INSTALLATION EFFECTS CHARACTERISATION OF A TYPICAL HIGH BYPASS RATIO ENGINE USING NUMERICAL SIMULATIONS AND PARTICLE IMAGE VELOCIMETRY

PART 1: EXPERIMENTAL SETUP AND WIND TUNNEL IMPROVEMENTS

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OVERVIEW

As part of the VITAL European research project (FP6), an extensive aeroacoustic wind tunnel test campaign is being conducted in ONERA CEPRA19 facility, with the aim of characterising installation effects of typical VHBR (Very High Bypass Ratio) engines.

The test objectives are, on one side to gather a comprehensive noise and aerodynamic database in order to better understand mechanisms involved in jet noise installation effects, and on the other side to validate the steady CFD RANS computations (Reynolds Averaged Navier Stokes) - carried out on the same nozzle configurations - and their coupling with analytical acoustic computations based on Tam and Auriault or MGB formulations.

The far field noise measurements are acquired by two arrays of 12 microphones located in the sideline and under flight paths, every 10° from 40° upstream to 150° downstream the nozzle exit plane. The aerodynamic field measurements are acquired by ONERA PIV (Particle Image Velocimetry) system. This system has been implemented and commissioned in CEPRA19 wind tunnel facility by ONERA with its own funding, and is now used for the VITAL experiment. It is configured to provide PIV windows at any region in the jet plume from nozzle exit to 20 diameters downstream, for sections parallel and perpendicular to the facility convergent axis, for isolated and installed configurations. The PIV system measures the 3 components of the velocity field which are processed into mean and unsteady components for evaluation of the statistical property of the turbulence.

Two 1/10th scale separate flow nozzles, selected from the SILENCE® FP5 program, are being investigated: a baseline configuration and a low noise configuration equipped with serrations on the fan and core cowl. The isolated nozzle configurations are equipped with a simplified but realistic pylon, whereas the installed nozzle configurations are tested with two different pylons representative of close-coupled installations. A 2D high lift wing profile is used with two flaps deflections of 0° and 30°.

Different engine operating conditions representative of takeoff are being tested, in static and with a free stream Mach number of 0.25.

This paper is the first part of a series of three papers presenting the installation effects characterisation of a typical high bypass ratio engine using numerical simulations and particle image velocimetry. It describes the CEPRA19 wind tunnel, and the developments funded by ONERA (outside VITAL) to install a 3 components PIV system. The validation of the PIV measurements made by ONERA is then presented, as well as first preliminary PIV and noise measurements made in the VITAL European programme.

The following upcoming papers will describe the aeroacoustic methods, the PIV and acoustics measurements and the comparison with calculations.

1. EXPERIMENTAL SETUP

1.1. Wind Tunnel

Both aerodynamic and acoustic experiments are conducted in the CEPRA19 wind tunnel test chamber. The CEPRA19 facility belongs to the ONERA GMT department, which regroups the ONERA large wind tunnels. CEPRA19 is located in the "Centre d'Essais des Propulseurs" (CEPr) at Saclay, south of Paris (Figure 1). This facility is an open wind tunnel whose test chamber is covered with acoustic absorbing wedges, which gives excellent anechoic properties above 200 Hz. The chamber is roughly a quarter of a sphere with an internal radius of 9.6 m. The flow axis is 3.85 m above the floor and 4 m from the vertical sidewall. A 2 or 3 meters diameter convergent can be used. With the 2 meters one, the maximum flow velocity is 127 m/s (Mach 0.37).

For jet studies, the wind tunnel can be fitted with a special rig, called SMT2, which simulates turbofan flows. In this rig, the air supply is provided by a compressor delivering a mass flow rate up to 12 kg/s. Maximum achieved temperatures are 500 K for the secondary flow and 1150 K for the primary flow, thanks to a 3 MW propane burner.

