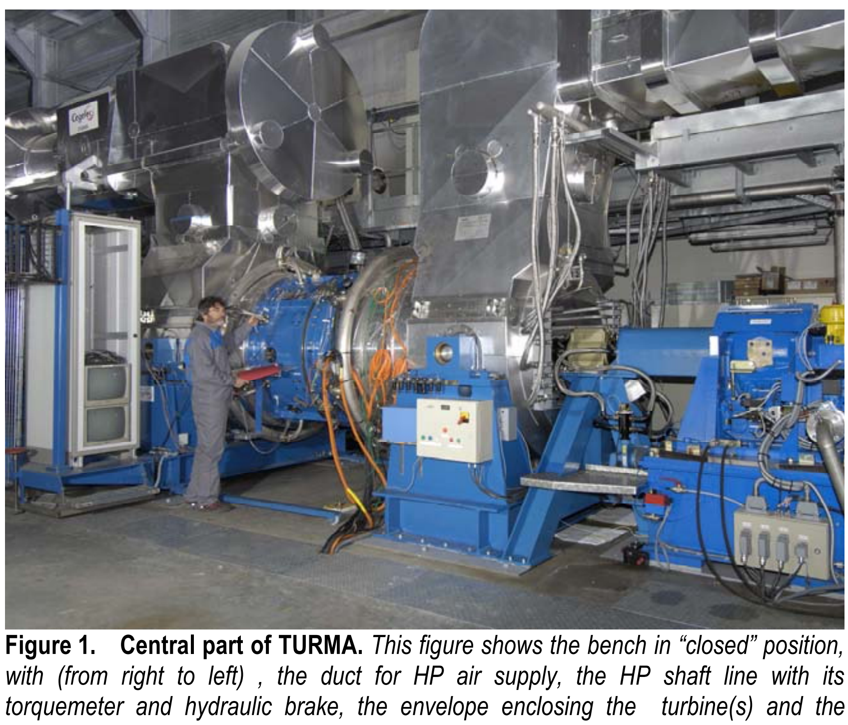

Figure 1. Central part of TURMA. *This figure shows the bench in "closed" position, with (from right to left) , the duct for HP air supply, the HP shaft line with its torquemeter and hydraulic brake, the envelope enclosing the turbine(s) and the measurement systems, and the exhaust duct (LPT exit).*

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analysis of the internal flows across the stators and the rotors of co or contra-rotating turbines to be performed.

In 1996, ONERA, the French National Establishment for Aerospace Research, decided to implement this facility in its Modane Avrieux Center (CMA), with the support of the French government and of public communities. This new test rig “TURMA” (for TURbine Modane Avrieux) has been recently commissioned and used for the first tests.

Figure 1 shows the central part of the bench, closed and ready to run.

SOME KEY DATES

2002 : End of construction (building, aerodynamic circuit);
2003 – 2004 : Installation of HPT and LPT shafts, brakes, exhaust compressor;
2005 – 2006 : Design and manufacturing of wake survey system;
2006 – 2007 : Design, manufacturing and calibration of probes;
2006 – 2007 : Design and manufacturing of turbine interface ducts;
10/2007 : Aerodynamic tests (HPT stator alone);
11/2007 : HPT wheel installation downstream from the HPT stator;
2008 : Adjustments of the HPT shaft line lubrication and of the HPT brake control loop;
11/2008 : Aerodynamic tests with HPT turbine (HPT Stator + HPT rotor).

MODEL DEFINITION AND SIMILARITY PARAMETERS

Model definition and engine parts simulated in TURMA

TURMA has not been designed to accommodate a complete turbojet engine with its compressors, combustion chambers, turbines and all the auxiliary systems, but it is designed for tests on the turbine part only, with a well defined and very stable upstream flow. Figure 2 shows a comparison between a typical complete turbojet engine and the turbine elements being tested in TURMA.

In TURMA, a “model” is defined as all the fixed parts of the turbine itself (stators, intermediate ducts), the rotating parts (rotors), and also includes all the elements necessary to connect the turbine onto the upstream and downstream ducts of the bench (interface ducts, not representative of the actual turbine). Even if the turbine in tests is identified as a “model”, TURMA can be rigged with an actual engine part, taken for

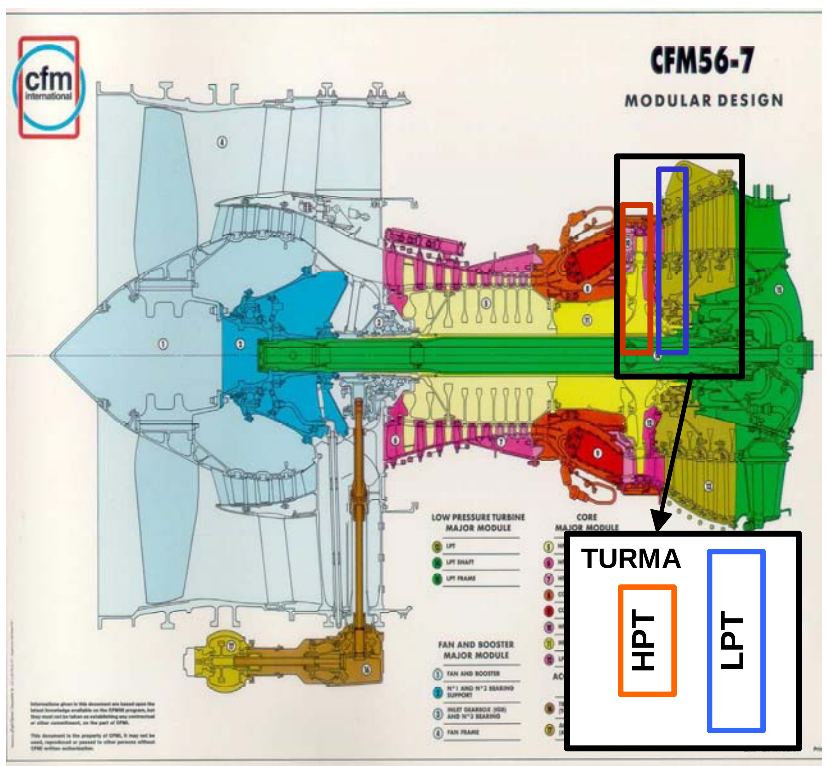


Figure 2. Parts of turbojet engine simulated in TURMA. *This figure shows a typical design of a complete turbojet engine and the parts of the turbine able to be tested in TURMA (the “model”).*

example among "on the shelves" elements.

