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Recent Improvements of CEPRA 19 Wind-Tunnel for Jet Noise Experiments

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The by-pass-ratio (BPR) of most modern jet engines kept steadily increasing in the past decades, which makes jet noise testing in wind-tunnel increasingly difficult. Indeed, when simulating these large high-BPR engines on the nozzle rig, the requested amount of by-pass mass-flow tends to grow, whereas the requested amount of core mass-flow tends to decrease. At the same time, the jet noise generated by the model decreases and shifts towards lower frequencies. At CEPRA19, this situation posed three threats on jet noise test results: the jet noise might become too small compared to the wind-tunnel background noise, the internal rig noise of the secondary flow might become larger than the jet noise, the primary flow might become too small for the propane burner to work properly. The paper describes the solutions that have been implemented to deal with these threats. Additionally, it was desirable that the rig boundary layer be reduced to a minimal thickness to better represent the full scale situation, and a boundary layer control system was created to fulfill that goal. Finally, some results from a recent test featuring such a high BPR engine are reported.

Nomenclature

C	=	Circumference of the nozzle rig
D	=	Diameter
$\delta_{0.99}$	=	Boundary layer thickness with edge of boundary layer located at 99% of external velocity
$\delta_{0.90}$	=	Boundary layer thickness with edge of boundary layer located at 90% of external velocity
δ_1	=	Boundary layer displacement thickness
f	=	Frequency
Q	=	Mass flow
ρ	=	Density
V	=	Velocity
d	=	Related to the by-pass duct in the nozzle rig
j	=	Related to the jet
0	=	Related to the flight stream
m	=	Related to the mixed jet conditions

I. Introduction

A. Overview of CEPRA19 anechoic wind-tunnel

CEPRA19 is a large anechoic wind-tunnel built in 1975 and located near Paris, France. It is described in details in ref. [1] and in the older ref. [2], but some elements are reiterated in this paper to provide the reader with some context of the facility.

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The wind-tunnel was primarily designed to perform dual-stream jet noise measurements with simulation of the forward flight stream, a topic of importance regarding the prediction of aircraft noise [3]. Its usage was further extended to the investigation of the effect of flow control [4], to airframe noise [5][6], fan noise and installation effects [7]. Aerodynamic measurements were complemented with LDV and PIV capabilities [8][9][10].

Figure 1: Overview of CEPRA19 facility

The wind-tunnel (Figure 1) is built around an anechoic chamber large enough to position the far-field microphones at 6 m distance from the nozzle exhaust, i.e. about 30 engine nozzle diameters away, over sound emission angles from 40° to 150° . The flight stream is generated with the help of an open-circuit wind tunnel, featuring numerous sound absorption devices. This stream is fed into the anechoic room with either a 2 m or a 3 m diameter convergent, then collected by a bellmouth collector, followed by a diffuser, an exhaust muffler, and a 7 MW centrifugal blower. For the jet noise experiments, the model of the aircraft nozzle is mounted on the CEPRA19 nozzle rig called SMT2 (*Simulateur de Maquette de Tuyère n°2*), which is installed on the centerline of the 2 m diameter convergent. The rig can supply the model with a primary hot stream of air (from 550 K up to 1150 K) and a secondary cold stream (from ambient to 450 K), with a mass-flow of up to 12 kg/s in total.

The wind-tunnel is operated by ONERA wind-tunnel Direction, within the “low-speed” wind-tunnel department located near Toulouse, and in strong connection with the aerodynamic and acoustic department near Paris.

B. Requirements of high by-pass-ratio engines and summary of wind-tunnel improvements

Over the past decade, there was a clear trend in increasing the By-Pass Ratio (BPR) of transport aircraft. With this trend, for a given thrust level, the engine diameter tends to increase and the jet exhaust velocity tends to decrease, which provides both higher propulsive efficiency and a quieter jet. These two outcomes are of course beneficial to the community, but they tend to make jet noise testing increasingly challenging.

