INSTRUMENTATION IMPROVEMENTS FOR NGV AERODYNAMIC CHARACTERIZATION AT HIGH MACH NUMBERS

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ABSTRACT

One of the most important new engine concepts is the Geared turbofan. In these engines a gear box allows the decoupling between fan and turbine rotational speeds. As a consequence, the separate aerodynamic optimization of both components becomes possible leading to an increase in engine bypass ratios, higher propulsive efficiency and lower specific fuel consumption.

The multi-stage intermediate pressure turbine (IPT) is one of the key parts of the thermodynamic cycle in geared turbofan architectures. During the characterization of a LPT NGV row, it is important to have detailed pressure losses measurements as accurate as possible. Because of the aerodynamic differences with conventional low pressure turbines (LPT), this becomes mandatory when the NGV is designed for an IPT. The main error sources are related to circumferential anisotropy, to repeatability of US and DS measurements, to effects of instrumentation in 2D losses and to static pressure measurement in the probe environment.

NOMENCLATURE

2D:	Two dimension.
BLP:	Boundary Layer Probe.
CMa:	Mach Coefficient (5 holes).
CMab:	Mach Coefficient (6 holes).
Cp:	Pressure Coefficient.
Cpitch:	Pitch Coefficient.
Cpt:	Total Pressure Coefficient.
Cps.	Static Pressure Coefficient.
CTA:	Centro de Tecnologías Aeronáuticas.
Cyaw:	Yaw Coefficient.
DS:	Downstream.
FRP:	Fast Response Probe.
FRP5H:	Fast Response Probe of 5 holes.
FRP6H:	Fast Response Probe of 6 holes.
HWP:	Hot Wire Probe.
IPT:	Intermediate Pressure Turbine.
kPaa:	Kilo Pascals absolute.
L:	Immersed probe length.
LPT:	Low Pressure Turbine.
NGV:	Nozzle Guide Vane.
OTL:	Over Tip Leakage.
Pd:	Dynamic pressure.
Ps:	Static Pressure.
Pt:	Total Pressure.
RIC:	Rotating Intermediate Case.
SFC:	Specific Fuel Consumption.
US:	Upstream.
VT:	Vehicle for Test.

INTRODUCTION

IP Turbine presents a number of significant challenges in comparison with LP Turbines for direct drive engines. Due to the higher rotational speed, rotor blades are subjected to higher mechanical loads, which lead to limitations in the design. From an aerodynamic point of view, the combination of high Mach number and low Reynolds number (below 10^5) is considered the main technology gap in the design of the IP Turbine. These conditions were considered to be the main challenge in some previous studies [3,4]. In these studies it was considered that the potential decrease in aerodynamic efficiency would be close to the benefits associated to higher rotational speeds. However, there is another study (Vazquez and Torre [5]) about the benefits of Higher Mach numbers in row losses comparing two designs with the same loading distribution and different exit Mach numbers: 0.61 and 0.88. They achieved a 14% reduction on profile losses and a 7% reduction on overall losses due to the higher pitch-to-chord ratio required in the high Mach number case. Reducing the airfoil count was identified as one of the benefits of the IP turbines due to the aerodynamic losses but also because of weight and cost savings.

However, despite the challenges mentioned above, a significant portion of the SFC reduction of the Geared turbofans is expected to come from IP Turbine performance. A comprehensive rig program has been carried out supported by Clean Sky 2 Joint Undertaking to reach the desired level of technologic maturity with the aim to reduce the risks associated to the IP turbine design.

As part of the conclusions arisen from some of these rigs, detailed NGV row characterization at a higher (>0.88) design Mach number could be a good approach to explore the limits of the Mach number at which the detriments are more than the benefits from the aerodynamic efficiency standpoint.

A rig (VT4-4) was designed to compare slightly different NGVs designed for slightly different Mach numbers.

The main parameter that will be measured and characterized in these rigs is the pressure loss coefficient of the vane under study, but due to the small differences in the NGV design, it is expected to have also small differences in pressure losses that need to be assessed.

