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Experimental Characterization of the Sound Power Radiated by Impinging Supersonic Jets

Jean Varnier* and Wilfrid Raguenet†
ONERA, 92322 Châtillon Cedex, France

The MARTEL test rig of Centre National d'Etudes Spatiales, located in Poitiers, France, is designed to study the noise of highly supersonic hot jets under conditions approaching those of a launch vehicle at liftoff. The nonanechoic character of the site (concrete ground, large plate representing the launch pad) requires a specific measurement device in order to calculate the sound power radiated by the jets. The integration process defined by ONERA is discussed and is tested using a freejet noise model derived from the work of NASA, which has been extended to the jet-plate interaction by assuming that the sound power radiated by the jet remains unchanged in this case. First results concerning jets of various velocities seem to confirm the preceding hypothesis and the reliability of the method used.

Nomenclature

D	=	nozzle-exit diameter, m
D_x	=	jet diameter, m
f	=	frequency, Hz
h	=	plate-to-nozzle distance
I_x	=	acoustic intensity vector, W/m^2
M_x	=	Mach number
m_x	=	mass flow, kg/s
P_x	=	static pressure, bar
R	=	radius of measurement, m
r	=	constant of gas, J/kg · K
s, S	=	sound sources
s_x	=	elementary surface
T_x	=	static temperature, K
V_x	=	velocity, m/s
Wa	=	acoustic power, W
Wm	=	mechanical power, W
γ_x	=	ratio of gas specific heats
η	=	acoustic efficiency Wa/Wm
Σ	=	nozzle area ratio (exit area/throat area)
(Σ)	=	integration surface

Subscripts

e	=	jet exhaust data
i	=	chamber stagnation conditions
j	=	fully expanded jet data
k	=	discrete data
x	=	small index

I. Introduction

THE sound power radiated by highly supersonic hot jets interacting with the ground has been studied in the context of the launch vehicles at liftoff[1,2] and of the vertical takeoff aircraft.[3,4] Other studies have been carried out using subsonic or weakly supersonic cold jets[5–7]: in these studies it is shown that the interaction of a jet with a deflector causes a sizeable increase of the measured sound-pressure levels, related to the wall-pressure fluctuations in the jet impingement area[5] and to the ground-to-nozzle feedback phenomena,[6,7] which appear in some configurations. In contrast, in the case of rocket engine jets impinging on deflectors of various shapes, a decrease of the radiated sound power is ascertained, more particularly for short interaction distances.[1] A model developed by Sutherland and Brown[3] for predicting the sound environment of vertical takeoff and landing aircraft takes into account the wall jet noise and the reflected jet noise to the exclusion of other interaction effects, which are only suggested. In fact, the full-scale noise investigations of Harrier aircraft carried out by Soderman[4] show much lower sound-pressure level (SPL) than predicted by this method. Note however that a "ground amplification" in SPL is found near the landing zone (13 m), but this amplification is not clear farther away (50 m), where the presumed ground effect varies generally between -10 and $+5$ dB according to the ground-to-nozzle distance. Besides, no feedback effects are found. As indicated by Krothapalli et al.,[8] in high-temperature supersonic jets the broadband mixing noise levels are high enough to disguise the discrete tones, which contribution to the overall (OA) SPL is minimal. A test program carried out by ONERA with a weakly supersonic hot jet impinging on a large plate has shown that the sound power integrated in far field remained more or less constant when the plate-to-nozzle distance varied.[9] This result can be related to the study made by Powell, which demonstrates the passive role of a plane rigid surface in the presence of a noise-generating flow.[10] In a recent study a semi-empirical method has been developed on experimental bases for predicting the sound environment of a launcher at liftoff.[11,12] Based on this model, calculations concerning theoretical jets (Koudriavtsev, V. V., personal communication, June 2000) show that the jet-plate interaction effects are dependent on the jet exhaust parameters (see Appendix). In particular, the strong sound power level (PWL) increase ascertained with a cold jet for some interaction distances disappears with very hot jets of same Mach number. Thus, this study seems able to explain and to reconcile the contradictory results concerning this topic found in the literature. However, some uncertainties seem to be partly related to the process used for estimating the radiated sound power from the measured SPLs. For instance, when the observations are made using a very small number of fixed microphones,[7,8] the increases in OASPL, which are given often around 10 dB, suggest to the reader a similar overall (OA) PWL increase, which is very uncertain. In another study[5] the sound power of the freejet cannot be directly calculated, which gives a deceptive idea of the sound power increase in the interaction cases (see Appendix). Generally, it is admitted that the jet-plate interaction noise is maximum when the plate is located in the vicinity of the jet core tip and that a very short interaction distance causes a damping of the noise levels at the lowest frequencies. But, in fact, as suggested by the complete review of Rajakuperan,[13] one does not find in the literature a study giving precise and exhaustive results on the sound power radiated

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*Research Engineer, Département Simulation Numérique des Ecoulements et Aéroacoustique, BP 72.

†Test Engineer, BP 72; currently Test Engineer, PSA Peugeot-Citroën, DTA/DO/Physique, 18, rue des Fauvelles, 92250 La-Garenne-Colombes, France.

by an impinging jet. The purpose of the present paper is to partly fill this gap in the case of highly supersonic hot jets similar to those of the rocket engines.