Indeed, when simulating these large high-BPR engines on the nozzle rig and assuming the nozzle diameter stays roughly the same (usually about 20 cm), the requested amount of secondary mass-flow grows, whereas the requested amount of primary mass-flow decreases. At the same time, the jet noise generated by the model decreases and shifts towards lower frequencies, like on the real aircraft. This situation poses three threats on jet noise test results:

- the jet noise might become too small compared to the wind-tunnel background noise;
- the internal rig noise [11][12] of the secondary flow might become larger than the jet noise;
- the primary flow might become too small for the propane burner to work properly.

The paper will describe the solutions that have been implemented to deal with these threats by:

- reducing the tunnel background noise (section II);
- identifying and reducing the rig noise (section III);
- identifying the burner operating range (section IV).

Additionally, as these larger high-BPR engines are installed close to the wing, it was desirable that the rig boundary layer should be reduced to a minimal thickness to better represent the aeroacoustic interaction between the jet and the wing surface, as was initiated in other facilities [13][14]. This external flow boundary layer was also shown to have effect on isolated jets [15]. This led to the design and commissioning of a Boundary Layer Control System described in section V.

Finally, an overview of the combined effect of these different improvements will be provided in section VI, which will describe the wind tunnel test of a modern high-BRP nozzle, isolated and installed under a wing.

II. Background Noise Improvement

A. Sources of background noise and their reduction

Noise in an acoustic wind-tunnel has multiple origins summarized in Figure 2. In this figure, the dominant sources at CEPRA19 have been highlighted in red. The present work has addressed the noise from the collector and from the flow recirculation in the chamber.

Figure 2: Sources of background noise in CEPRA19 wind-tunnel (adapted from [18]). Dominant sources indicated in red.

The role of the collector in an open-jet wind-tunnel was already explained in the 1930s [16], and again carefully considered during the wind-tunnel design [17]. Due to turbulent mixing, the quiescent air in the chamber is entrained by the jet stream, so that an excess of mass-flow exists towards the downstream end of the jet. This excess must be diverted sidewise at the entrance of the collector, and this causes recirculation in the chamber. Flow simulations and historical measurements in CEPRA19 indicate that recirculation velocities in the chamber can reach 5 to 10% of the jet velocity [17].

When impinging on the collector, the flow generates noise through two mechanisms: the impact of turbulent structures on the collector hard surface, and the whistle caused by the air flowing through the perforations of the porous parts of the collector. Means of reducing this noise have been previously investigated with success in other facilities, first in Japan [18][19][20], then in Germany [21][22]. A solution widely adopted and which was also installed in CEPRA19 is to cover the collector with faux fur fabric. This resolved both noise generating mechanisms mentioned above, while keeping the collector partially acoustically transparent.

A second issue regarding background noise is the pseudo-sound generated by the recirculating flow in the anechoic chamber that impinges on some microphones. This pseudo-sound was suppressed by shielding the microphone with windscreens [23]. However, experiments indicated that the windscreens create spectral distortions above 20 kHz, so that every far-field microphone was actually doubled: one shielded, one unshielded.

B. Results of improvement

Some results are displayed in Figure 3 for a microphone in the downstream arc which is important for jet noise measurements. It can be seen that the combination of the above-mentioned noise suppression techniques brought a reduction of the background noise of 10 to 20 dB over most of the spectrum for the 3 m diameter convergent, and a reduction of 5 to 10 dB for the 2 m diameter convergent. The benefit of windscreens is thought to become much

larger when a model is installed in the test section. Indeed, in that case the lift of the model can deviate the wind-tunnel flow and strongly increase recirculation in the anechoic chamber.