To allow an accurate NGV characterization some instrumentation improvements need to be developed to reduce the uncertainty associated to measurements in a high Mach number environment and comparison between similar NGVs designs.

VT4-4 rig was measured in the Centro de Tecnologías Aeronáuticas (CTA) facility located in Bilbao, Spain. It includes a transonic wind tunnel with continuous flow, open circuit with mass flow levels up to 20 kg/s. Reynolds Number and Mach Number can be set independently. More information on the facility characteristics and how it operates can be found in Vazquez et al. [6].

A layout of the rig can be seen in Figure 1. It consists in a stator/rotor/stator configuration. Also, a deswirler is placed at the rig exit in order to reduce the exit dynamic head. Although there are six area traverse measurements plane, only GAP and CLUP are needed for the characterization of NGV2 performance. For these measurements, miniature fast response five-hole probes were used that were specifically designed and manufactured for these tests. These probes had ø 1.6 mm conical head with 30º and 45ºangle. The size of the holes was 0.3 mm. The probes were L-shape type, with 5.5 mm head length, due to the small blade row gap available. Details of the probe measurement process can be found in [8].

In addition to the area traverse measurements, a NGV2 was instrumented with static pressure tappings in pressure and suction surfaces at several span locations. These measurements are important in order to verify that the measured NGV2 loading distributions is in line with the design intend.

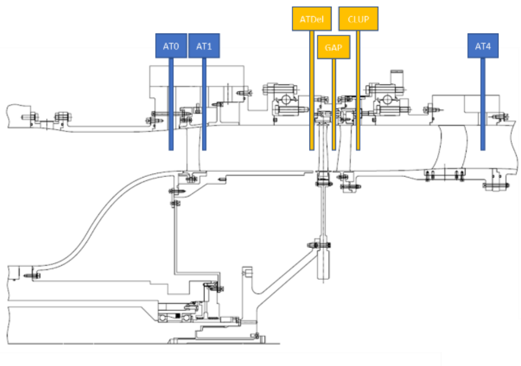

Figure 1. VT4-4 Measurement planes.

One of the main error sources when measuring pressure losses at high Mach number is the Mach number measurement itself, as it is necessary for the pressure losses calculation. In the transonic region (~0,85-1,25) a shock wave appears just US the probe head making the Mach number DS subsonic independently of the Mach number US and with very low sensitivity to it. Theoretically when M=1 any static pressure DS the shock wave is insensitive to US Mach number as explained in [1].

In order to have a correct P_s measurement from the probe, a new six-hole probe has been manufactured. The 6th hole should be far enough from the shock wave to be sensitive to the Mach number variations. The probe has been in-house manufactured from 5-hole fast response head built by Micromachining [9] and the static tapping in the rear part with a 45º cut (6th hole). All connected to the pressure sensors with stainless steel tubes brazed to low temperature. The probe can be seen in the figure below.

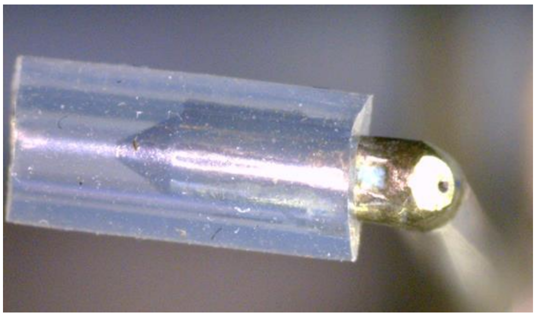

Figure 3. Detail of FRP6H.

An intensive dynamic calibration was performed at two different calibration facilities, one sited in CTA that was performed up to Mach 0.8 and static pressures from 20 kPaa to 100 kPaa using the same measurement chain as for the rig test campaign, and another at ITP Aero-LIFT facility up to Mach 0.99 and static pressure of 95 kPaa.

LIFT CALIBRATION	
MACH	DISCHARGE PRESSURE (kPaa)
0.30	95
0.60	95
0.70	95
0.80	95
0.85	95
0.90	95
0.95	95
0.97	95
0.99	95

CTA CALIBRATION	
MACH	DISCHARGE PRESSURE (kPaa)
0.30	95
0.60	95
0.70	95
0.80	95
0.60	20
0.70	20
0.80	20

Figure 4. FRP6H calibration matrix.