The present study of the acoustic effects of highly supersonic hot jets impinging on a large plate was conducted in the MARTEL test rig of Centre National d'Etudes Spatiales (CNES). This test rig reproduces in a simplified manner the environment of a launch vehicle at liftoff. In a first step we describe the research conducted to define the operational procedure for calculating the sound power radiated by a jet interacting with a normal plate. This procedure is discussed according to the criteria of the International Standards concerning the PWL calculation methods[14–16] and is numerically tested in order to estimate the calculation biases. The freejet noise model used derives from the NASA's work[2,17] and has been extended to the jet-plate interaction case by ONERA.[18] Then, experimental results concerning jets which velocity varies between 1200 and 1800 m/s in the presence of a normal plate at various interaction distances are presented. The consistency of these results seems to confirm the reliability of the proposed PWL integration method. It appears that the sound power radiated in the case where there is a jet-plate interaction remains practically constant and very close to that of the freejet. This result, which does not seem to be precisely mentioned in the literature, confirms the findings of a study made previously[9] and the basic hypothesis of the jet-plate interaction model, which is the apparent conservation of the sound power. This hypothesis is implicit in earlier prediction methods concerning deflected or impinging jets.[2,3] In contrast, other studies indicate a decrease[1] or a small increase[11] in the sound power radiated by impinging rocket engine jets.

II. Experimental Context

In the framework of the research and technology program supported by CNES, ONERA participated in designing and developing the MARTEL test rig located in Centre d'Etudes Aérodynamiques et Thermiques of Poitiers. This facility includes a nozzle vertically suspended 3 m over the ground and supplied with an air–hydrogen combustion. The convergent–divergent nozzle in question has an exit diameter D of 6 cm. A metal nozzle body of $4D$ in diameter and more than $30D$ in height represents the wall of a launch vehicle (Fig. 1). The velocity of the fully expanded jet can reach 1800 m/s in practice. Four jets called I, II, III, and IV′ of different velocities have been tested. The aerodynamic data of Table 1 come from measurements or computation and have an uncertainty of about 5%. The Mach number of the jets is similar to those of common solid-propellant rocket engines ($M_e \approx 3$). The ground-to-nozzle distance is equivalent to $50D$, which is assumed sufficient for freejet conditions. (There are no free-field conditions because of the acoustic reflections off the ground.) A large metal disk, the radius of which is $20D$, can be interposed in the jet stream to represent the launchpad at varied launch vehicle altitudes. The central piece of this disk can be open to represent a flue entry. The test hall is partially open (no wall under the nozzle plane). Walls over the nozzle plane, pillars, and ceiling are covered by fiberglass plates. For practical reasons, it was not possible to install an acoustical treatment on the concrete ground: thus, the sound power radiated by the jet must be determined in a nonanechoic environment.

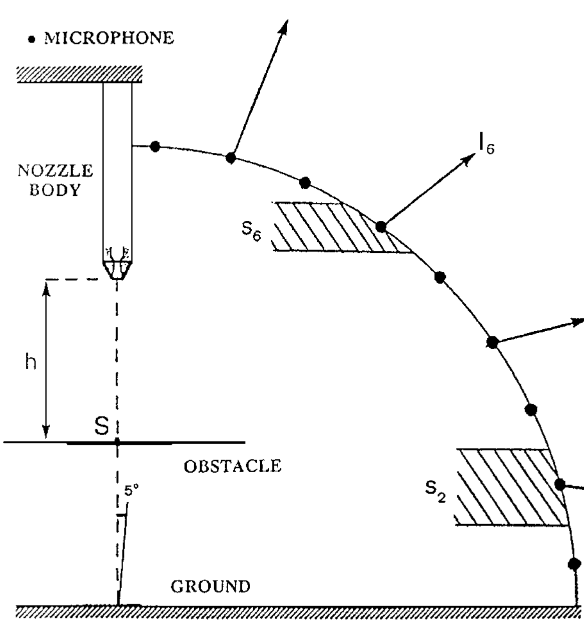

Fig. 1 MARTEL test rig: dome-shaped arrangement of the microphones and sound power integration method. S = resulting source, I_k = sound intensity vector, and s_k = elementary surface.

Table 1 Aerodynamic characteristics of the jets (air + hydrogen combustion)

Symbol	Jet I	Jet II	Jet III	Jet IV′	Unit
P_i	30	30	30	30	bar
T_i	2060	1700	1400	1080	K
γ_i	1.260	1.278	1.295	1.320	——
r	325	316	309	302	J/kg · K
Σ	6	6	6	6	——
m_e	1.115	1.260	1.435	1.480	kg/s
D_e	6	6	6	6	cm
P_e	0.610	0.580	0.550	0.465	Pa
V_e	1910	1700	1480	1290	m/s
T_e	875	675	500	370	K
M_e	3.10	3.15	3.21	3.27	——
D_j	4.90	4.85	4.80	4.60	cm
P_j	1.013	1.013	1.013	1.013	bar
V_j	1800	1600	1400	1200	m/s
T_j	950	755	580	460	K
M_j	2.81	2.82	2.83	2.77	——

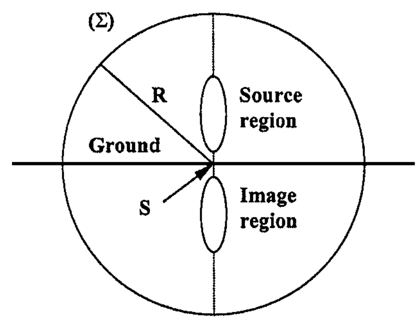

Fig. 2 Sound power integration principle using an enveloping surface over the ground.

