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## Use of semi-empirical models to predict jet noise radiated by unsuppressed and suppressed nozzles

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### ABSTRACT

*ONERA is involved in two R&T projects related to supersonic aircraft : a self-funded project called PINSON in which a realistic 10-passengers supersonic concept-plane is developed with an aim of reducing consumption, sonic boom and take-off noise and EU-Project SENECA aiming at providing insights on i) achievable noise levels during takeoff and landing and ii) global climate impact of civil supersonic aircraft. In both project, the semi-empirical models developed by Stone et al. [1, 2] have been identified as valuable tools for predicting jet noise, which is assumed to be the main contributor to supersonic aircraft noise at take-off. With an aim of extending the work initiated by Jaron et al. [3] in the SENECA framework, ONERA applied Stone et al.'s models to various jet configurations to better understand their domain of validity. Ultimately, the objective is to use those models during engine pre-sizing phase of PINSON project in which a low-noise nozzle equipped with chevrons will be optimized from a multidisciplinary point of view. The objectives of the paper are i) to present the results obtained by applying those models on the EXEJET configurations and ii) to discuss the ability of the latest version of the model to predict chevrons acoustic impact.*

### 1. INTRODUCTION

In recent years, supersonic air transport has seen renewed interest from the aeronautical industry. Almost 21 years after the last Concorde flight, the development of new commercial supersonic aircraft, pushed by growing needs for shorter trips, is today more likely than ever. Several major projects have been launched to prepare for the potential arrival of a second generation of civil supersonic aircraft by 2030. As examples, one can cite the european projects RUMBLE and SENECA or the unveiling by Lockheed Martin of its X-59 Quiet SuperSonic Technology which will be delivered to NASA for flight testing scheduled in 2024. Be that as it may, this comeback constitutes huge challenges in terms of reducing emissions and noise pollution.

In this context, ONERA launched a self-funded project called PINSON in which a realistic 10-passengers supersonic concept-plane will be developed with an aim of reducing consumption, sonic boom and take-off noise. One of the objectives of the project is to lower engines jet noise contribution, which is assumed to be the dominant source at take-off for supersonic aircraft, by i) taking it as a constraint during the engine cycle optimization and ii) designing a low-noise nozzle configuration equipped with chevrons. During the pre-sizing phase, the engines (including chevrons key parameters) and cycles will be optimized from a multidisciplinary point of view. ONERA is also involved in European project SENECA whose one of the objectives is to provide a

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reliable supersonic aircraft noise database to support the discussions on certification levels for this kind of aircraft. For both project, the semi-empirical models developed by Stone et al. [1, 2] have been identified as valuable tools for fast and reliable jet noise predictions. Those models allow the prediction of noise radiated by single or co-axial jets either in subsonic or supersonic conditions. A first version of the model published in 1983 [1] was optimized for nozzles characterized by relatively low bypass ratio  $BPR$  ( $< 5$ ). The latter was the subject of an extension in 1999 to handle inverted velocity profiles [4]. A second version of the model has been proposed in 2009 [2] to better take into account the physical mechanisms generating noise on nozzles showing higher  $BPR$ , up to  $BPR = 13 - 14$ . Today, those models, recognized for both their simplicity and precision, are incorporated in many system noise prediction tools [5–7], including ONERA's code called *CARMEN* [8]. Recently, Jaron et al. used those models to study the EPNL sensitivity to aircraft trajectory changes [3].

Despite the experience cumulated on the application of these models [3, 9–11], their respective domain of validity remains an open question. Consequently, it is essential to maintain a continuous effort to apply and evaluate them on varied jet noise databases. The work presented in this paper is part of a broader initiative to further assess and compare the validity range of both versions of the model. After a brief reminder of the main differences between the 1983 and 2009 versions, results obtained by applying those models to EXEJET unsuppressed nozzle [12] will be presented. This database offers the advantage of being complementary to that used by Stone et al. [2] for the validation of the 2009 version of their model. Indeed, the EXEJET nozzle has been tested under varied operating conditions, characterized by  $BPR$  in the range [4.5, 12]. Then, results obtained by applying the 2009 model to nozzles equipped with chevrons, namely i) the single jet nozzles tested by Bridges and Brown [13] and ii) the EXEJET suppressed configurations ( $9.5 < BPR < 10.5$ ), will be used to discuss the model ability to predict chevrons impact on a wide range of  $BPR$ .

## 2. OVERVIEW OF STONE ET AL. MODELS

Stone's models [1, 2] are able to predict sound pressure levels (SPL) radiated by single or co-axial jets either in subsonic or supersonic conditions. This acoustic field is computed by a log-sum of mixing noise and shock noise contributions. The main difference between those versions is the subset of source contributions that needs to be considered to build the "mixing" and "shock" noise components. One should notice that all those noise components can be computed from the nozzle characteristics, its operating points and the ambient conditions, whatever the formulation.

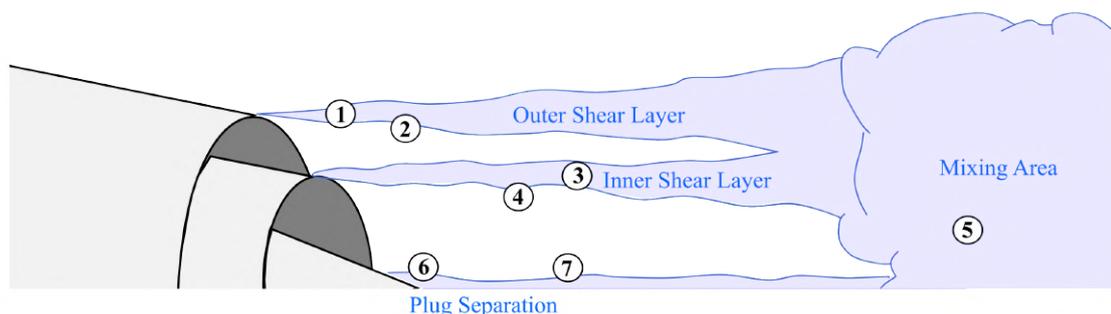


Figure 1: Scheme of a coaxial jets configuration equipped with a plug showing the subset of noise components used in the 2009 version of Stone's model. 1: Small scale mixing noise, 2: Outer stream shock noise, 3: Intermediate scale mixing noise, 4: Inner stream shock noise, 5: Large scale mixing noise, 6: Plug separation noise, 7: Plug/Downstream shock noise.