Main similarity parameters used for turbine tests

Actual running conditions of turbojet engines, like high pressure, high temperature, combustion gases, presence of environmental systems or lubrication, are difficult to accommodate with the use of accurate and miniaturized instrumentation needed for fine and detailed flow analysis.

Figure 3 shows a comparison between orders of magnitude of the typical aerodynamic conditions in standard turbojet engines and those achieved in TURMA.

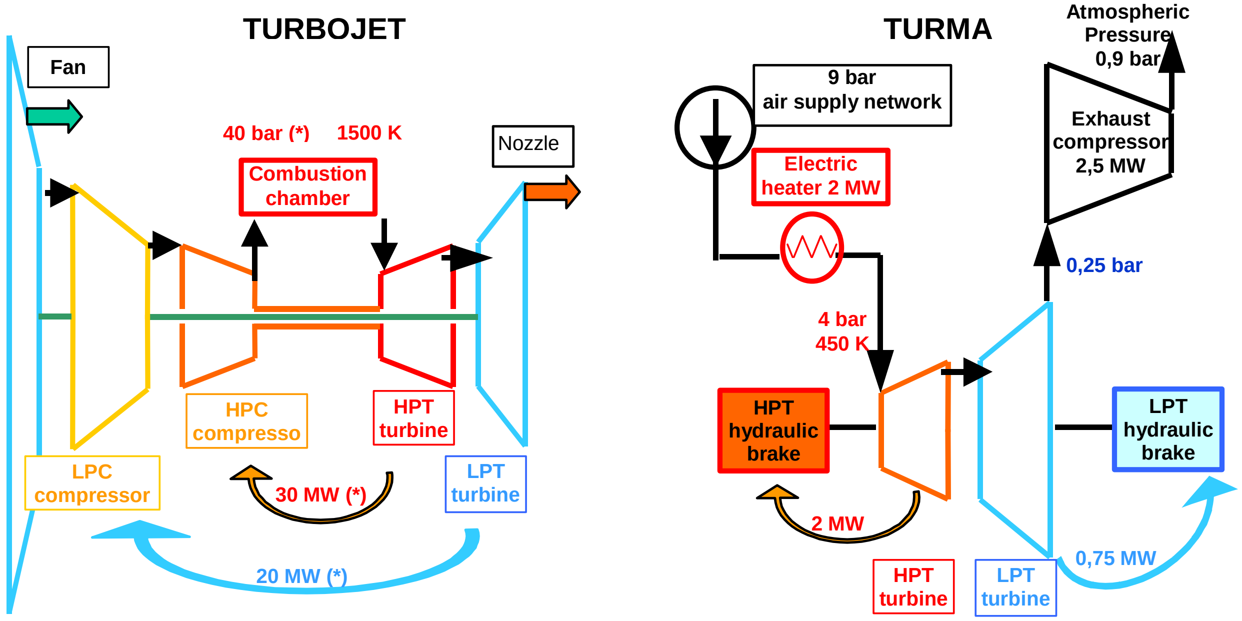


Figure 3. Differences between actual turbojet engine and TURMA. *This figure shows typical orders of magnitude of aerodynamic conditions and power in complete turbojet engines and the test conditions in TURMA.*

On condition that they are set respecting of the usual aerodynamic similarity parameters for rotating machines, it is possible to decrease the level of the operating pressure and temperature while achieving the same aerodynamic conditions for the model in the test bench as for those in the actual engine (local pressure coefficients, Mach numbers, etc).

Similarity parameters:

_ Geometry (model scale ≈ 1);
_ Pressure ratio : $P_{usptream}/P_{downstream}$
_ Reduced speed : N/RT
_ Reduced mass flow : D*RT/P
_ Reduced enthalpy drop : ΔH/T
_ Reynolds number.

TURMA is thus designed as a "lukewarm" test rig, running at "moderate" pressure and temperature, but with full scale stators and rotors. Experimental conditions in TURMA are thus "soft" enough to comply with the use of delicate and various instrumentation. Using full scale models enables the rotor mechanical plays (radial or axial clearances) to be accurately simulated, and the complex aerodynamic phenomena occurring in these area to be accurately analysed.

TURMA CHARACTERISTICS

Possible model configurations

TURMA has been designed for studies of the internal flow behavior across the wheels of two-stages turbines, co or contra rotating. Subsequently, TURMA is fitted with two independent shaft lines, each line being controlled by a hydraulic brake. The bench can accommodate various model designs and sizes, models being owned and provided by the customer.

Several turbine configurations can be tested:

HP stator alone;

HP stator + HP rotor (HP turbine, clockwise or anticlockwise rotation);

HP turbine + LP NGV

HP turbine + LP NGV + LP rotor (HP turbine + LP turbine with clockwise or anticlockwise rotation).

The rotating direction (clockwise or anticlockwise) and the rotation speed of each turbine are fully independent and controlled.

All combinations of rotation speeds and directions are possible.

Figure 4 shows a sketch of the central part of the rig, in which the turbine has to be fitted, and indicates orders of magnitude of the model sizes.