III. Sound Power Calculation Method

The sound power radiated by a jet is generally calculated from SPL measurements made in the far field. In this case, the sound sources are considered to be concentrated at the nozzle exit ("resulting source"). The sound power is integrated on a spherical or hemispherical measurement surface centered at the nozzle, assuming that the sound intensity vectors are perpendicular to this surface. In the presence of a reflecting plane perpendicular to the jet axis, it is logical to take the resulting source S on this plane between the source region and its image (Fig. 2). Note that S is also the center of the wall jet, when existing. In the ideal case the integration surface (Σ) is centered at S. But generally, S is off-centered, and the direction of the sound intensity vectors must be taken into account, more particularly when the radius R cannot be very large because of the constraints of the site. In Fig. 1 the dome-shaped arc of sensors generates a hemispherical surface of revolution surrounding the noise region. This integration surface is divided into elementary surfaces s_k. The resulting source S is taken as origin of the sound intensity vectors I_k, the modulus of which is given by the measured SPLs. The calculation of the sound power radiated through a given elementary surface takes into account the normal component of the corresponding sound intensity vector.

In fact, this method found independently by the authors appears to be a particular case of more general methods recommended by the International Organization for Standardization. These methods, divided into three grades of accuracy,[14–16] concern the determination of the PWL of noise sources from SPL measurements made on an enveloping surface. In the precision method[16] a hemispherical measurement surface is recommended. The criteria of accuracy concern the number of microphones, the calculation repetitiveness, the background noise level and the reverberated noise level. Of course, it is necessary to estimate here the uncertainty caused by the experimental conditions and by the calculation process.

As shown in Fig. 1, the basic measurement device adopted by ONERA consists of a circle arc of nine microphones of $70D$ radius centered on the ground. In fact, there are three additional microphones in the vicinity of the nozzle body and two symmetry witnesses located in the nozzle plane at different directions, knowing that the revolution symmetry of the sound field is a basis condition for the exactness of the PWL integration. The microphones ($\frac{1}{4}$-in.; Brüel and Kjaer) are used perpendicular to the measurement plane and without protection grid.[5] Experimental SPL values are obtained with an integration time of 4 s. This duration appears sufficient for having at the same point an uncertainty of the measured OASPL of ± 1 dB for several tests made with the same jet. (The differences between the witness microphones are also within ± 1 dB in OASPL.) Thus, the PWL integration result on the entire arc of measurement remains practically constant, knowing that a test is validated if the error on the target chamber stagnation conditions (P_i, T_i) is less than 5%.

The main criterion of a calculation method is the repetitiveness of the PWL integration, in terms of standard deviation. Figure 3 shows results of two tests made with jet III after one week. The standard deviation in third octave levels is here clearly within 1 dB, the shift in low frequencies being rather caused by the change of the plate-to-nozzle distance h.

The background noise in the test rig only concerns the lowest frequencies ($f \leq 1000$ Hz) because of the combustion noise transmitted by the nozzle body. However, the recorded SPL decreases quickly with the distance from the metal wall. Therefore, a small part of the integration surface is concerned, and the phenomenon cannot have an appreciable influence on the PWL integration result.

The reverberation times recorded in the hall vary between 0.1 and 0.2 s according to the frequency. Thus, the sound reverberation effects in the presence of a jet cannot be ignored but are difficult to evaluate because of the half-open character of the site. However, it is obvious that the reverberated noise level cannot be higher than the smallest measured SPL, which occurs near the nozzle body in freejet case ($h = 50D$ in Fig. 4). By assuming that this SPL is equal to the reverberated noise level, we obtain by difference at each measurement point the minimum SPL caused by the direct sound field and finally the minimum value of the sound power radiated by the jet (minimum PWL). On the other hand, the maximum value of the radiated sound power (maximum PWL) is given by the direct integration of the measured SPLs. In Table 2 the calculations are made for jet III in octave band levels, knowing that the minimum SPL does not occur always at the same place. The difference between the maximum and the minimum values of the sound power level

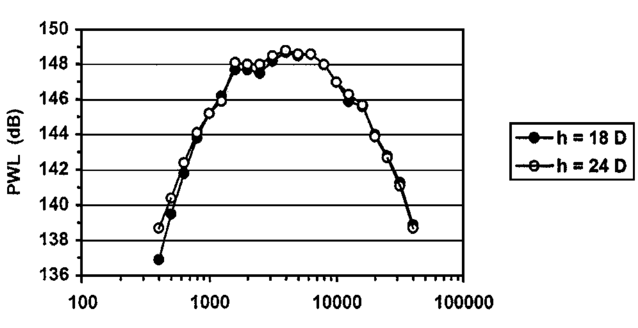

Fig. 3 Jet of 1400 m/s: integrated PWLs in third-octave bands for two nearby plate-to-nozzle distances.

Table 2 Jet III: calculation of the PWL uncertainty caused by the reverberated noise for $h = 50D$

f, kHz	Maximum PWL, dB	Minimum PWL, dB	Difference, dB
0.5	146.4	144.6	1.8
1	151.1	150.3	0.8
2	152.0	151.0	1.0
4	151.8	150.5	1.3
8	151.4	150.5	0.9
16	149.2	148.4	0.8
31.5	145.3	144.3	1.0
All	158.7	157.7	1.0

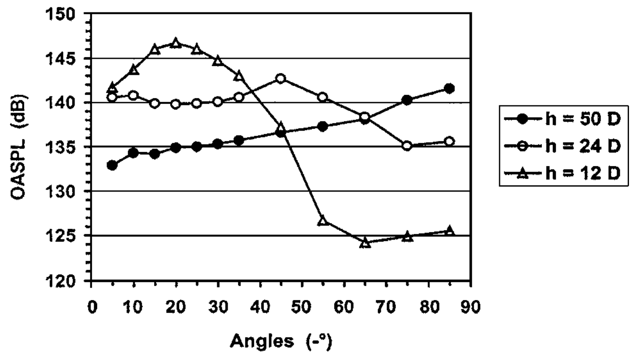

Fig. 4 Jet of 1400 m/s: OASPLs recorded on the measurement arc for several plate-to-nozzle distances. Angle 0 deg corresponds to the jet axis in the upstream direction.

gives the uncertainty range caused by the reverberated noise, which remains close to 1 dB in each frequency band except the lowest one. In OAPWL the uncertainty range found is equal to 0.8 dB for jets I and II, 1 dB for jet III, and 1.3 dB for jet IV′. Thus, the OAPWL can be estimated by taking maximum OAPWL minus 0.5 dB. In the presence of the plate, the influence of the reverberated noise seems to be unchanged, as suggested by the sound power integration results (see Sec. V).