Fig. 1 : CEPRA19 wind tunnel facility

1.2. Acoustic measurements

Two 6 meters radius arrays of fixed microphones are centred on the secondary exhaust centre of the nozzle. Each array is composed of 12 microphones located every 10° between 40° upstream to 150° downstream with respect to the tunnel axis, zero being on the forward nozzle axis. These arrays of microphones are located in the flyover plane below the model (0° in the polar arc), and in the sideline plane (56° in the polar arc), outside the wind tunnel flow to avoid spurious noise. Measured data are monitored, and converted into third octave band spectra, from 200 Hz to 80 kHz, and corrections are applied on the raw test data for ambient pressure, microphones calibration, background noise, free-jet shear layer refraction, and atmospheric absorption.

1.3. Aerodynamic measurements

The aerodynamic measurement method used for this VITAL test campaign is the PIV (Particle Image Velocimetry) technique. This non intrusive method requires a continuous particles seeding in the external flow, and in both engine flows. The measurement section is successively lit by a couple of lasers, whose beams are converted to thin light sheets. Once the particles cross the measurement section, the scattering they produce on the light is detected by two digital cameras. A rigorous post processing of the pictures provides the three components of the velocity field. Depending on the demand, these measurements are then processed to get the mean and the unsteady averaged velocities, the turbulent kinetic energy, the Reynolds stresses, vorticities, divergence, streamlines…

The PIV technique implemented in CEPRA 19 provides information in cross sections from the nozzle exit to 20 nozzle diameters downstream to cover the acoustic sources distribution in the jet plume, and in longitudinal sections on the jet centreline or any of the azimuthal positions.

1.4. Hardware

1.4.1. Nozzles

VITAL WP7.2 aims to investigate the installation effects of a low noise nozzle when used in a VHBR engine application. Therefore, acoustic and aerodynamic tests will be performed with a baseline and a low noise configuration. The chosen designs are two of the SILENCE® BPR9 1/10th scaled nozzles: the baseline nozzle, and the low noise nozzle with 10° square corrugations on the bypass nozzle and 15º square corrugations on the core nozzle (Figure 2). Both nozzles have a plug, an internal bifurcation, and an external pylon, i.e. the same properties as the VITAL engines (short cowl, separate jets with a pylon and C-duct splitter).

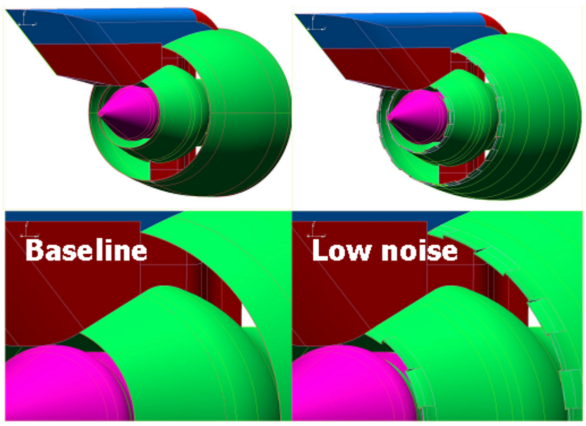

Fig. 2 : SILENCE® BPR9 nozzles

1.4.2. Wing and support

In order to experimentally assess the installation effects, a 2D wing with flap is installed in the wind tunnel. This wing, the EUROPIV profile, has a 1.5 meter span, and two flap positions: 0° and 30° (Figure 3).

Fig. 3 : EUROPIV profile

It is supported thanks to a twin sting support, holding it by its sides, bolted to the 15° quadrant of the AMCI (body of the support) mounting (Figure 4). Although this capacity is not used for VITAL, the airfoil can be tilted on its axis to get the requested angle of attack. It can be moved 2 m on the axial and the lateral directions using the AMCI mounting built-in translations. Two side plates made from a metal body covered with melamine foam are installed to ensure good bi-dimensional flow characteristics while limiting spurious acoustic reflections.