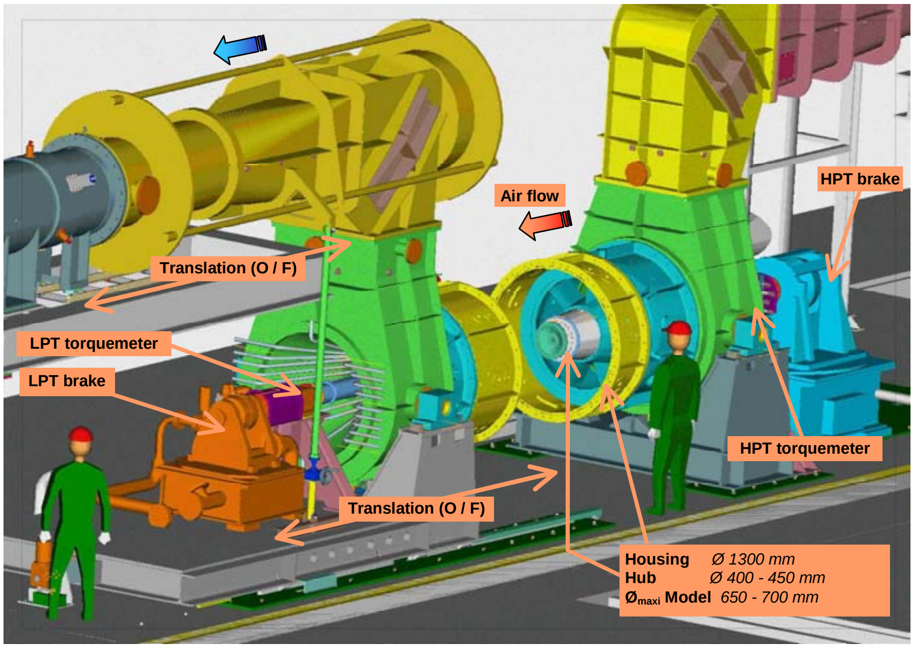


Figure 4. View of the central part of TURMA (Bench shown opened and empty). *This figure shows the arrangement of the central part of TURMA with the bench in position opened. The bench is shown empty (no turbine and no measurement systems installed), showing the room available for turbine(s) and for the installation of the measurement devices.*

TURMA functional (test conditions, test parameters)

TURMA is supplied from the high pressure air storage and network of the Modane Centre, itself continuously supplied by the continuous air compressors of the centre, whose capacities are widely beyond TURMA needs. Thus TURMA can be run in continuous mode with very stable test conditions along several hours without stop.

Figure 5 shows the block diagram of the aerodynamic circuit.

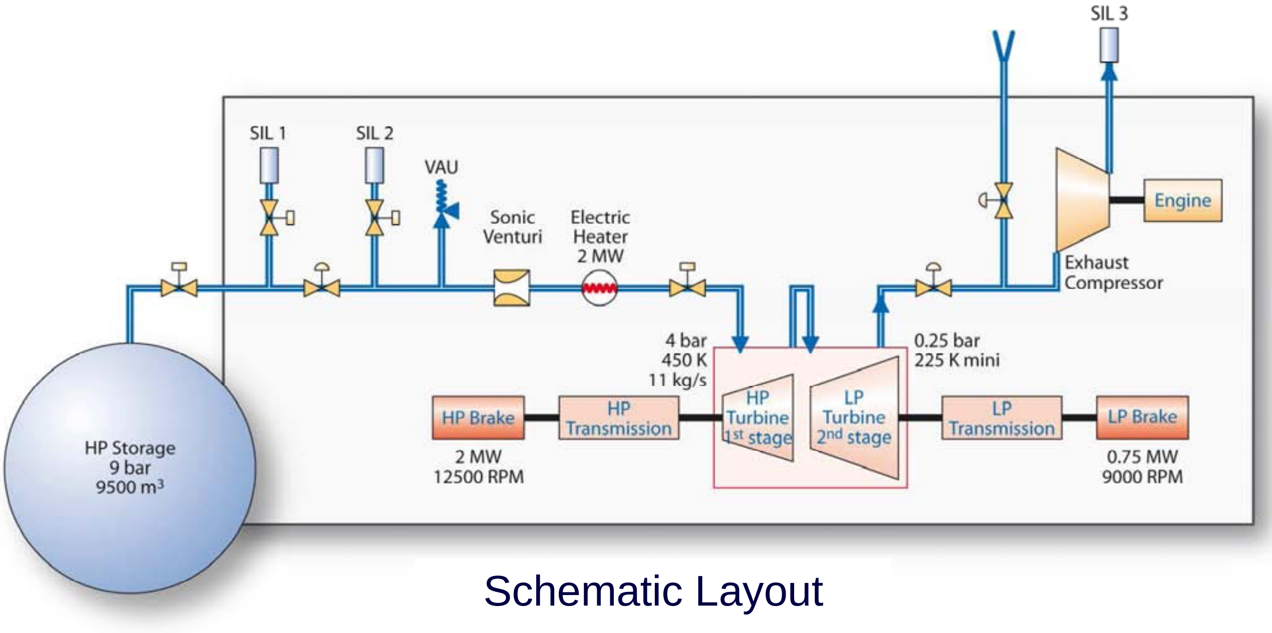


Figure 5. Block diagram of TURMA aerodynamic circuit..

Figure 6 shows the main characteristics of the bench (power, temperature, mass flow, speed, etc).

In TURMA, the Reynolds number at the inlet of the HPT stator is depending on the pressure and temperature of the set points; a rough order of magnitude is about 1 to 5 * 10^6, based upon a reference length of 1 m and an average inlet Mach number of 0.1.