Following the preceding study, the degree of accuracy related to the experimental conditions is at least the one of an engineering method[15] (1.5 dB in OAPWL). The strong point of the method is the repetitiveness of the integration results for given test conditions.

IV. Numerical Simulation

Before installing the measurement apparatus and operating the rig, ONERA conducted numerical simulations designed to test the theoretical accuracy that could be expected from the PWL calculation method considered for both a freejet and with an interposed plate. The purpose of the simulations was to estimate the biases caused by the calculation hypotheses shown in Fig. 1 and to the relative proximity of the sound source region and of the integration surface. (The optimum radius of the measurement arc taking into account constraints related to the site is $R = 70D$.)

The freejet noise model used is a semi-empirical model derived from the work of NASA,[2,17] which has been adapted to the simulation of the near sound field of the rocket engine jets tested by ONERA.[19] In the original model the main parameter is the jet core length, which is calculated from the jet exhaust Mach number. In fact, the supersonic length of the flow and the sound power peak location on the jet axis seem to be more precise references to relate the aerodynamic field and the acoustic field. For a jet of 1200 m/s tested in the MARTEL test rig, sound power peak and supersonic tip are located respectively at around 10–12D and 25–30D from the nozzle.[19] The sound power peak location given by the model used is in agreement with the experimental data. The corresponding source region extent is smaller than $40D$ and therefore smaller than the ground-to-nozzle distance.

The model was extended to the simulation of a semi-anechoic environment (presence of a reflecting plane) and of jet-normal plate interaction, assuming that the overall acoustic power remains unchanged in all cases. This assumption is based on experimental data obtained in an anechoic wind tunnel with a weakly supersonic hot jet impinging on obstacles of various shapes.[9] The main characteristics of this heated air jet were $D_e = 6$ cm, $P_e = 1.8$ bar, $T_e = 875$ K, $m_e = 1.125$ kg/s, $M_j = 1.4$, and $V_j = 780$ m/s.

The sound power radiated by the jet was integrated on a sphere of radius $100D$. In the case of the jet impinging on a large plate, the difference ascertained with the free jet OAPWL stayed in the range ± 1 dB except for a very short interaction distance (PWL loss of 2 dB for $h = 6D$). Therefore, the obstacle is considered in the model as a simple deflector, and the source region extent (freejet length over the plate plus wall jet radius) is assumed constant. The wall jet is divided into elementary jets, which sources s of the same nature as the free jet sources S radiate in a half-space (Fig. 5). The directivity of the sound sources of the impingement area has been empirically modified in order to improve the simulation of the SPLs recorded in the vicinity of the nozzle body, which are stronger than expected.[18] The Russian model described in the Appendix considers as dominant the sound sources of the impingement region and neglects the other sources of the wall jet.

In the particular case of the MARTEL test rig, there are in fact two reflecting planes: the ground and the plate. In practice, the ground is replaced by a symmetric arc of virtual sensors (Fig. 6). The SPL calculated for a virtual sensor that is not masked by the plate is added to the direct-field SPL calculated for the corresponding real sensor. The computation also takes into account the acoustic reflections off the plate, as well as the effects of the wall jet sources.

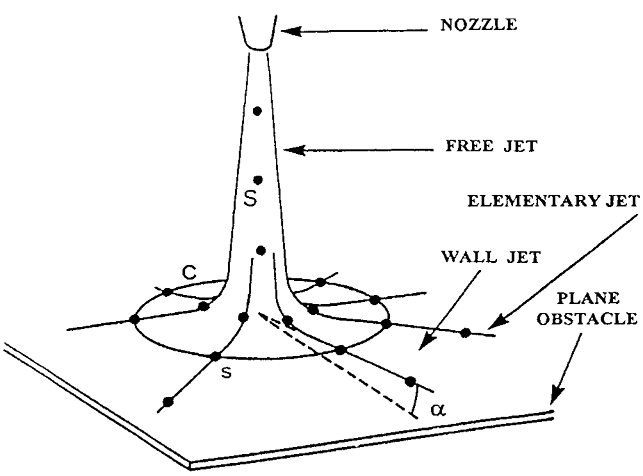

Fig. 5 Acoustic model of jet-plate interaction. The total sound power of sources *s* on a given circumference *C* is equal to the sound power of the corresponding freejet source *S*.

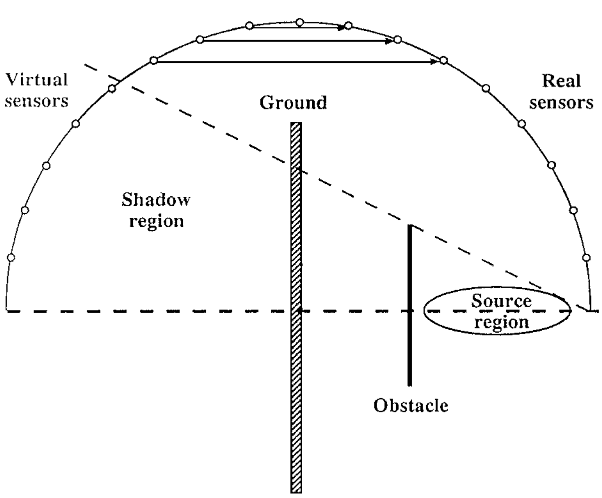

Fig. 6 SPL calculation principle taking into account the reflecting ground in the presence of the plate. (Here the ground is taken vertical by convenience.)