A high density mesh has been used for the dynamic calibration combining whirl and radial angles of the flow at the probe head within the $\pm$ 30 degrees range giving a ‘square’ calibration mesh of 1627 points.

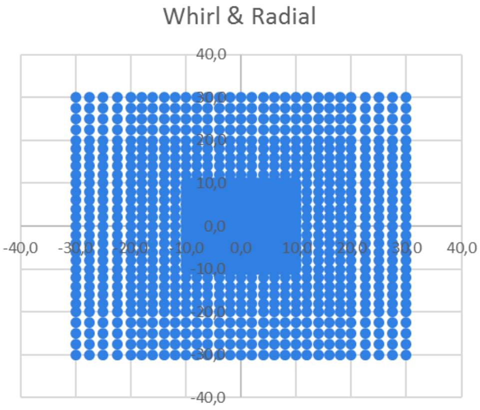

Figure 5. 2D FRP6H calibration mesh.

The common part of the two calibrations showed a good repeatability between facilities. As an example of repeatability, the picture below compares the total pressure coefficient (cpt) for two different calibrations performed at Mach number 0.8 and static pressure about 95 kPaa for both facilities

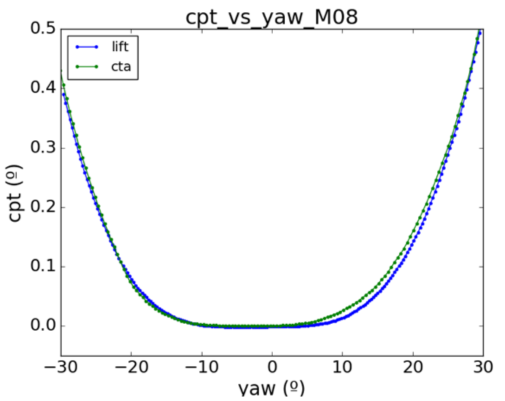

Figure 6. cpt Vs Yaw @M08&pitch 0 deg.

From the probe calibrations, the coefficients cpt, CMab, cyaw and cpitch are defined as follows:

$$cpt = \frac{(P_t - P_1)}{(P_1 - P_{ave})}$$

$$CMa = M\left(\frac{P_1}{P_{ave}}\right)$$

$$CMab = M\left(\frac{P_1}{P_6}\right)$$

$$cyaw = \frac{(P_4 - P_5)}{(P_1 - P_{ave})}$$

$$cpitch = \frac{(P_2 - P_3)}{(P_1 - P_{ave})}$$

Where:

$$P_{ave} = \frac{(P_2 + P_3 + P_4 + P_5)}{4}$$

In the next figure these coefficients are plotted as a function of pitch and yaw angles.

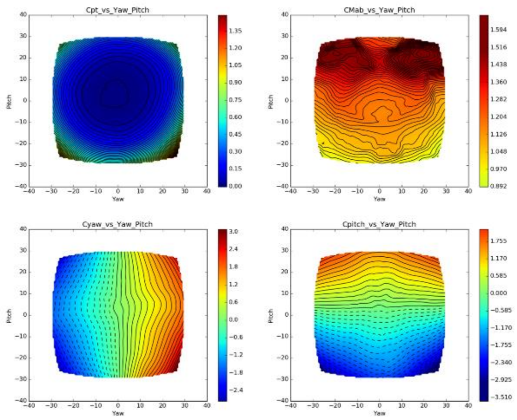

Figure 7. Calibration coefficients

During the dynamic calibration, probe bending due to dynamic head was observed with values up to 10º in radial angle for higher Mach numbers so the bending effect needs to be characterized to be corrected in the calibration results and also in the rig test measurements. This effect is very dependable of the probe architecture and for this particular probe the bending angle α has been defined as function of dynamic pressure (P_d) and the length of the probe immersed in the jet flow (L):

$$\frac{\propto}{L} = 0.021 - 0.0003 \cdot P_d + 0.00003 \cdot P_d^2$$

The results of the calibration of this probe was compared to a typical FRP5H calibration showing a better sensitiveness to the mid-high Mach numbers variations and a new Mach coefficient, CMab has been defined to calculate Mach number using the 6th hole instead of the CMa original coefficient that used the average of the five ports to calculate the P_s. The CMab coefficient has showed a low sensitiveness to Reynolds number as can be seen in the next figure where CMab is plotted as a function of Mach number for two different discharge pressures.