Control system

The pilot team can control TURMA by a set of two computers working in parallel in a fully independent way. In case of one computer failure, it is possible to continue with the second alone and to stop the bench safely.

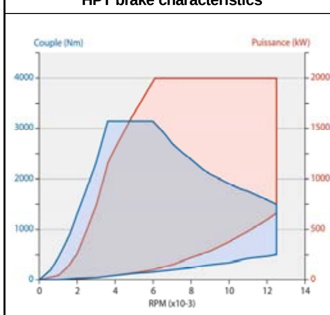
Environmental and auxiliary systems.

Absence of leakages between the turbine flow and the central or external cavities around the turbine wheel duct and shaft is controlled by setting the relevant pressures to levels close to the static pressure at the hub or casing ducts.

TURMA main characteristics

Parameter	Range		Design specifications
Mass Flow	2 < m < 11 kg/s	Measurement : Sonic throats Ø 79,975 mm Ø 89,906 mm Ø 100,063 mm	DRT/P 40 to 60 50 to 70 60 to 80
Upstream pressure	0,5 bar < P1 < 4,0 bar	Adjustment : Stability : Response time :	Regulation vane VRP1 +/- 0,1% 0,3 s
Upstream temperature	293 K < T1 < 450 K Transient : < 493 K	Adjustment : Stability :	Electric heater +/- 1 K
HPT shaft line	Speed < 12500 RPM Overspeed: 13750 RPM Torque < 3100 N.m Axial thrust : < 47 kN	Adjustment Stability :	HPT hydraulic brake $\Delta N/N < 2*10^{-3}N$
LPT shaft line	Speed < 9000 RPM Overspeed: 9900 RPM Torque < 1600 N.m Axial thrust < 15 kN	Adjustment Stability :	HPT hydraulic brake $\Delta N/N < 2*10^{-3}N$
Downstream pressure	0,25 bar < P2 < 1,20 bar	Adjustment Stability : Response time :	Regulation vane VRP2 +/- 0,3% 1,0 s
Downstream temperature	223 K < T2 < 323 K		

HPT brake characteristics



LPT brake characteristics

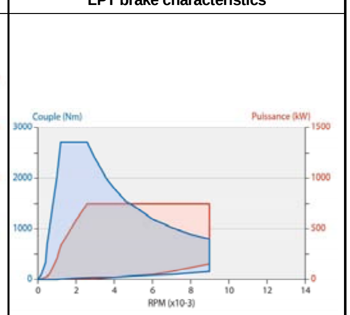


Figure 6. TURMA main characteristics (design)..

Instrumentation

Figure 7 shows an example of a typical arrangement of instrumentation used in TURMA. Other instrumentation designs, other locations or other kinds of measurement devices are possible.

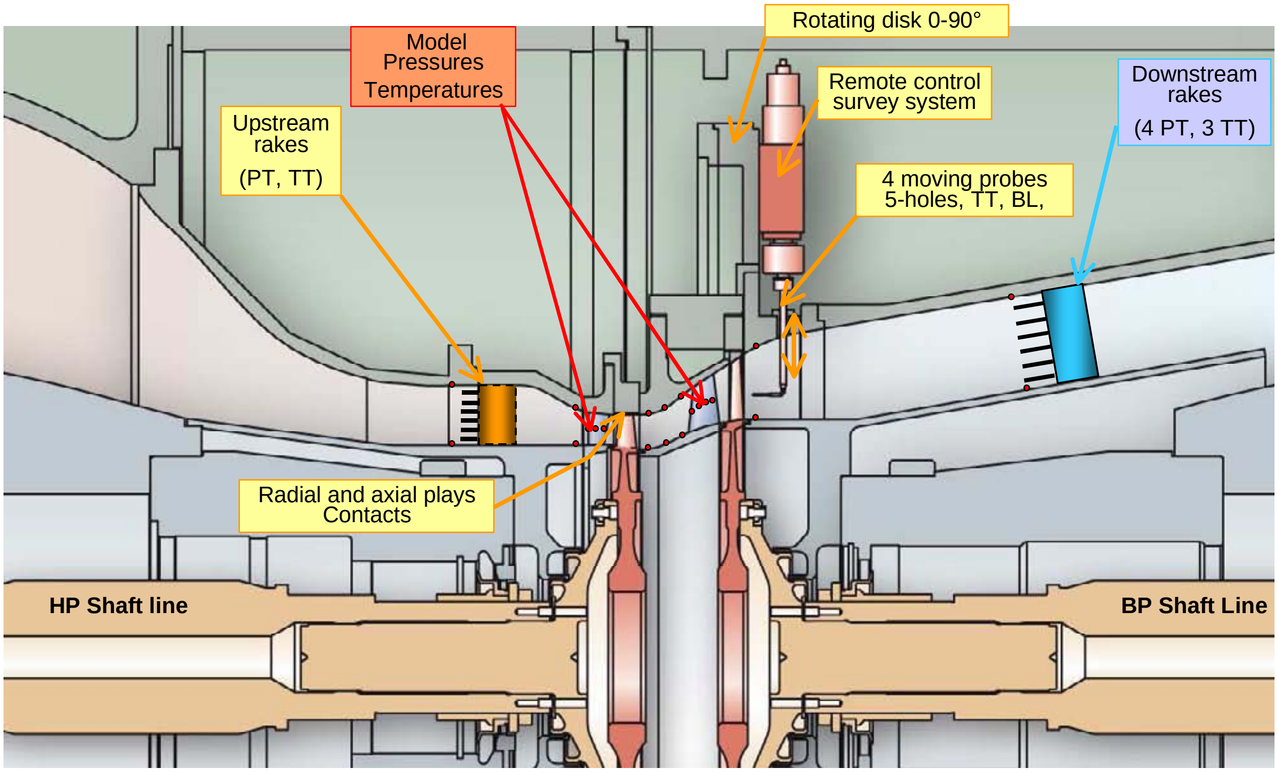


Figure 7. Example of possible instrumentation arrangement in TURMA.. *This figure shows typical instrumentation around the model only; it does not show the instrumentation of the full aerodynamic circuit. The positions of the instrumentation (probes, rakes) and of the measurement planes (wake survey)shown on this figure can be changed following the test requirements.*

Wake survey measurements

In addition of the usual instrumentation commonly found in turbine test rigs (pressure and temperature probes, accelerometers, mass flow meters, torque, speed) a special wake survey system is located around the turbine, inside the pressurized envelope (see figure 8).