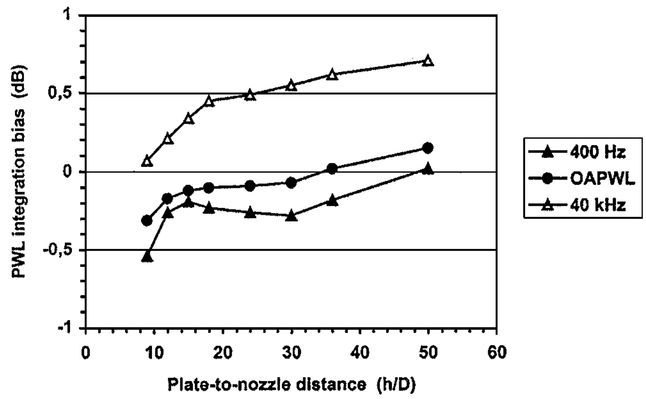

Fig. 7 Computed integration biases of the sound power in characteristic frequency bands.

The main advantage of simulation over experimental investigation is that known data can be compared exactly: for instance, the OASPLs computed at the reference points (sensor positions) are integrated to give the radiated overall sound power, using the method summarized in Fig. 1. This result can be compared to the sound power introduced in the computer code as input data, which allows one to check simultaneously the procedures of the jet noise model and the integration method accuracy. The same calculation can be made in octave bands or third-octave bands in order to estimate the influence of the space distribution of the sound sources: the high frequencies are indeed emitted preferentially in the neighborhood of the nozzle, and the lowest frequencies correspond to the maximum extent of the source region. This is why we give in Fig. 7 the calculation results in OAPWL as well as at the limits of the sound power spectrum (third-octave bands 400 Hz and 40 kHz), where the probable error of sound power integration is highest because of the relative proximity of the integration surface when the acoustic sources are off-centered.

The calculation is made for a 1400-m/s jet similar to jet III of Table 1, but the jet velocity has here a minor influence. In a first step the SPLs are calculated at the reference points given in Fig. 1 for plate-to-nozzle distances between $9D$ and $50D$ (ground). Then, the PWL resulting from integration of these computed SPLs is compared to the PWL allocated to the sound sources of the model in the frequency band (reference 0 dB in Fig. 7). We can make the following remarks:

1) The positions of the reflecting plane and of the sound source region according to the frequency have a minor influence on the results.

2) For all configurations except one, there is an uncertainty of 0.2 dB on simulation of the OAPWL.

3) For all configurations except over $f = 20$ kHz and $h = 30D$, there is an uncertainty of 0.5 dB on simulation of the third-octave band PWLs.

The word "uncertainty" designates here a calculation bias, which is known and can be possibly corrected.

Thus, it is established that the procedure used allows us to accurately calculate on the chosen integration surface the sound power that is emitted by a theoretical cluster of acoustic sources.

The jet noise model can be tested by comparing the measured and the computed SPLs at the measurement points. Figure 8 shows computation-measurement differences in octave bands in a jet-plate interaction case. (If the broken line runs through a microphone, the difference is equal to 0 dB at this point.). The OAPWL of the model has been adjusted in freejet configuration ($h = 50D$) to obtain at least in this case the same integration result with calculated and measured SPLs. The simulation of Fig. 8 and the other ones for various jet-plate interaction distances show that the jet noise model is accurate enough to consider as valid in reality the theoretical integration biases, which appear to be negligible.

In conclusion, the proposed PWL integration method does not introduce appreciable errors, which confirms the qualitative assessment given in Sec. III.

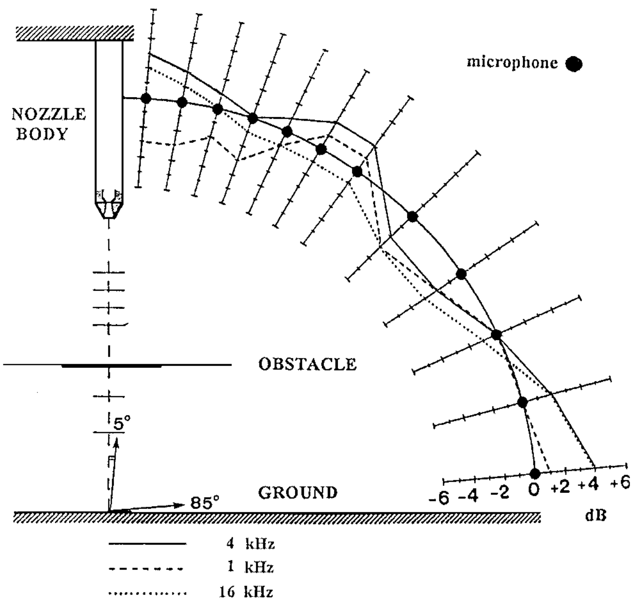

Fig. 8 Computation-measurement differences in octave-band SPLs for jet I of 1800 m/s. The plate-to-nozzle distance is equal to 24 D.