The Figure 1 depicts the subsets of components for the 2009 version, where the three shock related contributions are computed only in the presence of shocks. In the 1983 version, only the shock and mixing noise induced by both core and outer flows were modeled (analogous to

components 1 to 4 in Figure 1). An other major difference between the versions is the ability of 2009 formulation to model the impact of chevrons (on the inner and/or outer nozzles) on the large, intermediate and small scale mixing noise components. Those impacts can be directly computed from the  $BPR$  and suppressed-to-unsuppressed wetted perimeter ratio for the inner and outer streams, respectively  $PR_I$  and  $PR_O$ .

ONERA's implementation of those models have been validated through benchmarks [3]. More recently, they have been applied to an extended list of validation configurations. This list includes :

- The 4 nozzles tested by Goodykoontz et al. [14] at several primary nozzle exhaust velocity and temperature conditions, used by Stone et al. to validate the 1983 version [1]. Among those, there are 3 coplanar and 1 non-coplanar nozzles presenting secondary-to-primary ratios from 1.2 to 3.2 with a common primary nozzle of 10 cm.
- Various configurations used by Stone et al. for the validation of the 2009 model [2] taken from i) the GE/GRC Free Jet database, namely the GR/GRC External Plug Nozzle unsuppressed configurations at  $BPR$  5.0 and 13.3 in addition of 3 configurations with chevrons at  $BPR$  5.0 [15] (see Table 1 for more details) and ii) a simple jet conical nozzle tested by Plumbee [16] (test run number 22).

Table 1: List of configurations considered from the GE/GRC external plug test data. Configuration name and test point number refers directly to the nomenclature in Janardan et al. [15]

Index	Configuration	BPR	Point number	Chevrons
0	3BB	5.0	392	-
1	3IB	5.0	773	12 core chevrons
2	3IB	5.0	770	12 core chevrons
3	3IC	5.0	892	12 core chevrons + 24 Fan chevrons
4	7BB	13.3	1268	-

In Figure 2, SPL computed at two observation angles with ONERAS's 1983 version from the 3.2 area ratio coaxial coplanar nozzle at various primary jet velocities  $V_1$  are compared to Stone et al.'s [1]. Results are in very good agreement. In total, 16 nozzle-flow configurations from the 1983 paper have been reproduced. Figure 3 shows differences retrieved between ONERA's and Stone et al.'s 1983 version model in terms of OASPL maximum overall and root-mean-square error. For most of the configurations, the discrepancies are within  $[-1, +1]$  dB range compared to the reference despite some uncertainties remaining concerning the inputs used to run the calculations.

Spectra computed at two observation angles for the GE/GRC External Plug Nozzle with core chevrons (configuration 3IB at point number 773) with ONERA's 2009 version are compared to Stone et al.'s [2] in Figure 4. Predicted spectra for both mixing noise components and total noise are in very good agreement with the reference. Figure 5 summarizes the differences in terms of OASPL maximum overall and root-mean-square error between ONERA's and Stone et al.'s calculations of the configurations listed in Table 1. Due to a lack of geometric information concerning the plugs, plug related mixing noise components have not been computed. Despite the uncertainties on the geometric and flow inputs, results are in good agreement, especially in terms of maximum OASPL. One can notice that small scale components related errors are larger compared to the other contributions. This is certainly due to its sensitivity to inputs uncertainty. However, despite the

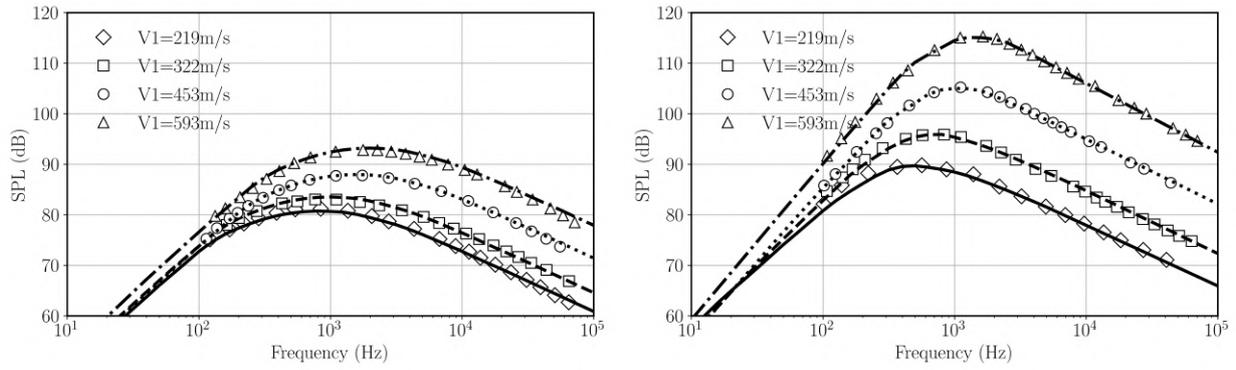


Figure 2: Comparisons between Stone et al. [1] (symbols) and ONERA's computations (lines) on the 3.2 area ratio coaxial coplanar nozzle with varying primary jet velocity  $V_1$  (constant secondary velocity  $V_2 = 216$  m/s and temperature  $T_2 = 280$  K). Sound pressure levels at  $45^\circ$  (on the left) and  $125^\circ$  (on the right).

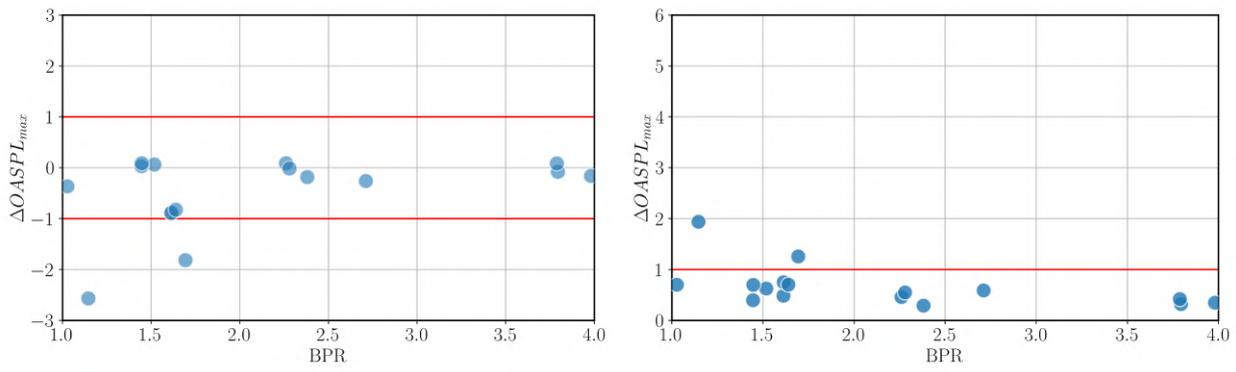


Figure 3: Differences between ONERA's and Stone et al.'s [1] computations of Goodykoontz configurations [14] using the 1983 model. Differences in terms of maximum OASPL (on the left) and root-mean-square error (on the right).