This system is designed to be installed at different axial positions around the HPT turbine (upstream the stator, downstream the wheel, etc).

The wake survey system is remote controlled from the master computer of the measurement system, and is usually driven in a "step by step" displacement mode. Using the 4 motorized probe

Figure 8. Wake survey system.. *The system is shown with its 4 modules, as rigged for flow analysis downstream the rotor.*

holders, it is thus possible to make measurements over the whole height of the annular duct of the turbine, from the inner wall to the outer wall over a 360° area.

A second wake survey system designed for LPT tests is presently planned, but not yet ordered; this second system will have the same design and characteristics as the existing one, but with a wider diameter and extended travel courses due to bigger sizes of LPT turbines. Figure 9 shows the accuracy of positioning and course ranges of the movements of these two systems. Their characteristics enable very thin measurement meshes being used during tests in TURMA.

Wake survey system n°1 (HPT turbine, existing)			
Axis	**Range**	**Accuracy & repeatability**	
Θ (TETA)	0 to 90°	± 0,0085°	
R (4 modules at 90° each)	-35 to +35 mm	± 50 µm	Convergence of the 4 axis: sphere of 0,2 mm radius 90° ± 0,0085°
Ψ (4 associated with R)	-90 to +90°	± 0,1°	

Wake survey system n°2 (LPT turbine, *planned*)			
Axis	**Range**	**Accuracy & repeatability**	
Θ (TETA)	0 to 90°	± 0,0085°	
R (4 modules at 90° each)	-65 to +65 mm	± 50 µm	Convergence of the 4 axis: sphere of 0,2 mm radius 90° ± 0,0085°
Ψ (4 associated with R)	-90 to +90°	± 0,1°	

Figure 9. Main characteristics of TURMA wake survey systems.

Probes for wake survey system

(Present status, 2009): the wake survey measurements have been done using vented total temperature probes and 5 hole probes. These probes (head diameter of 2 mm for the 5 hole probes, 3 mm for the temperature probes) have been designed, manufactured and calibrated by ONERA over the whole range of experimental conditions.

Calibration ranges of the 5 hole probes :

Mach number : 0.1 to 1.2 — Accuracy : $\Delta M \approx 0{,}005$
Pressure : 0.6 bar to 2.0 bar — Accuracy : $\Delta P \approx 0{,}2\%$
Pitch angle : -35° to +35° — Accuracy : $\Delta\beta \approx 0{,}3°$
Yaw angle: -35° to +35°. — Accuracy : $\Delta\alpha \approx 0{,}3°$

In addition to the probes described here above, the wake survey can accommodate other kinds of probes (hot wire, boundary layer probes, etc).

Measurement system and data acquisition

The TURMA control system uses its own instrumentation (temperature, pressures), based upon industrial transducers. These transducers are reliable (industry design), but cannot be used as data inputs for accurate measurements. Data used in computer processing are thus issued from a measurement system enabling (2009 status) up to 64 analog steady state transducers signals to be conditioned, digitalized and recorded for data processing. In addition to these 64 analog inputs, numerous digital values (counters, digital transducers, encoders, etc), data from the electronic pressure scanners (PSI system), and up to 64 scanned analog signals (slowly variant data such temperatures, power supplies, etc) are also recorded.

Most of the steady state pressures (static or total) of the aerodynamic circuit and of the turbine are connected onto electronic sensors of PSI system; in the present status (2009), this system has a capacity of 416 pressures (26 ESP of 16 ports each).

TURMA - Characteristics of the steady state data acquisition system *(2009 status)*					
Signal conditioning	-10 V ←→ +10 V		Usual bandwith [0 – 10 Hz]		
Channels	32 analog inputs		With power supply ("gauge bridges" transducers)		
	11 analog inputs		Without power supply (hot wires, accelerometers, …)		
Conversion analog to digital	MXCAN CELI	64 channels		16 bits	
Filtering	L.P. 1.55 Hz	Digital filter			
Kind of measurement	**Device**	**Number**	**Range**	**Resolution**	**Accuracy** *(Std deviation)*
			Pressures		
Reference pressures (fixed)	Reference transducers	1 1	0.9 – 1.1 bar 0 – 3.5 bar	1 Pa / digit 1 Pa / digit	5 Pa 5 Pa
Absolute pressures (aerodynamic)	Reference transducers	1	7,5 bar	1 Pa / digit	< 1*10^{-4} F.S. (< 75 Pa)
Aerodynamic circuit & model	ESP scanners	1 8 17	± 45 psi ± 15 psi ± 5 psi	20 Pa / digit 7 Pa / digit 3 Pa / digit	± 3*10^{-4} F.S. (± 150 Pa) ± 3*10^{-4} F.S. (± 30 Pa) ± 3*10^{-4} F.S. (± 10 Pa)
5 hole probes *(Survey system)*	Kulite	2x5	± 5 psi	3 to 7 Pa / mV	≈ 2 to 5 Pa
			Temperatures		
Reference 0°	Thermocouple Reference Unit				
Aerodynamic circuit & model (*Scanned)*	Type K	Up to 8			
Aerodynamic circuit & model (*Scanned)*	Type T	Up to 56			
Lubrication circuit	PT100	2			± 0.5 °
			Other measurements		
Lubrication mass flow		2			2 % F.S.
Torque & speed	Speed	1			± 1 rpm
	Torque	1			± 2*10^{-4} F.S. (± 0.5 N.m)
Thrust	Capacitive sensors	1	2500 daN		
Radial & axial clearances	Capacitive sensors	n	0 – 2.5 mm	0.2 µm / mV	± 50 µm (gages)

Figure 10. Main characteristics of TURMA data acquisition systems.