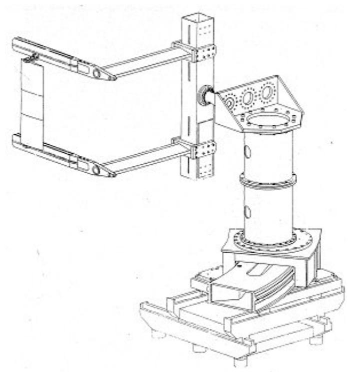

Fig. 4 : Wing and support

1.4.3. Pylons

Two pylons have been designed and are representative of a close coupling installation (Figure 5). The acoustic penalty of the under wing installation being one of the main drivers of this study, all possible acoustic effects will be highlighted (weak or strong reflection under the wing, jet/wing interaction or not), depending on the pylon and on the flap setting.

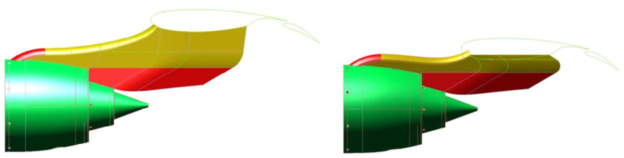

Fig. 5 : Pylon designs

1.5. Test matrix

The nozzle models, baseline and low noise, are tested with and without wing, with and without flap deflection, with 2 different pylons, and for a wide range of operating conditions, in static (0 m/s) and with simulated flight effects (90 m/s).

2. IMPLEMENTATION OF THE PIV SYSTEM AT CEPRA19

The development of the PIV in CEPRA19 benefits from the numerous years of experience of several ONERA PIV teams: specialists of the Aerodynamic Applied Department (DAAP), of the Fundamental and Applied Energetics (DEFA) and of the Fundamental and Experimental Aerodynamics (DAFE) are involved in the implementation of these techniques in the CEPRA19 context. The DEFA acts more specifically as advisor for the jet seeding system, which appears to be one of the main problems to solve. The DAAP department advises the CEPRA19 team and checks the quality of the PIV output data while the DAFE is instrumental on refining the calibration techniques and on identifying the motions and position of the test hardware (calibration grid, nozzle, airfoil).

2.1. Description of the system

2.1.1. PIV rig

Two dedicated PIV rigs have been designed and manufactured to receive the cameras. The first PIV rig is basically a beam holding each camera at each extremity. This beam, attached to a structure which can be set at any position between the convergent and the collector inside the test chamber, can be traversed in a plane normal to the longitudinal direction. Due to geometrical constraints, this configuration doesn't allow measurements close to the nozzle exhaust planes. Therefore, a second rig has been specially designed. It is a double octagon centred on the free jet axis, attached to the remote controlled, 4 m transverse, X carriage of the instrumentation table (Figure 6). For acoustic measurement, the PIV rig is moved on the convergent side of the test chamber, and covered with acoustic foam panels to avoid parasitic reflections.

Fig. 6: Second PIV rig - Double octagon

2.1.2. Seeding systems

Three independent seeding systems are used: a DEHS aerosol seeding array fed by two Laskins nozzle generators for the free jet coming out of the 2 meter-diameter convergent, a MgO submicronic particles cyclone generator for the nozzle rig primary flow and a MgO submicronic particles twin cyclone generator for the nozzle rig secondary flow. All of the three seeding systems are operated at the same time for the VITAL test campaign.

2.1.2.1. External flow

For seeding the external flow, an array (Figure 7) is positioned in the settling chamber, right after the most downstream anti-turbulence grid. It provides a 1 x 0.75 m seeded area in the test section. The DEHS aerosol is produced by two pressure vessels, each of them being fitted with a Laskins nozzle; the amount of aerosol fed into the seeding array is remotely controlled.

Fig. 7 : External flow seeding

2.1.2.2. Internal flows

Due to the high temperatures generated by the propane burner, the primary and secondary streams are seeded with submicronic particles of magnesium oxide (MgO). These particles are injected in the compressed air supply through 3 “cyclone generators” positioned in the facility basement (Figure 8). The cyclones swirl the particles so that they are homogeneously in suspension, before they are injected in the primary or secondary flow pipes.

Fig. 8 : Internal flows seeding (Cyclone)

2.1.3. PIV optical devices

The PIV optical devices are part of the ONERA GMT department equipment The characteristics of the different devices have been optimised to be used in all the large wind tunnels.