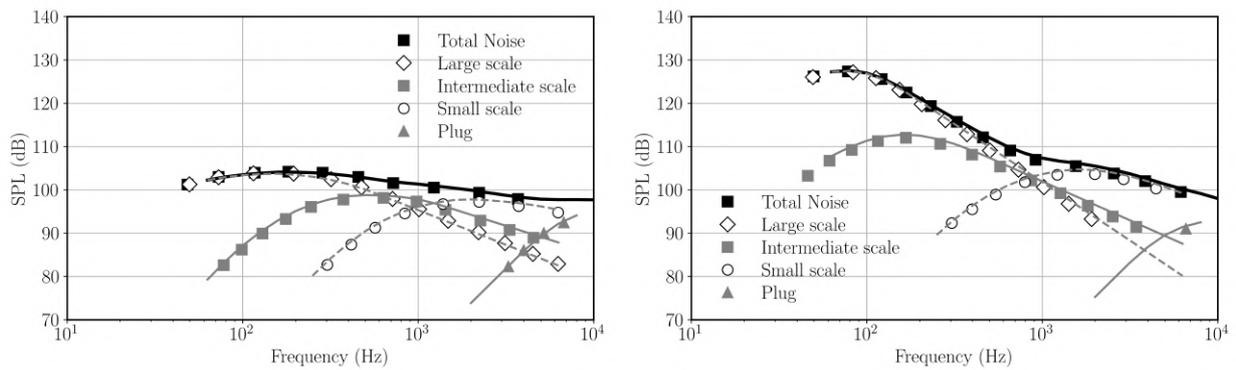


Figure 4: Comparison between Stone et al. [2] (symbols) and ONERA's (lines) computed spectra for GE/GRC External Plug Nozzle with Core Chevrons at  $BPR \approx 5$  and  $V_{mix}/c_{amb} = 1.047$  with flight Mach number  $M_f = 0$ . Sound pressure levels at  $60^\circ$  (on the left) and  $150^\circ$  (on the right).

uncertainties remaining on the inputs, the very good agreement between ONERA's computations and the references validates ONERA's implementation of both versions of the model.

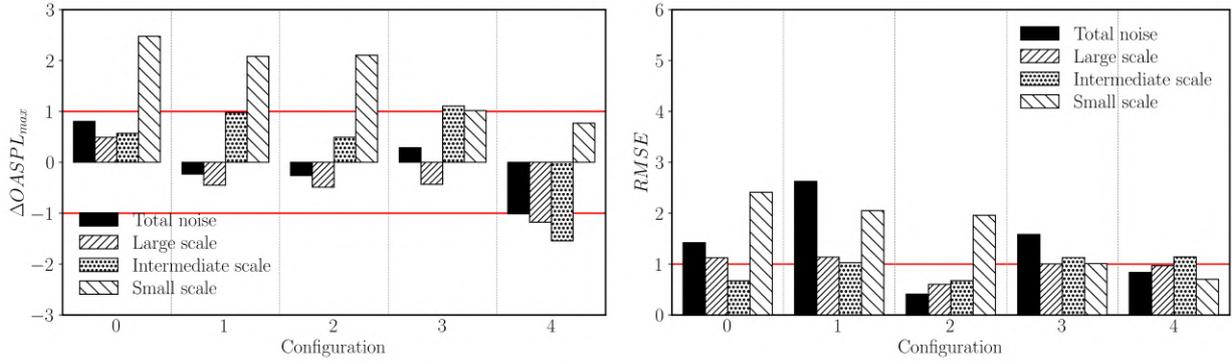


Figure 5: Differences between ONERA's and Stone et al.'s [2] computations with the 2009 version in terms of maximum OASPL and OASPL root-mean-square error for the configurations listed in Table 1.

### 3. APPLICATION ON EXEJET JET NOISE DATABASE

Despite the experience accumulated using those models, the number of flow and geometric variables impacting the predictions makes it still difficult today to clearly define their area of validity. In order to better understand and define their domain validity, ONERA has initiated an in-depth models assessment work by applying both versions of the model on all available in-house experimental jet noise data. The results obtained on EXEJET's unsuppressed nozzle configuration is detailed in this section. EXEJET was a French-funded *R&T* program [12, 17] concluded in 2013 involving 3 partners : Airbus, ONERA and Safran Aircraft Engines (formerly Snecma). Its objective was to improve the understanding, assess and reduce installed aircraft jet noise. In this framework, two nozzles configurations, one unsuppressed and one equipped with chevrons on inner and outer duct, have been designed by Safran Aircraft Engines. Both configurations include a cold fan flow, an external hot core flow and an external plug. The exhaust diameter is around 0.2 m. An experimental campaign was also held in ONERA's CEPRA19 anechoic facility. Despite being dedicated to installation effects, around 60 runs were achieved to measure isolated jet noise. Even if the nozzles' design operating point was characterized by a *BPR* of 9, a wide range of operating conditions were tested, with  $4.5 < BPR < 12$ . EXEJET's isolated operating conditions are depicted in Figure 6. They are compared to the data points used by Stone et al. [2] to validate the 2009 version of their model. EXEJET's data turn out to be complementary to Stone et al.'s.