In the 2009 status, dynamic data (accelerometers, dynamic pressures) have been recorded by using one of the standard dynamic acquisition system of the center.

In the future, it is planned to fit TURMA with a dedicated dynamic acquisition system specially tailored for measurements in rotating machines.

TURMA COMMISSIONING TESTS

Quality of the aerodynamic flow provided by TURMA to the turbine:

Qualification of the characteristics (pressure and temperature distortion, gradients, stability in time) of the flow provided by TURMA at the HP turbine inlet (leading edge of the HP stator) was performed in October 2007. These tests used the wake survey system installed upstream from the stator (note that this measurement plane is included in the "model" part of the set up). These tests showed that the flow provided by TURMA was very stable in time and had a very good homogeneity both in temperature, pressure, and direction one the bench has reached its thermal equilibrium.

Figure 11 shows an example of temperature distribution , axial Mach number and flow deviation upstream from the turbine stator. Recording the complete map over 360° with the wake survey system needed about 3 hours of continuous running, after the bench reached its thermal equilibrium (needing about 1 hour after the bench start up). This figure shows also the gradients of pressure and temperature at different angular positions upstream from the turbine inlet.

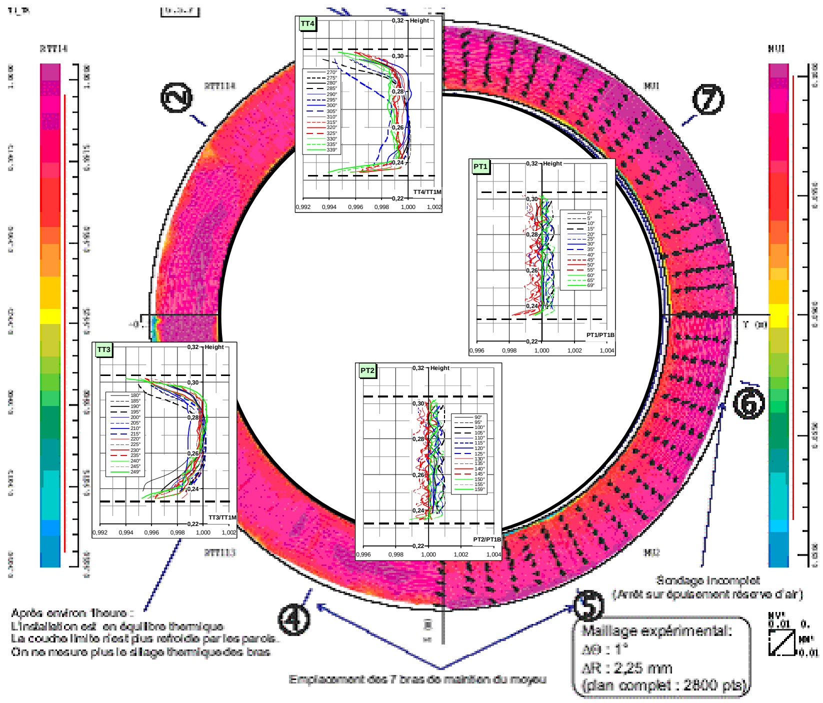


Figure 11. *(Looking forward)*

Commissioning tests:

The commissioning tests with a rotating HPT wheel have been then performed from December 2007 to October 2008. As the model available for these tests was a single HPT turbine, commissioning the LPT brake control loops is to be done when a convenient turbine will be available.

These commissioning tests aimed at checking the correct technologic functional of the rig (Control loops for HP air supply, temperature, HPT brake, vibrations, lubrication, etc), checking the functional of the measurement system and of all the instrumentation, to qualify the quality of the flow supplied to the turbine inlet, and to validate the methodology for the wake survey measurements.

After a few problems of vibrations of the HPT brake have been solved, and after modifications of the lubrication system in the summer 2008, the final commissioning tests were performed in October 2008. During these tests, all the instrumentation, wake survey system included, was running. These commissioning tests were performed up to the limits of speed and power permitted by the turbine used for these tests.

These model limits were reached at :

Speed : 9200 RPM;
Mass flow : 10 kg/s;
Temperature : 390 K;
Power : 1,2 MW.

All the bench control systems (control loops for temperature, mass flow, pressure or turbine pressure ratio, lubrication or venting systems, HPT line shaft control) showed good qualities of accuracy and stability.

Figure 12 shows an example of stability of the main test parameters (speed, mass flow, pressure, temperature) during a continuous run of 6 hours (including time for start and stop). Fluctuations are within the limits required for these tests.