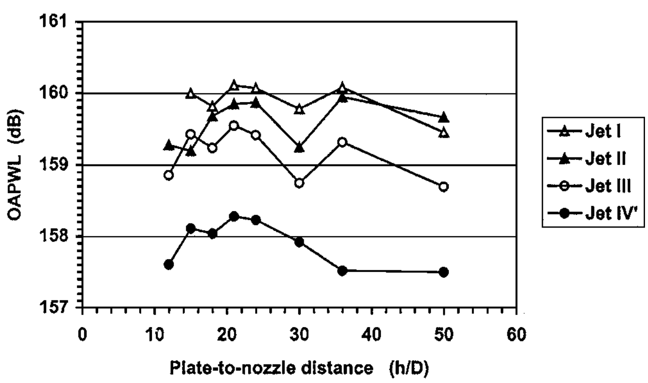

Fig. 9 Integrated OAPWLs of the four jets according to the plate-to-nozzle distance.

Table 3 Air–hydrogen jets: determination of acoustic efficiency

Data	Jet I	Jet II	Jet III	Jet IV′
OAPWL, dB	160.2	159.9	159.4	158.1
Wa, kW	10.5	9.8	8.7	6.5
Wm, kW	1890	1720	1500	1140
η, %	0.55	0.57	0.58	0.57

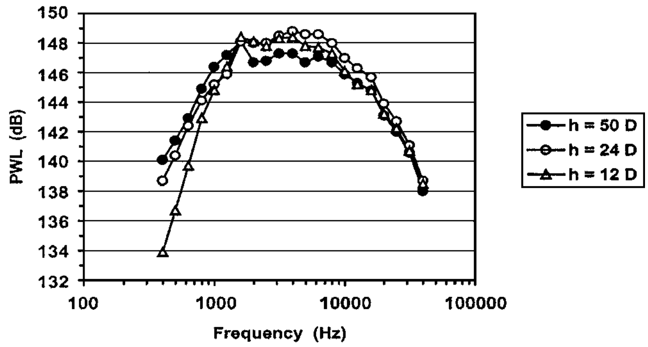

Fig. 10 Jet of 1400 m/s: third-octave band PWLs integrated for several plate-to-nozzle distances.

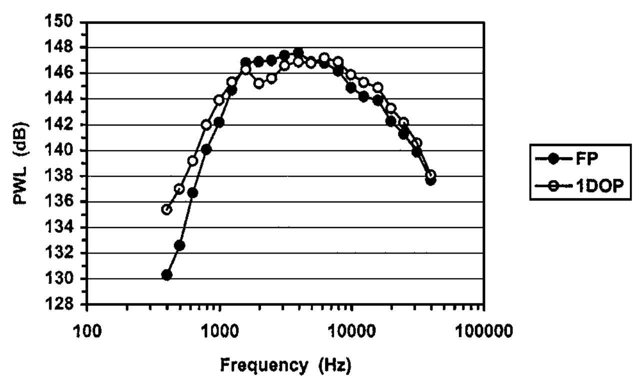

Fig. 11 Jet of 1400 m/s: third-octave band PWLs integrated in the presence of the full plate and of the 1 D open plate for a plate-to-nozzle distance of 9 D.

V. Experimental Results

The experiments made with the jets of Table 1 interacting with the full plate of radius $20D$ are summarized in Fig. 9. The integrated OAPWLs (reference 10^{-12} W) are deduced from the SPLs recorded with the microphones located on the measurement arc between 5 and 85 deg in steps of 10 deg (Fig. 1). It can be seen in Fig. 9 that the integration process gives very regular results for all jets and plate-to-nozzle distances and that the sound power radiated by a given jet remains within 1 dB.

However, we can note some anomalies. Thus, the OAPWLs of jets I and II are reversed for $h = 50D$ (freejet). The slight OAPWL increase noted at the medium interaction distances (20–25D) might be perhaps related to the interaction noise but does not seem to be very significant, knowing that the jet core length is in all cases smaller than $10D$. Because of these experimental uncertainties, we have chosen to estimate the sound power of each jet from the averaged OAPWL value taking into account all configurations from $h = 12D$ to $50D$ (Table 3). On the other hand, the mechanical power of each jet is calculated from the aerodynamic data of Table 1. The acoustic efficiency η is given by the ratio of the sound power *Wa* to the mechanical power *Wm*. It can be seen that the four jets, which have the same Mach number, also have the same acoustic efficiency.

In fact, we have shown in Sec. III that the bias in OAPWL as a result of the reverberated noise can be reasonably estimated at about 0.5 dB. Therefore, the real acoustic efficiency of the jets is probably closer to 0.5%, a value that is usually admitted for the rocket engine jets.[17]

Only jet III has been tested at $h = 9D$, with an integrated OAPWL of 157.7 dB: this result shows that the sound power reduction caused by the plate (damping at low frequencies) has a major influence despite the expected sound power increase from the proximity of the jet core tip. For larger interaction distances we know that the calculated OAPWL remains within 1 dB. In octave or third-octave bands (Fig. 10) the calculated PWLs remain in a range of 2 dB, except at the lowest frequencies, where a larger noise reduction is observed for a short interaction distance. These results seem to confirm the minor role played here by the interaction noise and by other experimental factors.

Otherwise, the directivity patterns in three configurations of the reflecting plane shown in Fig. 4 indicate that the variation of the OASPL measured upstream from the plate can reach 10 dB or more, as often indicated in the literature.[5,7,8] It is a bit surprising to know that the integrated sound power remains practically unchanged for these curves, which demonstrates the weakness of a sound power estimation directly deduced from some SPL measurements.