Figure 3: Background noise spectrum in the empty wind tunnel at 90 m/s, flyover microphone at 130°

III. Rig Noise Improvement

A. Description of the rig noise issue

An engine nozzle tested on the nozzle rig at CEPRA19 has to be supplied with a considerable amount of pressurized air to generate the engine jet. This supplied air flows through the rig piping before being exhausted from the nozzle. In doing so, the flow can generate an internal rig noise, especially in bends, constriction, valves and all kind of obstacles as fully detailed in [11][12]. Some examples are also provided in [13][14]. This internal rig noise typically scales with a 4th to 6th power of the flow velocity V_d in the rig duct [11][14], which is itself more or less proportional to the mass-flow in the duct. Consequently, large BPR engines requesting higher mass-flow in the secondary stream also generate more rig noise while at the same time they generally generate less jet noise. As a result, the rig noise can spoil the jet noise measurement.

The orders of magnitude can be further detailed using the following assumptions, where ρ is the flow density, V the velocity, D the diameter, the index j refers to the jet flow, the index d refers to the duct flow at its narrowest point and the index 0 to the flight stream:

- the jet noise is proportional to $\rho_j D_j^2 (V_j - V_0)^8$
- the rig noise is proportional to $\rho_d V_d^5$

The conservation of mass flow in the rig duct of fixed cross-section imposes that $\rho_d V_d$ is proportional to $\rho_j V_j D_j^2$. For large BPR engines, the density in the rig is not very different from the one in the jet, so that finally V_d is proportional to $V_j D_j^2$. Reporting this result in previous hypotheses on noise reveals that the ratio of jet noise to rig noise is strongly dependent on the model scale, proportional to:

$$\frac{(V_j - V_0)^8}{V_j^5} D_j^{-8}$$

The consequence of this dependency is made obvious in the Table 1 below, for given jet and flight velocities V_j and V_0 . Increasing the model size D_j quickly deteriorate the signal to noise ratio, as already discussed in [14].

The proportionality relationship also reveals that the jet noise decreases with decreasing V_j at a larger rate than the rig noise. Therefore, when jet velocity is too low, rig noise always dominate jet noise. In practice, for large BPR engines, most of the mass flow circulates in the by-pass duct so that V_j is not very different from the mixed jet velocity V_m and D_j is close to the nozzle diameter.

Table 1: Effect of increasing model size on jet and rig noise

If model size D_j is increased by:	jet noise increases by:	but rig noise increases by:
10%	0.8 dB	4.1 dB
20%	1.6 dB	7.9 dB
50%	2.3 dB	11.4 dB

B. Characterization of rig noise

In order to assess the level of spurious noise generated by the secondary flow in the rig, a special setup was created and is displayed in Figure 4. A conical piece is attached on the primary duct which allows expanding the flow towards an exhaust area 2.7 times larger than typical engine nozzles. For a given mass-flow, the flow exhausting from the rig has a considerably smaller velocity and the corresponding jet noise becomes negligible in front of the rig noise. The latter can then be measured using the far-field microphones.

Figure 4: Setup of the nozzle rig for rig noise qualification tests

Figure 5: Acoustic liners in the nozzle rig

Measurements revealed a broadband spectrum (see Figure 6), jeopardizing proper measurement of typical jet noise mostly between 400 Hz and 10 kHz. Overall noise level evolved as a 5th power of the in-duct velocity V_d , but a closer examination revealed that the lower frequency bands evolved as a 4th power, whereas higher frequency bands evolved as a 6th to 8th power of this velocity, which suggests that the rig noise is the sum of multiple noise sources involving different physical mechanisms.

C. Rig noise reduction

Investigations were conducted to locate the source of the rig noise in the rig piping, but were mostly unsuccessful. Finally, it was decided to fit the secondary duct with acoustic liners near the end of the rig, and to streamline or remove as much as possible the different obstacles in the rig. Two liners, on the internal and external walls of the duct, were developed and integrated in an acoustic spacer part, that is mounted immediately upstream of the model, see Figure 5.

The Figure 6 shows the rig noise spectrum on a far-field microphone for two large secondary mass-flows, before and after the installation of the acoustic liners. The rig noise was reduced by 5 to 15 dB over the 600 Hz – 100 kHz frequency band. The lack of room due to geometrical constraints made the design of the liners quite challenging for the absorption at low frequency (< 1 kHz). The external liner targeted the frequency larger than 1 kHz (labeled *ii* in Figure 6) and was of classical design, with absorbing foam covered with an optimized perforated sheet of metal. The internal linear relied on the new LEONAR design [24][25] to target the 600 Hz – 1 kHz frequency band (labeled *i* in Figure 6).