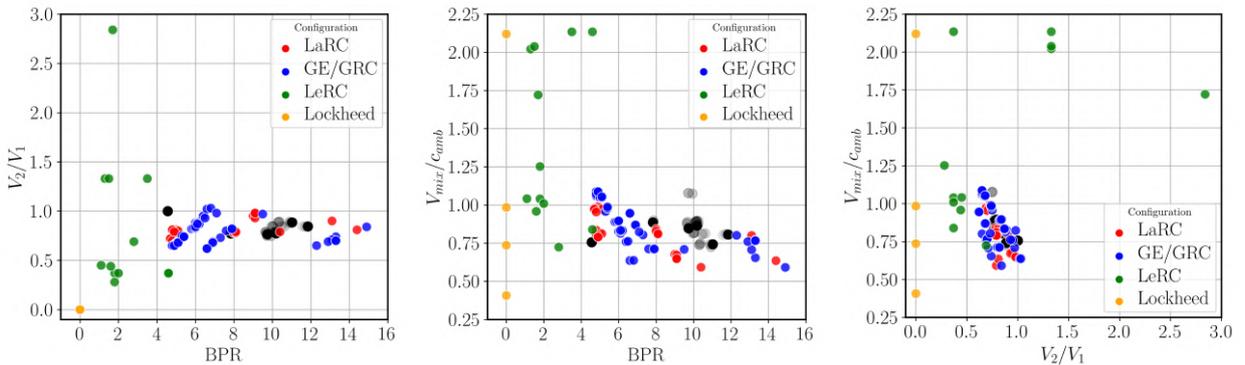


Figure 6: Configurations used by Stone et al. [2] to validate the 2009 model. Colors are used to provide insights on the data origin. Data in gray depicts EXEJET isolated configurations studied in the present work. Data in black describe a subset of EXEJET's data points for which spectra are plotted in this section.

In this section, the focus is put on the modeling of EXEJET 's unsuppressed configurations.

Table 2: Subset of operating conditions for which spectra are plotted in this section. Points are prescribed in terms of  $BPR$ , flight Mach number  $M_f$ , outer to inner flows velocity and total temperature ratio.

Run	BPR	$M_f$	$V_2/V_1$	$T_2/T_1$
61	4.6	0.0	1.00	1.0
80	7.8	0.0	0.77	0.49
66	9.7	0.0	0.77	0.41
28	11.0	0.26	0.89	0.43
92	11.8	0.26	0.84	0.39

Table 2 summarizes the subset of conditions for which SPL and directivities are plotted in Figure 7 and 8, depicting respectively comparisons with 1983 and 2009 versions of the model. For most of the configurations, the 1983 version overpredicts the SPL levels. For the highest  $BPR$ , it also fails to predict the "peak" frequency. On the opposite, results obtained with the 2009 model are in very good agreement with the experimental data. Below  $120^\circ$ , OASPL are predicted within 1 dB. Above  $120^\circ$ , the model tends to slightly overpredict the noise levels at peak frequency, mainly induced by the large scale component.

The microphones arc used during the experimental campaign was located at 6m for the secondary nozzle exhaust. In Stone et al.'s model, each noise source component is prescribed with its own source position depending on geometric and flow conditions. This overprediction at

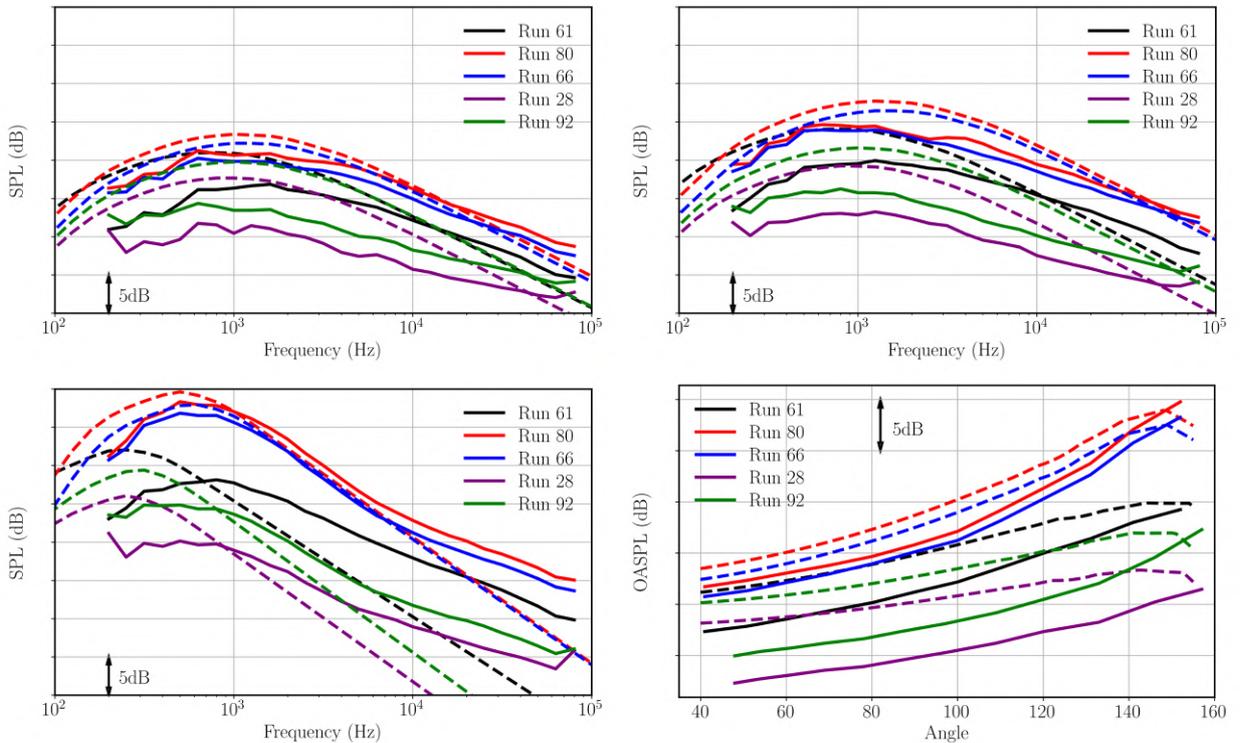


Figure 7: Comparisons between 1983 model predictions (dashed lines) and EXEJET experimental data (straight lines). On the top : SPL at  $51^\circ$  on the left and  $90^\circ$  on the right. On the bottom : SPL at  $141^\circ$  on the left and OASPL on the right.