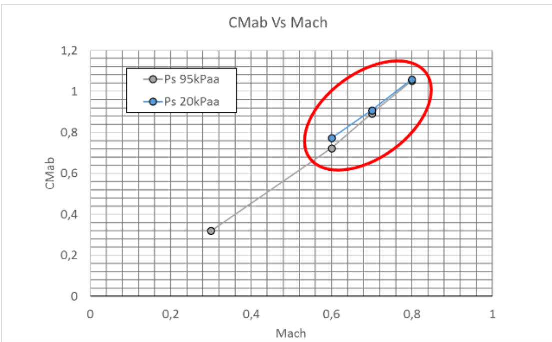

Figure 8. CMab Vs Mach at two discharge pressures

In addition to this, the behavior of the CMab coefficient as function of Mach number has showed to be as expected from lower Mach numbers up to Mach number of 1. In the figure below two plots are showed comparing the CMab calculated from the two facilities (in the left) and CMab from [9] (in the right).

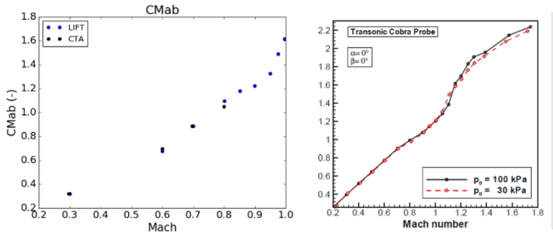

Figure 9. CMab behavior

Another error sources commonly observed in fluid dynamic tests are those due to circumferential anisotropy, facility repeatability and effects of the instrumentation in the main flow.

Conventional circumferential actuators limitations have influence in pressure losses calculation accuracy in different ways. The first limitation has to do with the circumferential range that can be measured, this is typically 28 deg and it is, sometimes, not enough to have a representative number of channels characterized. The second limitation comes from the reduced axial chord of the NGVs compared to the axial length of the actuators that makes impossible to assembly two actuators at the same time in two different axial positions to measure US and DS the NGV, so only one axial section can be measured across the same streamline. Other solutions were used in the past such as pitot probes to correct differences between different test days or the tandem system where the flow US was characterized by means of a radial traverse. However, these solutions did not show the desired accuracy. The third limitation is because a slot is needed in the cases to allow probes displacement and this slot disturb the flow in the walls and change the boundary layer behavior. A rotating intermediate case (RIC) has been designed and manufactured as the solution to the limitations of conventional circumferential actuators. Regarding the circumferential anisotropy, this RIC can rotate up to 360 deg and measure the complete NGV row. For the problem of facility repeatability due to measure US and DS of the NGV in different test days because of the impossibility of assembling two actuators, the RIC allows three axial sections to be measured across the same streamline and in the same test day. When using this new concept only a 13 mm hole is needed for each probe, not slots that disturb the end wall flows. This configuration also allows outer boundary layer probes to traverse tangentially and have a more detailed boundary layer characterization increasing the pressure losses evaluation accuracy.

The RIC axial and radial position is ensured by means of high precision ball bearings that support also the loads generated during the tests. These bearings are capable of supporting loads up to 1,800 kN and have a positioning accuracy better than 0.1 mm. The dynamic seal between static and rotating parts is made with quad-rings and checked during the different stages of assembly and test.

The RIC is heavily instrumented including: 24 static pressure tappings, 17 microphones for noise characterization, 30 bosses at three different axial positions (as showed in figure 4) where probes such as FRP, BLP or HWP can be mounted to perform traverses, one total temperature rake and three equi-spaced tipclearance bosses for OTL characterizations.