IV. Burner operating range

The primary flow is heated to the requested temperature by a propane burner that was originally designed to operate with larger primary mass flows than what is needed for most engines today. There was therefore a need to redefine the lower operating limit of the burner (avoiding flame blown out), as a function of temperature, operating pressure and mass-flow. This was carried out with a series of exhaust plates, fitted on the core-flow exhaust, and featuring holes of decreasing diameter. For each plate, the upstream total temperature and pressure (and consequently the mass-flow) was varied, until one the following limits was reached: maximum allowed material temperature,

maximum mass-flow, and flame blow off. The operating diagram presented in Figure 7 could then be derived. The propane burner actually has two sets of injectors (central and peripheral), which can be used separately or in combination, which leads to two diagrams. When the propane burner is not used, the compressed air supply can still feed the core flow with a total temperature of up to about 430 K, but this temperature is then equal to the one of the by-pass flow.

Figure 6: Internal noise produced by the flow in the nozzle rig, before and after improvement

Figure 7: Operational range of the propane burner in CEPRA 19 core flow

V. Boundary Layer Control System

A. Reason to reduce boundary layer thickness

The boundary layer that develops in flight on the cowl of a classical under-wing engine is very thin (of the order of 2% of the nozzle diameter). In comparison the boundary layer that develops on the SMT2 nozzle rig is about $\delta_{0.99} = 50$ mm thick, i.e. about 25% of a typical nozzle diameter. This boundary layer further develops on the model nozzle to reach about 65 mm at the nozzle exhaust, i.e. about 15 times too thick. This is due to the lower Reynolds number of the wind tunnel test, and to the length of rig upstream of the model where the boundary layer can develop, as can be guessed from Figure 4.

B. Suction system and its efficiency

The Boundary Layer Control System (BLCS) consists in removing by suction part of the boundary layer that develops along the nozzle rig. The air is aspirated through a perforated surface covered with a very thin wire mesh, similar to the BLS system described in [14]. Up to 1.1 kg/s of air can be aspirated and evacuated to the outside, using new piping inside the SMT2 rig nozzle, and a 22 kW pump in the facility basement. To maximize the effect, the suction area is located immediately upstream of the rig/nozzle interface, on top of the acoustic spacer (see Figure 5).

The effect of the suction on the boundary layer velocity profile can be examined in Figure 8, where two suction configurations are investigated. In the “full circumference” configuration, suction is distributed over the entire periphery of the rig. In the “1/3 circumference” configuration, the suction effect is concentrated on an area three times smaller, on the side of the engine that is facing the wing. The BLCS is efficient in reducing the thickness $\delta_{0.90}$ of the boundary layer (edge of boundary layer located at 90% of the external velocity) from about 30 mm down to about 15 mm in “full circumference” configuration or even 3 mm in “1/3 circumference” configuration, which corresponds to about 30%, 15% and 3% of a typical nozzle radius of 100 mm.

Figure 8: Boundary layer profile at the downstream end of the nozzle rig, at 90 m/s wind velocity and maximum possible BLCS mass-flow

Figure 9: Background noise spectrum of the wind-tunnel, at 90 m/s wind velocity and maximum possible BLCS mass-flow

Figure 10: Boundary layer thickness at the downstream end of the nozzle rig for the full circumference configuration, as a function of suction thickness parameter. Dashed vertical lines correspond to maximum possible suction thickness for different tunnel velocities.