The PIV laser is a Quantel Twins® lasers (Figure 9), made of 2 Quantel Brilliant B® Nd:YAG pulsed laser shooting at 7 Hz maximum. The maximum power of each pulse is 450 mJ, its duration is 5 ns, and the laser wavelength is 532 nm (green). The laser is generating a 5 mm diameter beam, generating the desired laser sheet through an optical device.

Fig. 9 : Laser

The pictures are taken thanks to 2 LaVision Imager pro PIV cameras, featuring a 2048 x 2048 CCD sensor. Each of them is mounted on a Scheimpflug adapter (which tilts the camera relative to the lens optical axis) on which a 25 mm, 50 mm, 85 mm, 100 mm, 135 mm or 200 mm Canon focus and aperture remote controlled lens can be mounted.

For PIV calibration, different reference grids can be used : either a LaVision type 30 300x300 3D grid, or a bigger, 1000 x 800 mm 2D grid.

2.2. Validation

In order to check out potential difficulties, ONERA has first organised a series of several commissioning and preliminary tests. The relevant PIV results are compared with available data performed with other measurement techniques (anemo-clinometric probes, LDV, hot films probes…) in order to validate the technique.

2.2.1. External flow validation

The aim of this test is to check out the external flow seeding, and to validate the PIV measurements by comparison with LDV (Laser Doppler Velocimetry) measurements in the near wake of a NACA0012 airfoil.

The PIV processing is the following: 1000 image quartets acquired (2048x2048 pixels), instantaneous velocity map calculations (~130x160 vectors), multi pass data reduction (64x64 pixels windows, then 32x32 pixels windows with 50% overlap), and false vectors elimination.

The LDV tests were previously performed in the ONERA Le Fauga F2 closed wind tunnel by using the same NACA0012 model as in CEPRA19.

The DEHS aerosol seeding proved to be very efficient in CEPRA19. As shown in Figure 10, both PIV and LDV velocity profiles measured in the wake of the airfoil are in close agreement. Figure 11 illustrates some exploitation of the PIV results with an analysis of the unsteady characteristics of the velocity field.

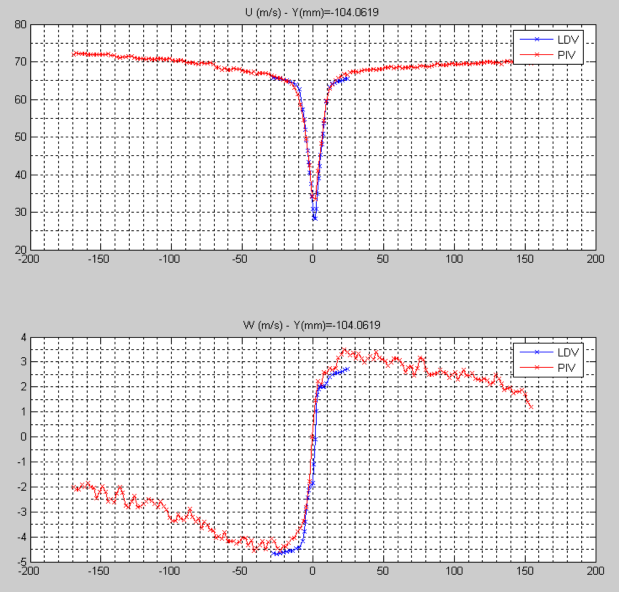

Fig. 10 : Mean velocity profiles (PIV at CEPRA19 and LDV in F2)

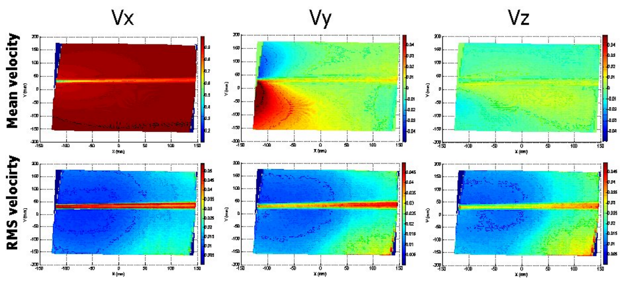

Fig. 11 : Mean and RMS velocity fields

2.2.2. Internal flows (Double stream confluent nozzle)

After validating the external flow, a second series of tests have been performed to validate the cyclones implementation and the primary and secondary flows seeding. A double stream confluent nozzle which was previously tested in CEPRA19 at take-off conditions, with a Mach 0.24 external flow, has been selected.