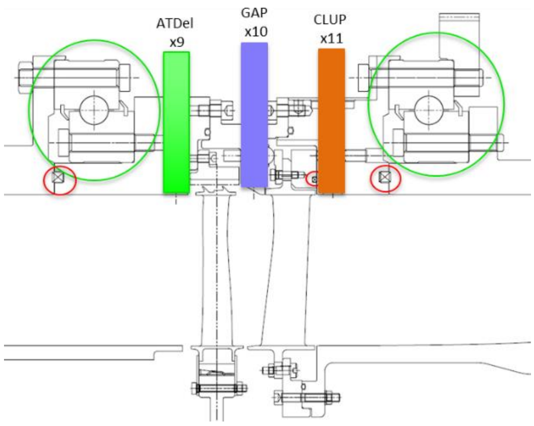

Figure 10. RIC measurement planes, seals and bearings.

One of the most challenging problem to solve during design is the NGV row positioning as it is ‘floating’ inside the RIC. In order to keep constant, and correct NGV position while the case is rotating, the NGV row is supported from the rear structure. An intermediate ring is provided for axial setting with free joint to radially center the row during assembly. The axial rolling balls are used to axially fix the floating outer NGV ring and subsequently the complete NGV row. These features can be seen marked in figure 5.

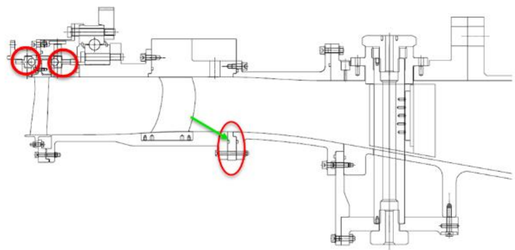

Figure 11. NGV row positioning features.

A wide variety of equipment need to be mounted in and rotate with the RIC to perform complete NGV characterization. This equipment includes two pressure bricks with 16 channels each for RIC static pressures measurements, three limit switches (one to have the absolute reference relative to the static cases and another two for limiting the rotation of the RIC within 360º), up to six radial actuators to perform (in combination with the circumferential traverse of the RIC) area traverses with different kind of probes, and 17 rotating microphones. The RIC with a typical instrumentation set-up can be seen in picture 6.

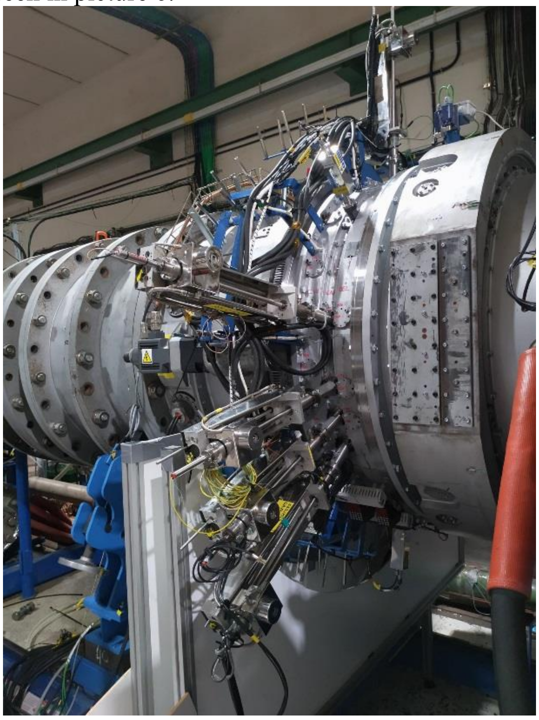

Figure 12. Typical RIC instrumentation configuration.

The lead-out of all the cables and tubes needed to connect probes and other devices mounted in the RIC has a big complexity because all these cables and tubes should roll/unroll in the RIC when it is rotating. Due to the high density of instrumentation and the reduced axial space these cables must be rolled over the desired surface. The cables are collected and guided by the collecting box as shown in figure 7.