The residual thickness of the boundary layer immediately downstream of the suction was correlated with a “suction thickness” parameter $\frac{Q_{BLCS}}{\rho_0 V_0 C}$, see Figure 10. This parameter represents the thickness of a layer of external flow around the rig circumference C , in which circulates a mass flow equal to Q_{BLCS} , at a velocity V_0 . The conventional boundary layer thickness $\delta_{0.99}$ was not regarded as the most pertinent criterion here, firstly because it is subject to considerable scatter from one rake to another (see Figure 10), and secondly because it says nothing about how “full” the boundary layer profile is. Other measures of thickness, such as $\delta_{0.90}$ or the displacement thickness δ_1 , are more informative about the BLCS efficiency.

From this correlation, the mass-flow required to control the boundary layer thickness increases proportionally to V_0 . Moreover, at large wind-tunnel velocity V_0 , the static pressure in the anechoic chamber falls below atmospheric pressure. The pump must overcome this additional pressure drop to generate the suction mass-flow, and the maximum mass-flow falls from 1.1 kg/s at $V_0 \approx 0$ to 0.9 kg/s at $V_0 \approx 100$ m/s. The combination of these two effects explains why the minimum achievable thickness gets larger with increasing wind-tunnel velocity.

It is tempting to increase the power of the suction pump, in order to increase the mass-flow to overcome these limitations. However, since required power grows roughly with the 3rd power of the mass-flow, significant increase in mass-flow quickly leads to considerable power requirements. A more serious problem would be the increased noise generated by the suction system.

Finally, the Figure 9 compares the tunnel background noise (with 2 m diameter convergent and nozzle rig installed, as in Figure 3a) with and without the BLCs being operated. Some suction noise exists in the mid/high frequency band (above 20 kHz) which raises the background noise by 5 to 10 dB, up to a level that is still judged acceptable for jet noise investigations.

VI. Wind-tunnel test of a high-BPR nozzle

A. Presentation of the test

All the above described improvements were used in the recent test of a dual-stream high-BPR (~11) engine nozzle, as shown in Figure 11. The test was heavily instrumented (50 far-field microphones, 2 antennas of 131 and 105 microphones, numerous steady and unsteady pressure sensors on the wing model), for a total of more than 300 channels acquired at about 262 kHz. The effect of different parameters was investigated during this test campaign, namely flight stream velocity, jet operating conditions, nozzle outer boundary layer thickness and under-wing installation effect, including flap angle deflection, axial and radial nozzle position versus wing, and pylon effect. Regarding room and test confidentiality, only a limited set of results is presented in this section, to illustrate the kind of analysis and physical insights brought by the test, and the benefits of wind-tunnel improvements.

Figure 11: Nozzle and wing models mounted in CEPR19

The array processing methods developed by ONERA are derived from the well-known DAMAS and DAMAS-C microphone array techniques, see Ref. [26][27]. Whatever the methodology, the task consists in finding the distribution of noise sources that best reproduces the measurements, in particular the microphone cross-spectral matrix. Considering the directive acoustic pattern radiated by the jet, a technique based on correlated source terms is also applied. The corresponding DAMAS-C algorithm [28] attempts to restore cross-spectra between source points. Due to the number of variables to restore, the problem is ill-posed. In order to control the deconvolution process, a Tikhonov's regularization technique is introduced, making use of basic physical properties concerning the searched solution. For instance, jet noise source cross-spectra should vanish when the distance between sources is larger than several jet diameters. The source cross-spectra obtained through the DAMAS-C processing are used to re-propagate sound from selected area to the far field. Acoustics sources localization techniques are interesting to breakdown the noise between different sources, and assess their relative contribution to the overall radiated noise.

B. Engine integration effect

One of the main purposes of such test is to study the installation effect on the radiated jet noise especially for close-coupled configuration. As an example, the Figure 13 shows the 1D distribution of noise sources along the jet axis and as a function of frequency, as obtained from the acoustic antenna using DAMASC processing. It compares the isolated nozzle configuration (left) with the installed configuration (right), when the nozzle is located close to the

wing. The sources pattern is dramatically modified because a strong interaction exists between the jet and the flap trailing edge. This interaction generates a sound that is by far larger than the isolated jet noise, especially at low frequency.