Some of the PIV measurements made during these tests are presented below. For this study, sets of 1000 images, with a correlation window of 32x32 have been analysed.

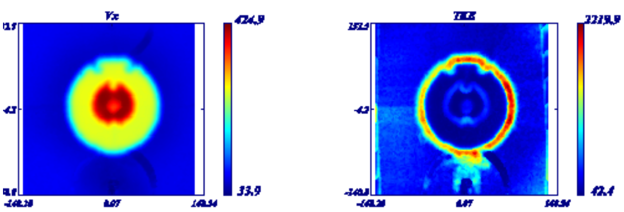

Fig. 12 : Mean axial velocity and turbulent kinetic energy for X/D = 1

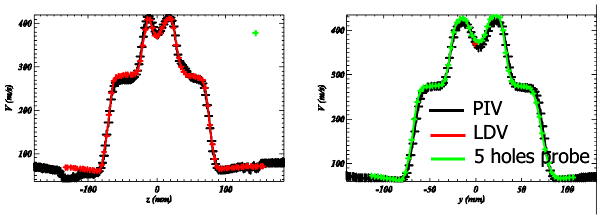

Fig. 13 : Mean axial velocities for X/D = 1

At 1 diameter downstream of the nozzle exit (Figures 12 and 13), the mean axial velocity profiles (vertical and horizontal planes) measured with the PIV technique are consistent with LDV and 5 holes probe data. Particularly, the three flows (external, secondary and primary) are clearly identified. The shear layers between the three flows are also well identified.

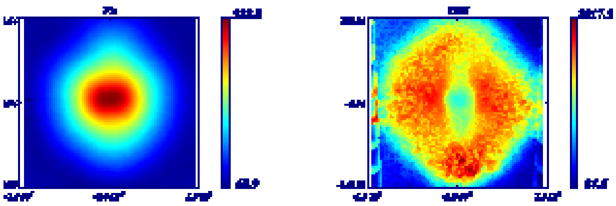

Fig. 14 : Mean axial velocity and turbulent kinetic energy for X/D = 8

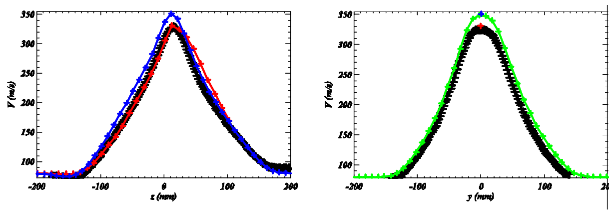

Fig. 15 : Mean and RMS axial velocities for X/D = 8

At 8 diameters downstream (Figure 14 and 15), the 5 holes probe data, PIV and LDV data are still in close agreement on the mean velocity profiles.

Figure 16 highlights the capability of the PIV system to describe the flow characteristics in parallel planes. Both the mean velocity plot and the turbulent kinetic energy plot show the different shear layers (a weak shear layer between the primary and the secondary flows, and a strong shear layer between the secondary and the external flows, which is characteristic of a confluent nozzle), and their merging at a distance of about 7 diameters downstream of the nozzle exit.

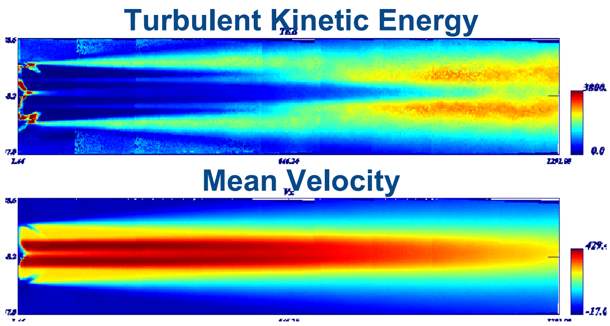

Fig. 16 : Mean axial velocity and turbulent kinetic energy between 0 and 8 diameters

3. PRELIMINARY AEROACOUSTIC RESULTS

The VITAL wind tunnel tests are currently in progress. The following plots show a preview of the acoustic (Figure 17) and aerodynamic measurements (Figure 18).