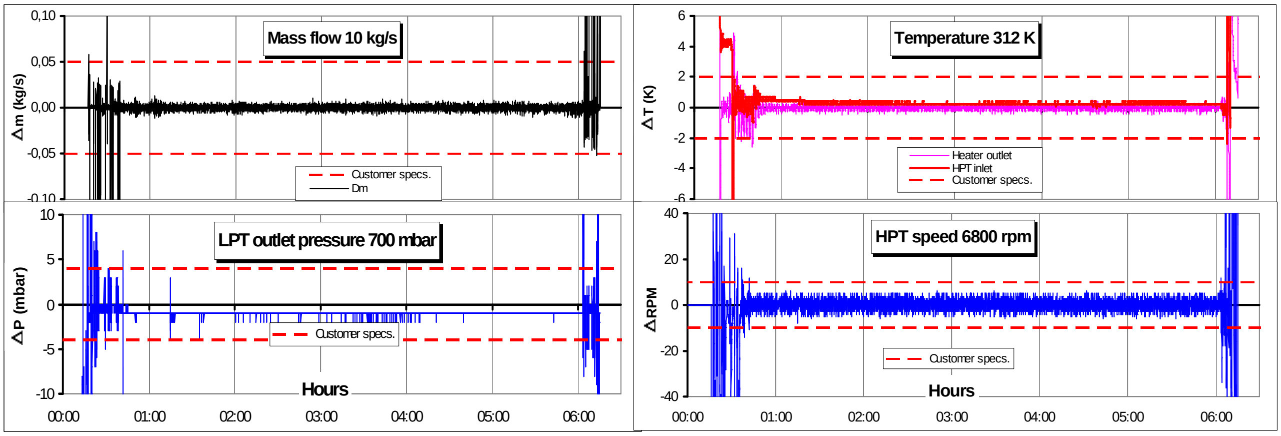


Figure 12. Example of stability of test conditions. *These figures show the differences between the actual experimental parameters and their values set points (mass flow, pressures, temperatures and RPM), recorded during a 6 hours run, including 1 hour for TURMA start and stop and 5 hours at constant set point.*

After a total of about 30 hours of running in different stabilized conditions, typical fluctuations are about :

Rpm : ± 5 rpm (6800 rpm), temperature: ± 1 K (312 K), mass flow and upstream pressure: ± 0.2 % (10 kg/s and 2.1 bar), downstream pressure: ± 0.4 % (0.4 to 1.0 bar).

Measurement accuracy was found satisfactory (transducers accuracy and sensitivity, absence of thermal drifts, crosscheckings between transducers, protection procedures). Demonstrations of accurate wake survey measurements could be done up to the model limits (9200 RPM and 390 K).

Vibration behavior

The two shaft lines of TURMA are fitted with 15 accelerometers each, in order to monitor the vibration behavior of the set up, and to enable unbalances to be corrected.

Figure 13 shows the distribution of these accelerometers along the HPT shaft line, and an example of a diagram of vibration levels along the HPT shaft line during the commissioning tests. The vibration levels are shown in RMS values of the displacement speed (mm/s RMS).

At the end of the commissioning tests, the vibration behavior of the HP shaft line is correct and complies with the usual standards for rotating machines.

The LPT shaft line behavior could still not be checked and will be set

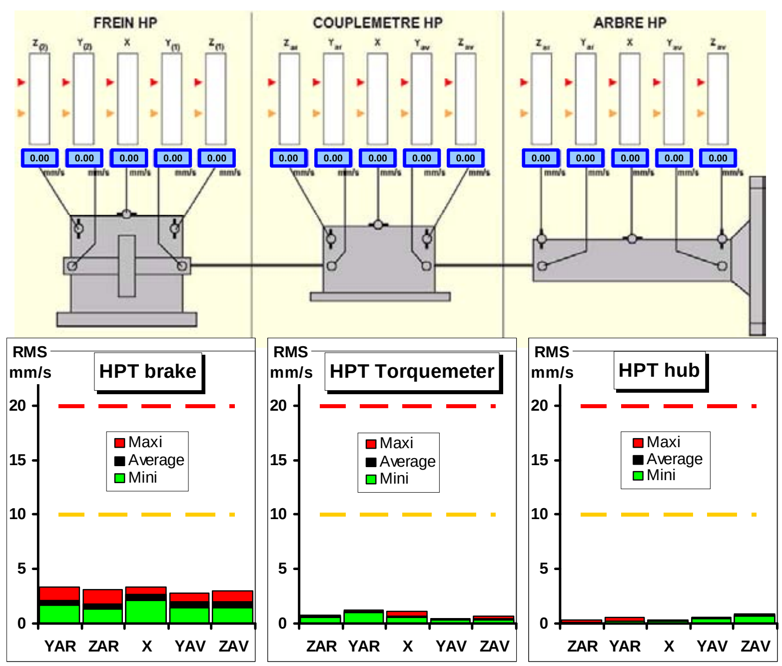


Figure 13. Example of vibration monitoring. *These figures reproduce the online displays of the vibration control system. They show an example of vibration levels(minimum, average, maximum) measured at 6800 rpm over a 5 hours run .*

only when a convenient LPT turbine will be available; however, experience gained during these HPT line adjustments makes ONERA confident in solving possible LPT line vibrations.

Response time of TURMA for steps of tests conditions (speed, temperature, pressure drop)

TURMA is designed to run in continuous conditions (several hours) with perfectly stable aerodynamic and turbine conditions. The control system enables the set points of all the parameters (pressures, speeds, temperature) to be modified instantaneously on the keyboard, but experience showed that the time needed by the bench to reach the new set point ranges from a few seconds (pressures, speeds) to several minutes (temperature).

TURBINE QUALIFICATION TESTS

Once the rig has been commissioned, the first tests were performed with the turbine already used for commissioning. These tests were performed in November 2008 for the French SNECMA company.

Performance measurements:

During these tests, measurements of power and efficiency over the whole useful range of turbine conditions (speed, pressure ratio) were performed (See figure 14). A critical speed of the model used for these tests did not allow stabilized points between 7200 and 8000 rpm to be recorded.

This test matrix represents an amount of roughly 100 set points, including repeatability points and Reynolds effects comparisons. For experimental reasons, these 100 points were not recorded into a single, but during different runs. The overall time needed for their settings and records can be estimated at roughly 5 hours, including times to let the bench reach its thermal equilibrium for the set points at different temperature levels.