Figure 12: 1D acoustic source map showing the effect of the engine integration

The Figure 13 presents 2D noise source maps, but considering uncorrelated monopoles, as obtained from the acoustic antenna using DAMAS processing. The map is plotted for the frequency corresponding to the higher level of the jet/flap interaction noise. This allows investigating the extent along the span of this interaction noise, and to confirm it is located on the flap trailing edge.

Figure 13: 2D acoustic source map showing the effect of the engine integration

C. Influence of the jet operating condition

The instrumentation of the test allows in-depth investigations of the noise being generated, both in terms of spectral distribution and in terms of spatial distribution. The Figure 14 displays the 1D distribution of noise sources along the jet axis and as a function of frequency, at a flight velocity of 90 m/s and for increasing jet velocity. At low jet velocity, sources located at the nozzle exit dominate the noise spectrum. Some of these sources are produced by the

jet, mostly at higher frequencies. Some others, mostly at low frequency, are produced by the rig noise (section III). At higher jet velocities, classical strong jet mixing noise is located near 8 mixed diameters downstream of the nozzle exit.

Figure 14: 1D acoustic source map showing the effect of the jet operating condition

a. sources near nozzle exit, normalized with a 5th power law

b. sources in jet mixing region, normalized with a 8th power law

Figure 15: Normalized spectra reconstructed from the DAMASC 1D acoustic source map of Figure 14

In a second step, the spectra relative to two different source regions were calculated: sources near nozzle exit (dotted line in Figure 14) and the large region corresponding to mixing jet noise sources (dashed line in Figure 14). The spectra reconstructed from these two areas were normalized according to two different velocity laws:

- a 8th power law of the velocity difference between the mixed jet and the flight stream (Figure 15a), corresponding to jet noise evolution law;
- and a 5th power law of the mixed velocity (Figure 15b) more adapted to airframe noise evolution.

It can be observed in Figure 15, that the spectra corresponding to the mixing jet noise sources are quite well collapsed with the 8th power law, whereas the spectra corresponding to the nozzle exit source region are properly fitted with a 5th power law of the mixed velocity, at least in the low to medium frequency range. These results suggest that some sources in the nozzle exit region are due to rig noise, which means that the model size was too large to properly investigate noise at low jet velocity.

D. Influence of the external boundary layer thickness on the nozzle

As illustrated in section V, the BLCS enables to vary the thickness of the outer boundary layer on the nozzle. Using different mass-flow rates for the suction, tests were conducted in order to study the corresponding effect on the far field radiated noise, both in isolated and installed nozzle configurations. Results are presented here for the “full-circumference” suction configuration.

Figure 16: Far-field noise level for different BLCS mass-flows, as a function of the thickness of the outer boundary layer (forward arc 60°)

Figure 17: Effect of BLCS (at maximum mass-flow) on noise spectrum on far-field microphone (forward arc 60°)

Decreasing the boundary layer thickness causes a continuous decrease of the overall radiated noise. A decrease of 1 to 2 dB is observed, see Figure 16. A similar trend was previously observed in isolated configuration [15], and was attributed to a shielding effect of the boundary layer between jet flow and flight stream. This noise reduction is distributed over the whole spectrum as can be observed in Figure 17, and over most of the jet volume from source localization map (not shown). In installed configuration, the dominant noise sources are located at the flap trailing edge (see section VI.B). Here again, this jet/flap interaction noise is reduced when the outer boundary layer is made thinner, without changing the spectrum shape or the localization map.

Therefore, the BLCS is a new interesting feature of the SMT2 nozzle rig, to better replicate installed jet noise in the wind tunnel.

VII. Conclusion

In order to meet requirements for the test of jet engine of ever increasing by-pass-ratio, several improvements were brought to the CEPRA 19 wind-tunnel in the past few years: reduction of the tunnel background noise, reduction of the rig noise, identification of the burner operating range and installation of a boundary layer control system. These improvements were reviewed in this paper. Some results from a recent test of a high-BPR engine were reported to illustrate of the in-depth analysis made possible by this aeroacoustic facility, regarding jet noise in both isolated and installed configuration.

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