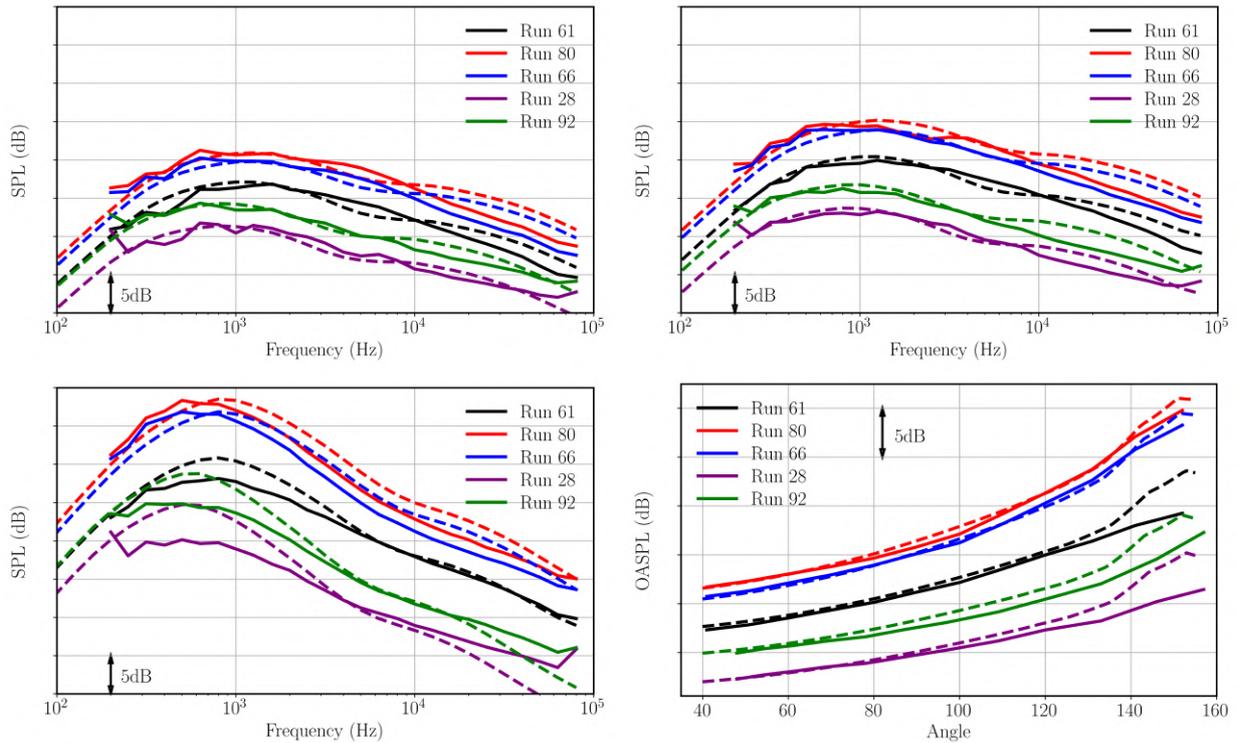


Figure 8: Comparisons between 2009 model predictions (dashed lines) and EXEJET experimental data (straight lines). On the top : SPL at  $51^\circ$  on the left and  $90^\circ$  on the right. On the bottom : SPL at  $141^\circ$  on the left and OASPL on the right.

large angles can be partly explained by the fact that the microphones located in this area are not in the acoustic Far Field in the sense of the model. The computations of each source component include a source to observer distance correction. This correction is plotted for observer angles of  $40^\circ$  and  $150^\circ$  in Figure 9. One can note that a microphone located at  $150^\circ$  and 6m is not located in the model Far Field.

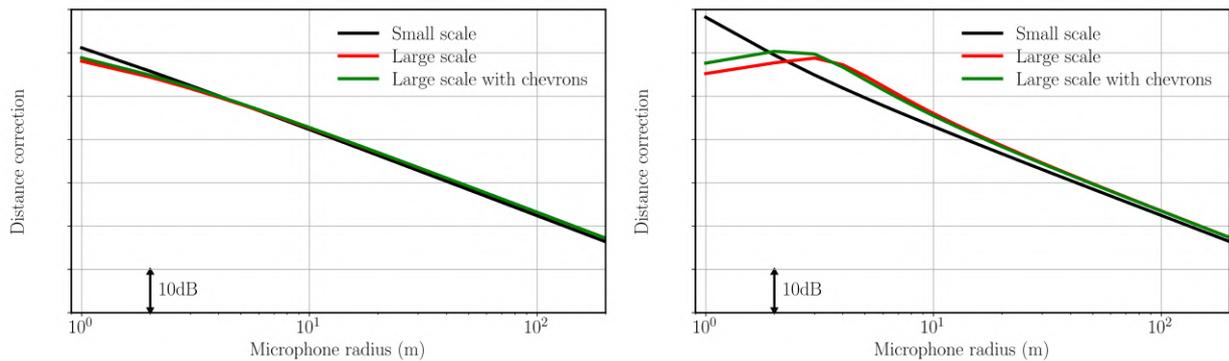


Figure 9: Source to observer distance correction used to compute large scale and small scale components on EXEJET configurations. Observer located at  $40^\circ$  on the left and  $150^\circ$  on the right.

Figure 10 shows a summary of the results obtained on the 60 experimental runs performed on the isolated EXEJET nozzles. Results are in very good agreement with the experimental data in terms of maximum OASPL and root mean square error, both being below 2dB for most of the unsuppressed configurations.

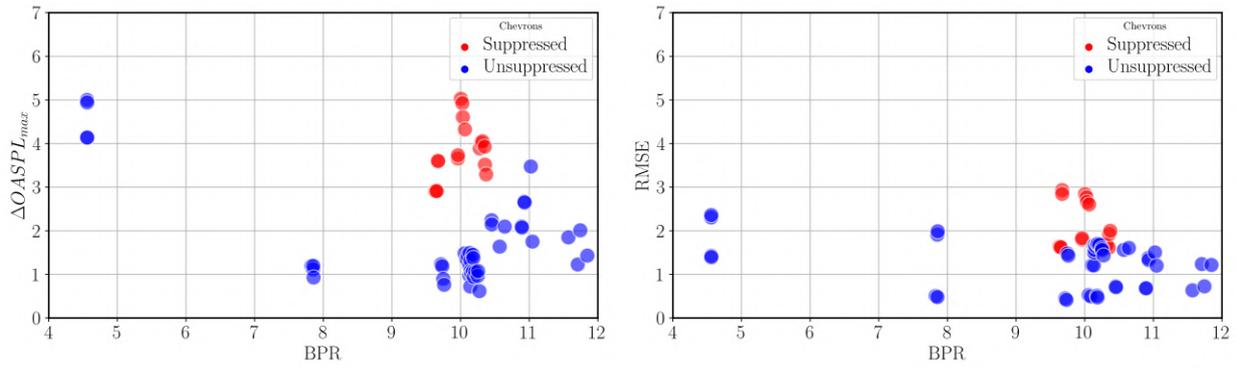


Figure 10: Differences between ONERA's computations with 2009 model and EXEJET isolated configurations prescribed in terms of maximum OASPL (on the left) and root mean square error (on the right).