Other tests have been carried out with an open plate simulating a flue entry on a launchpad. The circular aperture of the plate has a diameter of $1D$ (Fig. 11) or $2D$ (Fig. 12) according to the plate-to-nozzle distance and the assumed spreading of the flow. To calculate the PWL in the open-plate configurations, we have used the same resulting source as in the full-plate case. The accuracy of the integration method is probably similar. We can note the damping of the SPLs at low frequencies in the presence of the full plate and the local peak that appears at 1600 Hz with the open plates. In fact, the same peak appears in the freejet case (Fig. 10), which

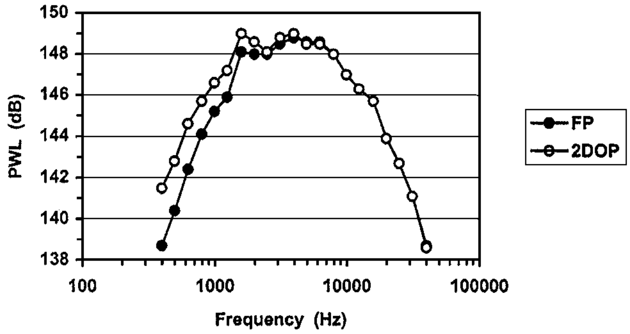

Fig. 12 Jet of 1400 m/s: third-octave band PWLs integrated in the presence of the full plate and of the 2 D open plate for a plate-to-nozzle distance of 24 D.

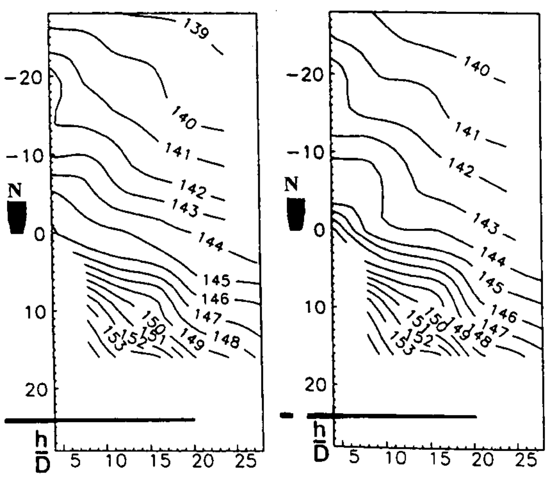

Fig. 13 Jet of 1200 m/s: compared SPL contours in dB (referenced to 2 × 10^{-5} Pa) with the full plate (left) and the 2 D open plate (right) for a jet-plate interaction distance of 24 D. N = nozzle body. The nozzle exit is located at (0, 0).

shows that the main part of the flow crosses the aperture. There are no impinging tones from the edge around the aperture (the PWL change concerns a wide band of frequencies), but a small increase of the OAPWL is noted.

Similar tests have been made with the heated air jet of Mach number 1.4: in contrast, a small loss in OAPWL was noted in the presence of the open plate. It is difficult to conclude, but we can remark that the OAPWL changes stay in both cases within ±1 dB. Thus, a small circular aperture centered on the jet axis does not give a significant variation of the sound power radiated by the jet.

Of course, the SPLs measured upstream from the plate and more particularly near to the nozzle body representing a launcher are reduced in the presence of an aperture, but this effect disappears very quickly when the interaction distance increases: for $h = 24D$ measurements made close to the plate and the jet axis using a microphone array show that the SPL contours are practically identical with or without the aperture 2D (Fig. 13).

VI. Conclusions

Tests have been carried out by ONERA in the MARTEL test rig of CNES with highly supersonic hot jets, in configurations reproducing more or less those of a launcher at liftoff. The nonanechoic character of the test rig raised the problem of the calculation of the sound power radiated by the jet. A method using a hemispherical surface of measurement over the reflecting ground has been designed, assuming that the sound power is concentrated in one point located on the ground or on the interposed plate. This method was successfully tested by numerical simulation, using a NASA's free-jet noise model extended to the case of jet-plate interaction. The model is based on the hypothesis of the sound power conservation, deduced from tests made earlier in an anechoic site with a weakly supersonic heated air jet. The sound field is correctly reproduced, and the sound power calculation biases might be neglected. Other analyses show that the uncertainty range related to the experimental conditions can be estimated at about 1 dB in OAPWL.

This estimation seems to be confirmed by the coherence and the repetitiveness of the results obtained with jets of various velocities. In the range of the tested plate-to-nozzle distances, the integrated OAPWL remains within 1 dB for a given jet. The same observation can be made with an open plate which small circular aperture represents a flue entry.

Finally, the apparent conservation of the sound power of the free-jet in impingement cases is here confirmed for highly supersonic hot jets. This observation, which is in agreement with more or less similar hypotheses or results found in the literature concerning the rocket engine jets, appears very interesting in the context of predicting the sound environment of launch vehicles at liftoff.

Appendix: Some Considerations Concerning the Jet-Normal Plate Interaction Noise

Koudriavtsev et al. Model

The model of impinging jet developed by TSNIIMASH (Korolev, Russia) is a semi-empirical model, where three distinct noise generation regions are taken into account: undisturbed jet over the plate, strong interaction region, and the plate as a reflector of jet acoustic radiation.[11,12] Acoustic radiation from jet, spreading along normal plate, is neglected because of very quick decay of this wall radial jet. The contributions of each region are calculated independently, from equations which coefficients have been empirically adjusted.