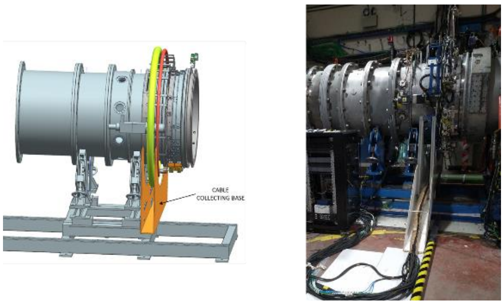

Figure 13. RIC cables lead-out.

These cables include 12 for radial actuators, 3 tubes for tip clearance probes cooling, 2 cables for pressure bricks power supply, 2 cables for digital communication of pressure bricks, 3 tubes for pressure bricks control pressures, 3 cables for tip clearance probes power supply and signals, and 3 cables for FRP power supply and signals.

During the first part of the VT4-4 rig test campaign a commissioning of the RIC was performed. The purpose of this was not only to validate the traversing system but also to optimize the cables lead-out, reduce the eccentricity effects on measurements and fix the correct rotation speeds for the different measurement planes and operating conditions.

The cable lead-out optimization was performed before the first test as it was independent from the operating point.

Regarding the effect of the eccentricity between the rotating case and the rotor in the measurements, it was seen that the main error source was the eccentricity between the seal and the RIC, because the seal and the rotating case moved together and this made the OTL to change in any absolute circumferential position when the case rotated. In order to avoid that, both eccentricities, between seal and RIC and between rotating case and rotor, were reduced as much as possible.

In order to fix the correct rotating speeds that allow the probes to perform traverses, slow enough but as fast as possible, several measurements were performed at different RIC speeds and compared with a case stopping at intermediate points.

Another part of the commissioning of the RIC was made measuring the same windows in the different measurement planes with different probes to ensure the same distributions in whirl angle, radial angle, and total pressure.

With the aim to reduce even more the uncertainty in pressure losses measurement and lead to a better comparison of slightly different NGV designs, as for this test there are NGVs designed for different exit Mach numbers, one new rig concept has been developed. It is called ‘rainbow’ and it consists of three different sectors of 120 deg approximately to divide the full 360 degrees NGV row in three parts with a different NGV design mounted on each part.

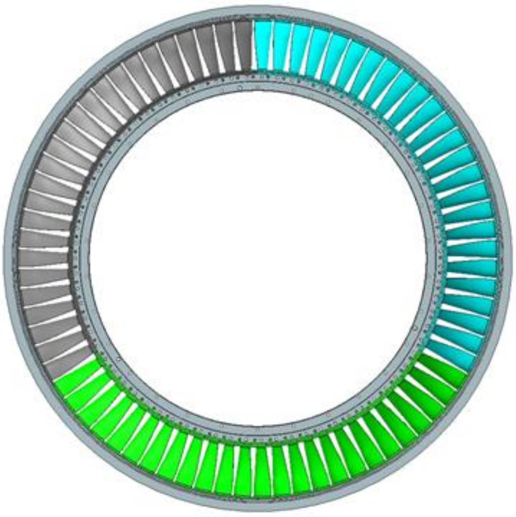

Figure 14. Rainbow of three NGV designs.

This concept includes also a high quantity of static instrumentation, specifically static tappings in pressure and suction surfaces located at 2%, 50% and 98%, for each NGV design to give the Cp and loading distributions at these span percentages that can be compared to the design intend. In addition, an array of hot film is installed in the suction surface for each NGV design to allow a qualitative analysis of the boundary layer on the NGV suction face.
At one hand, it is known from other tests that, in high Mach number conditions, 3 channels are needed to be between two measurement windows to avoid influence of the probe in the surrounding NGVs and also to avoid influence of different NGV designs assembled in the same row.

Figure 16. CFD showing the influence of a probe.

This effect can be studied in detail during the testing of this rig because the RIC allows probe measurements at any desired circumferential position.
This has to be fulfilled between two different NGV designs, but also between a measurement window and a NGV with static tappings or hotfilm instrumented. On the other hand, the number of channels needed to be measured to have a representative value of pressure losses are a minimum of 6. As it can be seen in the picture below, all these requirements can be fulfilled for three sectors of 120 degrees and 25 vanes each.