#### 4. ON THE IMPORTANCE OF DOMAIN VALIDITY CHECK FOR SUPPRESSED CASES

Most of the suppressed configurations listed in Stone et al. [2] and used to validate the 2009 version lies in a relatively tight  $BPR$  range, between 4.8 and 7.1. EXEJET's database offers the possibility to assess the ability of the model to predict chevrons impact at larger  $BPR$ , in the range [9.5, 10.5]. As it can be seen in Figure 10, the prediction errors for the suppressed cases are globally larger when compared to the unsuppressed cases. SPL comparisons between unsuppressed and suppressed nozzles operating at the same flow conditions ( $BPR = 10.2$ ) are shown in Figure 11. One can note that the chevrons impact, resulting in noise suppression at low frequencies at the cost of a slight increase at higher frequencies, is largely under-predicted.

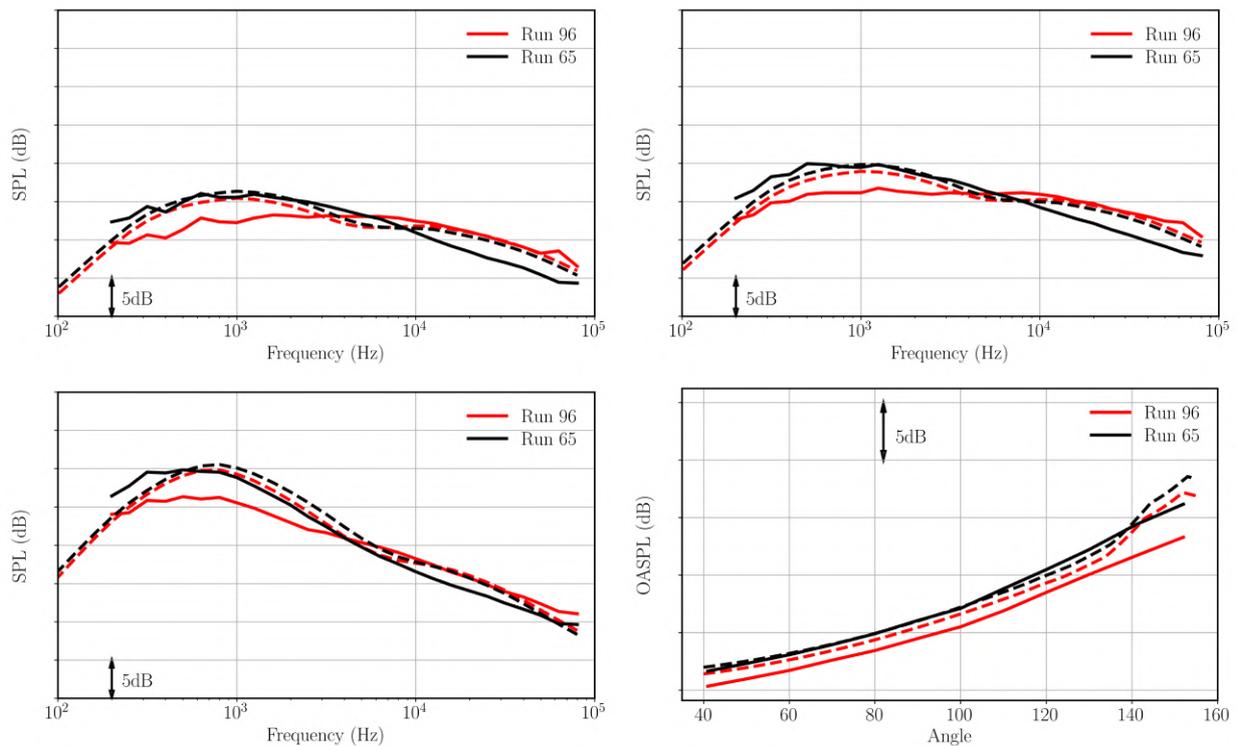


Figure 11: Comparisons between 2009 model predictions (dashed lines) and EXEJET experimental data (lines) for unsuppressed and suppressed nozzles operating at the same  $BPR = 10.2$  condition. On the top : SPL at  $51^\circ$  on the left and  $90^\circ$  on the right. On the bottom : SPL at  $141^\circ$  on the left and OASPL on the right.

The noise suppression term computed to assess the chevrons induced noise suppression on the large scale levels  $SPL_L$  in Stone 2009 is written as a function of the  $BPR$  as well as the inner and outer suppressed-to-unsuppressed wetted perimeter ratio  $PR_I$  and  $PR_O$  :

$$\Delta SPL_L = 45 \log(PR_I PR_O) / (1 + BPR). \quad (1)$$

The global under-prediction observed on the EXEJET suppressed cases is mainly driven by the under-prediction of noise suppression on the large scale component. Those results might be due to the  $(1 + BPR)$  term which might not be adapted to larger  $BPR$ .

In order to highlight the importance of domain validity check at  $BPR$  lower than 4.7, results obtained with the 2009 version to predict single jet noise radiated by Bridges and Brown [13] suppressed nozzles will be also shown in this section. Among the 11 nozzles tested by Bridges and Brown, 5 have been modeled in the present work. Those nozzles are presented in the Table 3 in terms of number  $N$  and axial length of chevrons, diameter at the chevrons base  $D_0$  and suppressed-to-unsuppressed wetted perimeter ratio  $PR_I$ . The SMC000 baseline nozzle has a 50.8 mm exhaust diameter. SMC001-004 have been built by cutting notches in a SMC000-like nozzle. Therefore, for those nozzles, chevrons penetration angle is equal to the baseline nozzle geometric angle which is convenient to compute the suppressed nozzle perimeter with a sufficient level of precision. The operating condition considered for the computation is the one referred as cold by Bridges and Brown, i.e setpoint 7 as defined in Tanna [18]. However, some inputs characterizing setpoint 7, required to apply Stone's models, are not specified in those papers. Therefore, it was chosen to carry out the calculations by taking a jet exhaust velocity and total temperature of respectively 309.3 m/s and 293.8 K. Ambient temperature was set to 294 K. Those settings reproduce a Mach number  $M_j/c_\infty$  of 0.9, a total temperature ratio  $T_t/T_\infty = 1$  and a static temperature ratio  $T_s/T_\infty \approx 0.84$  which seems consistent with setpoint 7 description in [18].