Figure 17 shows acoustic measurements on a microphone located at 6m and 130° relative to the inlet axis for both low noise and baseline nozzle configurations. These spectra which are third octave band data, with corrected atmospheric absorption (ISA+10), confirm the noise reduction provided by the optimised nozzle.

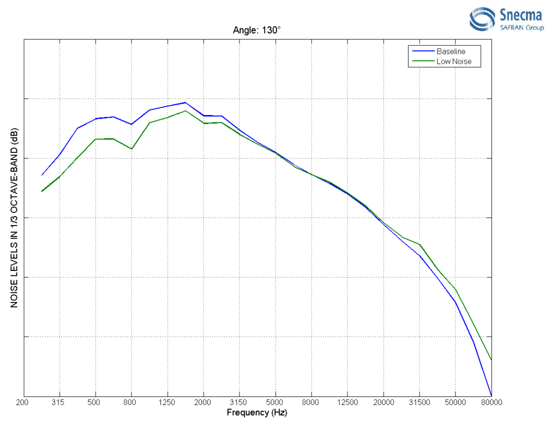

Fig. 17 : Baseline vs Low Noise - Spectra at 130°

On Figure 18, the mean velocity profiles measured by PIV illustrate the development of the shear layer on the boundary of the jet with external flow downstream of the nozzle.

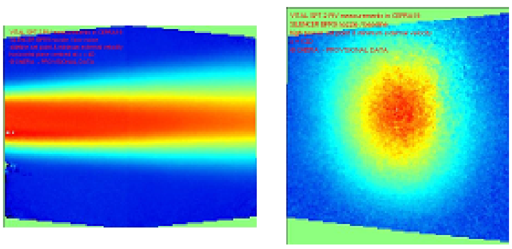

Fig. 18 : Mean velocity fields (parallel plane centred at X/D = 4 and normal plane at X/D = 12)

4. CONCLUSIONS

As part of the VITAL European research project (FP6), an extensive aeroacoustic wind tunnel tests campaign is currently being conducted in the ONERA CEPRA19 facility, with the aim of characterising installation effects of typical VHBR (Very High Bypass Ratio) engines by microphone measurements and aerodynamic PIV (Particle Image Velocimetry) measurements, to be compared to numerical simulations.

This paper was the first part of a series of three papers synthesizing this study. It has been shown that the developments made and funded by ONERA for using the PIV technique in CEPRA19 are fully successful. This has been checked by comparison with measurements made by other reference techniques on a set of different experiments. The preliminary measurements made during the current VITAL wind tunnel campaign confirm the capability of the applied measurement techniques to analyse in detail the aeroacoustic characteristics of the optimised nozzles of small and large diameter models.

5. ACKNOWLEDGMENTS

The authors would like to thank ONERA who funded (with the help of the French “Région Ile de France” and ENSAM) the adaptation of the CEPRA19 wind tunnel for PIV measurements, and funded the validation experiments on the isolated airfoil and on the double stream confluent nozzle. The following ONERA departments are in particular acknowledged: GMT and DSNA for all the validation work that has been achieved, and DAAP, DEFA and DAFE departments for their expertise during the implementation of the system.

The authors also thank the European Commission for supporting VITAL through the Sixth Framework Programme (FP6).

VITAL is a new collaborative research project, running for four years, which aims to significantly reduce aircraft engine noise and CO2 emissions. It has a total budget of 90 million euros, including 50 million euros in funding from the European Commission. Snecma leads a consortium of 53 partners gathering all major European engine manufacturers: Rolls-Royce, MTU Aero Engines, Avio, Volvo Aero, Techspace Aero Rolls-Royce Deutschland and ITP, and the airframer Airbus.

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