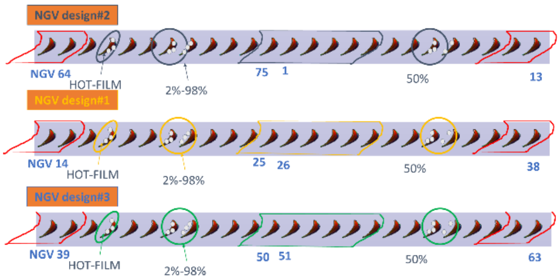

Figure 16. Instrumentation positioning in a Rainbow of three NGV designs.

This rig configuration yields a back to back design comparison measuring US and DS of each design, the same test day. Two different ways of characterizing the three designs can be performed depending on which part of the uncertainty associated to the test is prioritized. If the uncertainty associated to the probes calibration needs to be minimized, the same probe can be used to measure US the three sectors, one after the other, and another probe can measure DS the three sectors one after the other too, but the measurement of each sector will not be performed at the same time.
From another point of view, if the uncertainty coming from stability and repeatability of the facility needs to be minimized, then the three sectors can be measured at the same time US and at the same time DS but with 6 different probes.
As a conclusion, IP turbines are a key part of one the new engine concept, Geared Turbofan. The aerodynamic differences between the IPT and the conventional LPT due to the combination of high Mach number and low Reynolds number (below 10^5), needs to be studied and understood.
The main parameter in measurements for NGV characterization at high Mach numbers is the pressure losses that are very sensitive to some typical measurement errors. To be able of characterize slightly different high Mach designs the pressure losses accuracy needs to be improved.
Some instrumentation improvements have been developed to lead to a better measurement accuracy and test time optimization.

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REFERENCES

[1] Hancock, P.E., 1988. A theoretical constraint at M = 1 for intrusive probes and some transonic calibrations of simple static-pressure and flow-direction probes. In Proceedings of the 9th Bi-Annual Symposium on Measuring Techniques in Transonic and Supersonic Flow in Cascades and Turbomachines, Oxford, UK.

[2] ANSI/ASME, 2013. "Test Uncertainty." PTC 19.1-2013, American Society of Mechanical Engineers, New York, NY, USA.

[3] Giovannini, M., Rubechini, F., Marconcini, M., Arnone, A. and Bertini, F., 2016. "Analysis of a LPT rotor blade for a geared engine: Part I – Aero-mechanical design and validation." In ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition. Paper No. GT2016-57746.

[4] Malzacher, F.J., Gier, J. and Lippl, F., 2006. "Aerodesign and testing of an aero-mechanically highly loaded LP turbine." Journal of turbomachinery, 128(4), pp. 643-649.

[5] Vázquez, R. and Torre, D., 2012. "The effect of Mach number on the loss generation of LP turbines." In ASME Turbo Expo 2012: Turbine Technical Conference and Exposition (pp. 1131-1142). Paper No. GT2012-68555.

[6] Vázquez, R., Iturregui, J.J., Arsuaga, M. and Armañanzas, L., 2003. "A new transonic test turbine facility." In XVI International Symposium on Air Breathing Engines (ISABE), Cleveland, Ohio, August.

[7] Vázquez, R. and Sánchez, J.M., 2003. "Temperature measurement system for low pressure ratio turbine testing." In ASME Turbo Expo 2003: Power for Land, Sea, and Air. Paper No. GT2003-38685 (pp. 527-539).

[8] Vázquez, R., Quintana, P., Partida, F., 2006. "Miniaturized 5-hole fast response probes for annular cascade testing on transonic conditions." In Proceedings of the XVIII Symposium on Measuring Techniques in Turbomachinery Transonic and Supersonic Flow in Cascades and Turbomachines, Thessaloniki, Greece, September (pp. 21-22)

[9] Kost, F., 2009. The behavior of probes in transonic flow fields of turbomachinery. In Proceedings of the 8th European Conference on Turbomachinery, Graz, Austria.