Table 3: List of configurations considered from Bridges and Brown [13] experimental campaign.

Nozzle	N	Axial length (mm)	$D_0$ (mm)	$PR_I$
SMC000			50.8	1
SMC001	6	22.6	54.8	1.84
SMC002	4	32.0	56.4	1.70
SMC003	10	14.0	53.2	1.94
SMC004	5	26.6	55.4	1.79

Figure 12 shows a comparison between predicted SPL and experimental data for the unsuppressed SMC000 nozzle. Both versions of the model, especially the 1983 version, are in good agreement with the reference. Those results consolidates the choice of aerodynamic parameters used to specify setpoint 7. The 2009 version slightly overpredicts the peak level mainly induced by the large scale mixing noise component. Also, the prediction quality above 20 kHz is altered by the presence of a strong small scale mixing noise component. Stone et al. [2] showed a similar behavior while modeling Lockheed Georgia Conical Nozzle.

Figure 13 depicts the results obtained by modeling the suppressed nozzles SMC001 to SMC004. While the chevrons presence has a moderate 2 to 3 dB impact at low frequencies, Stone 2009 predicts a noise suppression of more than 10dB in the range of the large scale mixing noise component below 20kHz.

In the case of a single jet,  $\Delta SPL_L$  reduces to  $45 \log(PR_I)$ . Bridges and Brown suppressed nozzles shows relatively long chevrons characterized by axial lengths in the order of magnitude

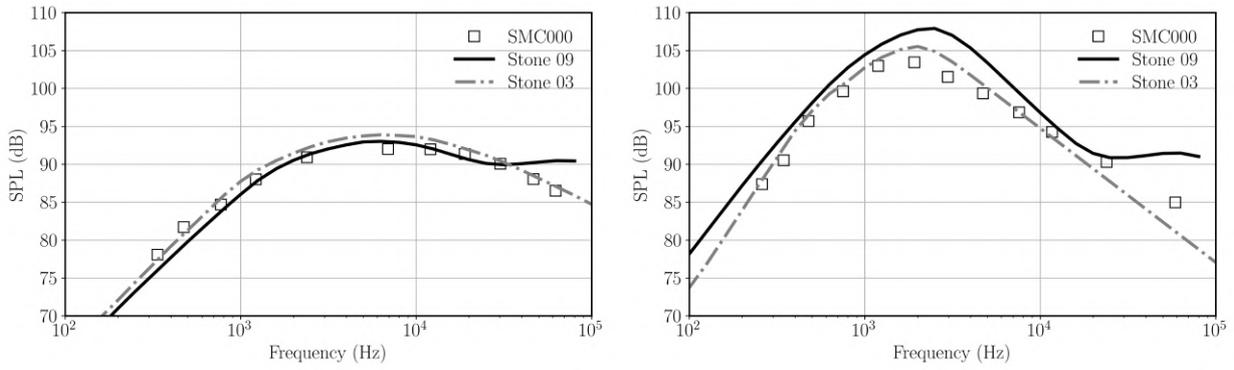


Figure 12: Stone 83 and 09 predicted SPL compared to Bridges and Brown [13] experimental data for SMC000 unsuppressed nozzle. SPL at  $90^\circ$  (on the left) and  $150^\circ$  (on the right).

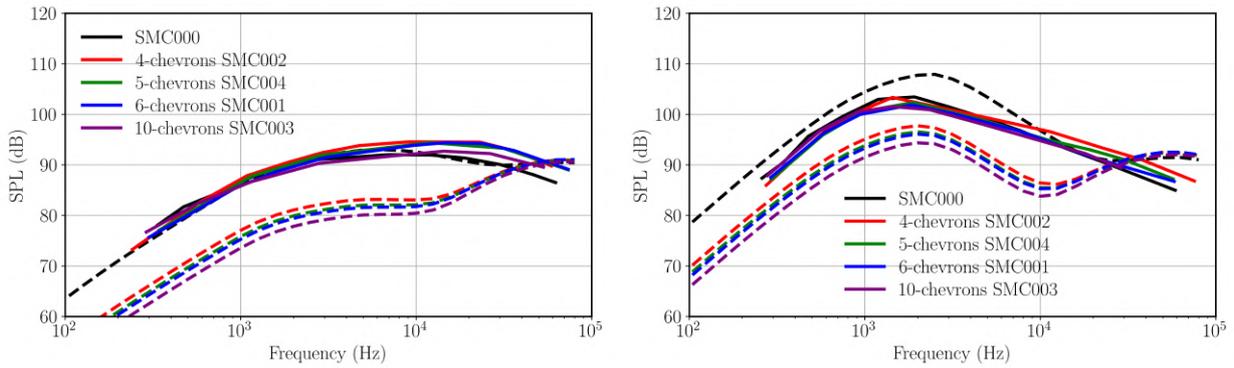


Figure 13: Stone 09 predicted SPL compared to Bridges and Brown [13] experimental data for SMC000 to SMC004 nozzles. Straight lines depict experimental data while dashed lines stand for associated Stone 09 computations. SPL at  $90^\circ$  (on the left) and  $150^\circ$  (on the right).

of the baseline nozzle radius. As a consequence, the resulting  $PR_I$  are quite large (in the range 1.7 – 1.94 for SMC001 to 004) causing irrelevant noise suppression calculation. As it is shown in Figure 14 showing  $\Delta SPL$  between SMC002 to 004 and the suppressed SMC001 nozzle, Stone 2009 was indeed able to roughly rank the suppressed nozzles between them.