The acoustic efficiencies that are given in Fig. A1 according to the plate-to-nozzle distance have been calculated on the basis of this model for three theoretical jets of Mach number 3.0, which are perfectly expanded at the exhaust (Koudriavtsev, personal communication, June 2000). The nozzle exit D is equal to 6 cm. The main characteristics of these jets are as follows: for jet 1, $T_i = 300$ K, $\gamma = 1.4$, $r = 300$ J/kg · K, $T_e = 107$ K, $m_e = 5.66$ kg/s, $\rho_e = 3.15$ kg/m^3, and $V_e = 636$ m/s; for jet 2, $T_i = 2500$ K, $\gamma = 1.25$, $r = 300$ J/kg · K, $T_e = 1177$ K, $m_e = 1.63$ kg/s, $\rho_e = 0.29$ kg/m^3, and $V_e = 1992$ m/s; and for jet 3, $T_i = 3500$ K, $\gamma = 1.2$, $r = 300$ J/kg · K, $T_e = 1842$ K, $m_e = 0.828$ kg/s, $\rho_e = 0.12$ kg/m^3, and $V_e = 2443$ m/s.

Figure A1 shows a remarkable result: the peak of the radiated OAPWL corresponding to a plate location in the vicinity of the core tip of the cold jet ($h \approx 17D$) disappears almost completely with the hot jets, the core tips of which are located respectively at $h \approx 9D$ and $8D$ according to this model. Thus, parameters of jet exhaust (temperature, specific heat ratio, and so on) seem to play a major role in the jet-plate interaction noise generation.

We can note also the quick decrease of the OAPWL for short interaction distances.

Preisser and Block Experiments

The study of Preisser and Block[5] concerns subsonic cold air jets, the Mach number of which are included between 0.54 and 0.85. The nozzle exit diameter D is equal to 6.35 cm. The experiments were conducted in an anechoic room for plate-to-nozzle distances of 5, 7, and 10D. The measurement arc ($R = 3$ m) is centered on the plate, as indicated in Fig. A2. The jet of Mach number 0.7 has an exhaust

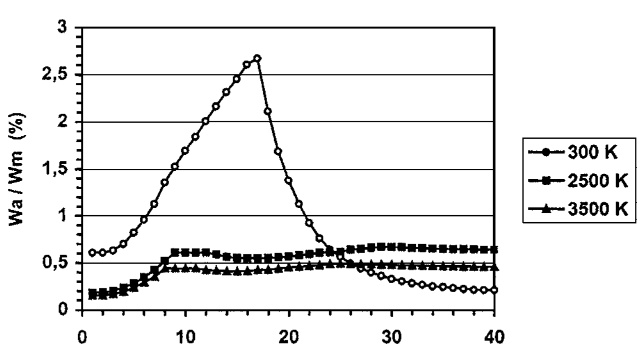

Fig. A1 Predicted acoustic efficiencies of three theoretical jets of different temperatures, according to the plate-to-nozzle distance (communicated by V. Koudriavtsev).

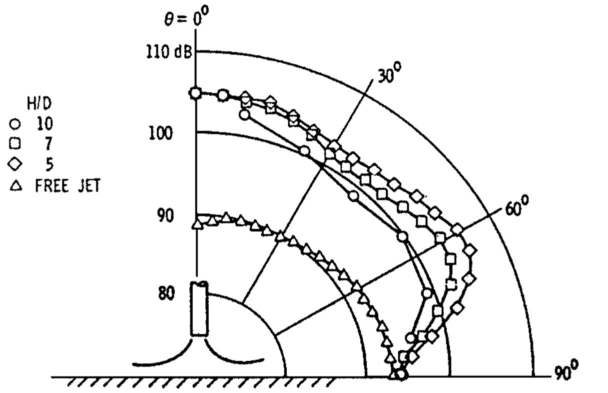

Fig. A2 Mach 0.7 air jet: directivity pattern of OASPL recorded over a large reflecting surface, except in the freejet configuration (anechoic room). Coming from Ref. 5.

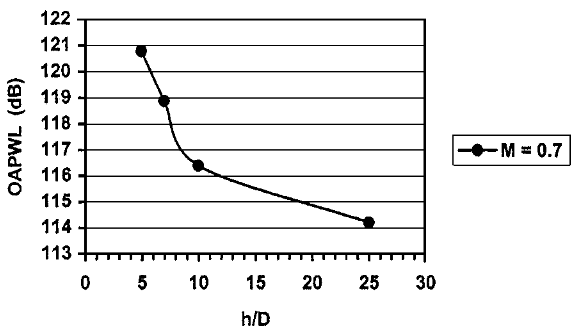

Fig. A3 Integrated sound power of the Mach 0.7 air jet from OASPLs indicated in Ref. 5.

velocity of around 215 m/s. For this jet the directivity patterns are given for the three positions of the plate and for the freejet without the plate (Fig. A2). Unfortunately, the center of the measurement arc is not mentioned in the latter case; the authors only indicate that the nozzle is suspended over the floor, which is acoustically treated using fiberglass edges. It is well known that typical directivity indices for a cold jet of such velocity have a difference of around 10 dB between the downstream and the upstream directions (0–180 deg). Thus, the freejet directivity of Fig. A2 seems to be only a half-directivity, which must be extrapolated in the downstream direction by applying, for instance, a SPL increase of 1 dB by step of 10 deg. Then, the SPL integration on the entire measurement sphere gives an OAPWL of a bout 114 dB. The acoustic efficiency corresponding to this sound power level ($\eta \approx 10^{-5}$) is very weak compared to the one of a supersonic jet.

The OAPWL can be integrated in the other cases by considering a resulting source located on the plate between the real and virtual source regions (see Fig. 2). The found values allow the establishment of the interpolated curve of Fig. A3. (Assuming that the maximum OAPWL is obtained at $h = 5D$ and that this location corresponds to the jet core tip, we know that the freejet conditions are reached at around $h = 25D$.) This curve seems to be consistent with the curve corresponding to a supersonic cold jet in Fig. A1, but a parametric study on the respective influences of the velocity and of the temperature appears to be necessary.

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P. J. Morris
Associate Editor