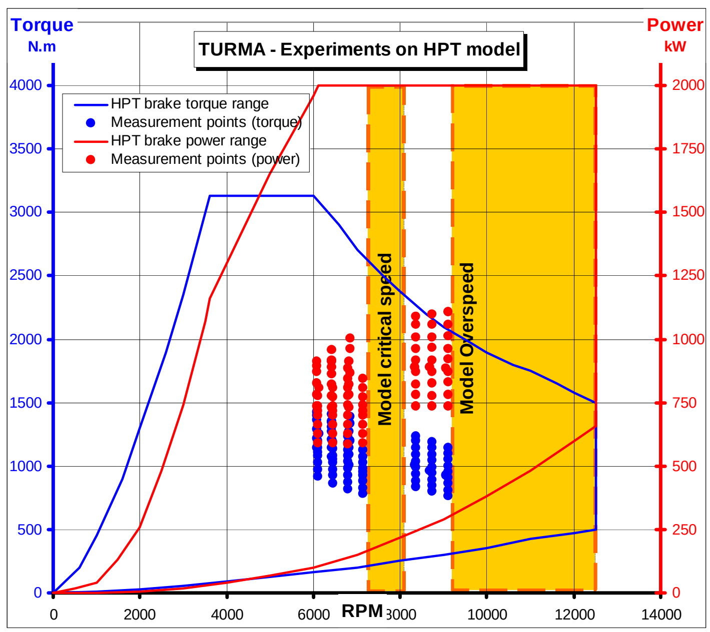


Figure 14. Example of experimental test matrix achieved in TURMA. *(With courtesy of SNECMA). Each point represents a measurement point shown within the torque (blue) and speed (red) limits of the HPT brake and those of he model (orange area, max power or critical speeds).*

The map of the turbine efficiency measurement versus speed (RPM) and load (DH/T) could be defined.

Detailed flow analysis

The wake survey system was used to analyze the flow in a plane located 12 mm downstream from the trailing edge of the HPT wheel.

Wake survey measurements were done for several turbine set points around the nominal operating point of the turbine. For each of these turbine set points, 4 sectors of 30° each were recorded simultaneously over the whole height of the annular duct for total pressure and vorticity maps, and 4 other sectors of 30° each were recorded for total temperature maps (see figure 15).

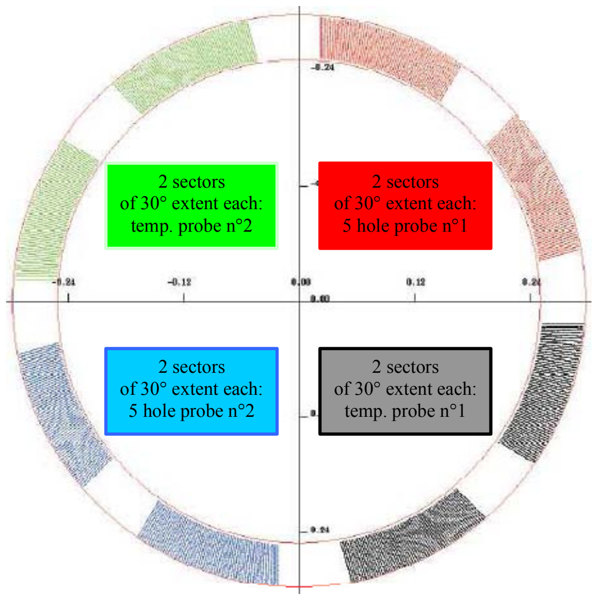


Figure 15. Visualization of wake survey measurement points. *This figure shows the positions of the measurement points for the 5 hole probes n°1 and 2 (red and blue), and for the temperature probes n°1 and 2 (grey and green).*

Test conditions	
Speed	6800 rpm
Mass flow	10 kg/s
Temp.	312 K
ΔH/T	about 100 %
Settings	
Duct height	42 mm
Radial steps	1,2 mm
Angular extent	30°
Angular steps	0,5°

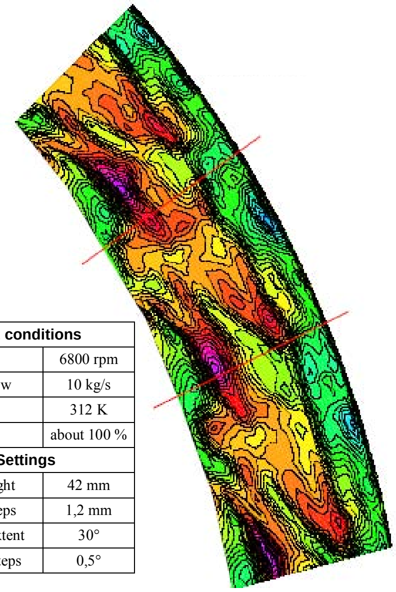


Figure 16. Example of result of wake survey measurement. *(With courtesy of SNECMA). This figure shows a map of total pressure recovery measured 12 mm downstream from the HPT rotor T.E..*

The typical mesh size for these analysis was roughly 1,2 (height) x 2 mm (width). With these settings, each sector includes around 2200 measurement points, and a wake survey measurement done in these conditions took roughly 3 hours while the control system of the bench keeps the test conditions perfectly constant.

These measurements enabled the maps of total pressure, total temperature, radial or circumferential deviations to be plotted for the several test set points requested by the customer. Figure 16 shows an example of a total pressure map for one sector of 30° (around 2200 points).

I. Conclusion

ONERA can now offer to the industrial or to the researcher community a new and efficient test rig for flow analysis around the different static or rotating parts of large scale turbines. The present status can be accommodated to fit with the different turbine designs or new measurement techniques.