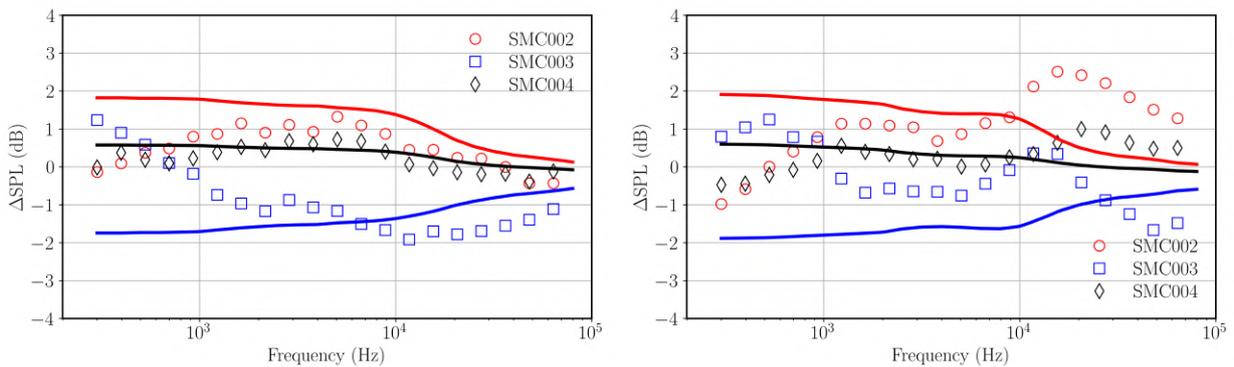


Figure 14:  $\Delta SPL$  between SMC002 to SMC004 suppressed configurations and suppressed SMC001 nozzle. Symbols depict experimental data while lines stand for predicted delta. SPL at a)  $90^\circ$  and b)  $150^\circ$ .

The results presented in this section tends to show that the terms implemented in the 2009 model to predict the chevrons impact seems optimized mainly for nozzles characterized by  $BPR$  in the range [4.7, 7.1]. The ability of the model to handle the presence of chevrons for supersonic

aircraft nozzles, that can be characterized by slightly lower  $BPR$ , is still in question. However, there might be some room to improve the way to handle chevrons presence for  $BPR$  below 4.7 and above 7.1.

## 5. CONCLUSION

Jet noise semi-analytical models developed by Stone et al. [1, 2] are proven to be fast and reliable. Those tools will be valuable especially during engine pre-sizing phases in which multidisciplinary optimization are needed. Despite the cumulated experience, their domain of validity seems still hard to define. In this context, ONERA launched a broad initiative to assess the ability of the models to predict in-house jet noise database. In this paper, the 2009 version of the model has shown tremendous abilities to predict EXEJET unsuppressed nozzles radiated noise when operating on a wide range of  $BPR$ . Then, the use of the 2009 model to predict noise radiated by suppressed nozzles, characterized by  $BPR$  seemingly out of its validity range, showed there might be some room to improve the way chevrons presence are taken into account in the 2009 model.

## 6. ACKNOWLEDGEMENTS

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## REFERENCES

1. James R. Stone, Donald E. Groesbeck, and Charles L. Zola. Conventional profile coaxial jet noise prediction. *AIAA Journal*, 21(3):336–342, 1983.
2. James R. Stone, Eugene A. Krejsa, Bruce J. Clark, and Jeffrey J. Berton. Jet noise modeling for suppressed and unsuppressed aircraft in simulated flight. Technical Report NASA/TM-2009-215524, NASA, 2009.
3. Robert Jaron, Matti Grabert, Remco Habing, Mark-Jan Van Der Meulen, Maxime Huet, Ingrid Legriffon, Francesco Petrosino, Mattia Barbarino, Katharina Lefarth, and Oleksandr Zaporozhets. Jet noise prediction benchmark for landing and takeoff noise of supersonic aircraft. In *Internoise 2023*, Chiba, Greater Tokyo, August 2023.
4. James R. Stone, Charles L. Zola, and Bruce J. Clark. An improved model for conventional and inverted-velocity-profile coannular jet noise. In *37th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 1999.
5. B. J. Clark. Computer program to predict aircraft noise levels. Technical Report NASA/TP-1913, NASA, September 1981.
6. W. E. Zorumski. Aircraft noise prediction program theoretical manual. Technical Report NASA/TM-83199, NASA, February 1982. Parts 1 and 2.
7. Lothar Bertsch, Laurent Sanders, Russel H. Thomas, Ingrid Legriffon, Jason C. June, Ian A. Clark, and Mathieu Lorteau. Comparative assessment of aircraft system noise simulation tools. *Journal of Aircraft*, 58(4), July 2021.
8. Ingrid Legriffon. Aircraft noise modelling and assessment in the IESTA program with focus on engine noise. In *The 22nd International Congress on Sound and Vibration*, Florence, Italy, July 2015.
9. Brenda S. Henderson, Dennis L. Huff, and Jeff J. Berton. Jet noise prediction comparisons with

- scale model tests and learjet flyover data. In *25th AIAA/CEAS Aeroacoustics Conference*, Delft, Netherlands, May 2019.
10. Francesco Petrosino and Mattia Barbarino. Survey of semi-empirical jet noise models for preliminary aircraft engine design. *Aerospace*, 10(7), July 2023.
  11. Junichi Akatsuka and Tatsuya Ishii. Comparative study of semi-empirical jet noise prediction models for future commercial supersonic aircraft. In *AIAA Aviation 2021 Forum*, August 2021.
  12. Jérôme Huber, Guillaume Drochon, Cyril Bonnaud, Azucena Pintado-Peno, Franck Cléro, and Guillaume Bodard. Large-scale jet noise testing, reduction and methods validation "EXEJET": 1. project overview and focus on installation. In *20th AIAA/CEAS Aeroacoustics Conference*, Atlanta, Georgia, June 2014.
  13. James Bridges and Clifford A. Brown. Parametrizing testing of chevrons on single flow hot jets. In *10th AIAA/CEAS Aeroacoustics Conference*, Manchester, UK, May 2004.
  14. Jack H. Goodykoontz and James R. Stone. Experimental study of coaxial nozzle exhaust noise. Technical Report NASA/TM-79090, NASA, 1979.
  15. B. A. Janardan, G. E. Hoff, J. W. Barter, S. Martens, P. R. Gliebe, V. Mengle, and W. N. Dalton. AST critical propulsion and noise reduction technologies for future commercial subsonic engines. Technical Report NASA/CR-2000-210039, NASA, 2000.
  16. H. E. Plumbee. Effects of forward velocity on turbulent jet mixing noise. Technical Report NASA/CR-2702, Lockheed-Georgia Company, 1976.
  17. F. Vuillot, N. Lupoglazoff, and M. Huet. Effect of chevrons on double stream jet noise from hybrid CAA computations. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, January 2011.
  18. H. K. Tanna, P. D. Dean, and M. J. Fisher. The influence of temperature on shock-free supersonic jet noise. *Journal of Sound and Vibration*, 39(4):429–460, 1975.