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RANS-BASED JET-SURFACE INTERACTION NOISE PREDICTION

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ABSTRACT

As the bypass ratio of modern turbofan engines continues to increase, the proximity between the wing and the engine in underwing installations tends to aggravate the noise generation due to jet-surface interactions (JSI). To ensure that increasingly strict legislation requirements will be met with minimal aircraft performance penalty, the capacity to predict the JSI noise is crucial. Although advanced techniques such as LES can effectively tackle this problem, they are still computationally expensive for optimization or design, especially at preliminary stages. Thus, there exists a demand for fast, yet reliable, predictive methods, that can be used to estimate the impacts of the engine relative position. In this work, the reduced order model proposed by Miller is used to provide the nearfield pressure, which is in turn used as an input for Lyu and Dowling's model for the prediction of farfield installation noise. The nearfield model parameters are first calibrated based on measurements of the nearfield PSD for a round nozzle and its respective RANS simulation. Once the optimal model parameters are calculated, the only input is derived from RANS simulations for the isolated jet, which yields a model for JSI that is fast and relies on minimal input.

Keywords: *jet-surface interaction noise, RANS, jet near-field prediction, reduced-order models*

1. INTRODUCTION

The noise generated by aircraft is known to have deleterious effects on human health, including sleep disturbance and cardiovascular disease. Since it became a public health issue in the late 1960s, legislative controls have become systematically stricter over the years, demanding the development of quieter aircraft.

When the noise sources from an aircraft are broken down, the jet is the dominant one during takeoff. It is also known that when the jet is close to the wing, in underwing-mounted configurations, the interaction causes a substantial augmentation in noise levels, especially at lower frequencies. Even though increasing bypass ratios results in lower jet velocity, which acts in the direction of mitigating the mixing noise produced, the engine must be installed closer to the wing because of its resulting larger diameter. This is a concern when dealing with Ultra-High Bypass Turbofan engines (UHBR).

First works on jet-surface interaction date back to the 1970s, focusing both on experiments [1] as well as on theoretical analyses [2]. Since then, tremendous advances in numerical methods, computer hardware and experimental techniques have paved the path for a better understanding of such complex phenomena and their mechanisms. LES, for instance, have been proven to be quantitatively predictive for different installation configurations and nozzle types [3]. Although such techniques yield a wealth of accurate information at virtually any position, its everyday use is still limited due to their relatively high computational cost. This is especially true at preliminary design stages, as the timescales are in the order of hours. Another restriction is their use in Multidisciplinary Optimization (MDO), which is commonplace in aircraft design, and demands quick turnaround times.

In response to the demand for faster predictive methods, numerous previous contributions have subsidized the

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development of so-called reduced order methods for predicting jet-surface interaction (JSI) noise. Of particular interest in this paper is the model proposed by [5], which was shown to be accurate and robust. Nonetheless, it requires the jet hydrodynamic pressure field as input. This implies that either measurements or LES must be carried out if the power spectral density is not available for a similar nozzle at positions close to the wing trailing edge. Alternatively, reduced-order models can be devised for the jet nearfield itself. The main goal of this work is to assess the predictive capability of farfield installation noise by the combination of two reduced-order models, namely the model proposed by Miller [6], which is used to predict the jet nearfield, and Liu and Dowling's model [5]. The former requires only RANS results as input. In essence, it is a generalization of Lighthill's analogy, applicable not only to farfield predictions. Given the difficulty in devising a universal model for the nearfield, the model constants must be calibrated for the specific nozzle geometry. This is achieved by an optimization procedure using a RANS simulation and the experimental PSD for a round nozzle. Miller's model is observed to reproduce experimental features of the nearfield pressure well for a given position, which ultimately results in good prediction for the farfield installed noise at that location. Nevertheless, further attempts to calibrate the nearfield model for other locations demonstrated it to be incapable of capturing the spatial variations that characterize the jet nearfield pressure. Intensive research efforts are being devoted to explaining and potentially improving such behavior.

2. METHODOLOGY

In the absence of a freestream, at a given observer position $\boldsymbol{x}$, the nearfield model proposed by Miller[6] for the Power Spectral Density reads:

$$PSD(\boldsymbol{x},\omega) = \frac{1}{16\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{A_{ijlm}\,l_s}{\bar{u}}\{F_t\omega^4 + M_t\omega^2 + N_t\} e^{\frac{-i\xi\omega}{\bar{u}}} e^{\frac{-|\xi|}{\bar{u}\tau_s}} e^{\frac{-\eta^2}{l_{sy}^2}} e^{\frac{-\zeta^2}{l_{sz}^2}} e^{\frac{-l_s^2\omega^2}{4\bar{u}^2}} d\boldsymbol{\eta} d\boldsymbol{\eta} \tag{1}$$

$\boldsymbol{\eta}(\xi,\eta,\zeta)$ denotes the vector inside the source region, with (ξ,η,ζ) representing the components in the streamwise direction and the two orthogonal cross-stream directions, respectively. $\bar{u}$ represents the axial velocity, whereas ω is the radial frequency. A_{ijlm} represents coefficients of the fourth-order two-point cross correlation of the stress tensor:

$$A_{ijlm} = P_y A_{ij} A_{lm} (\rho k)^2 \tag{2}$$

A_{ij} and A_{lm} incorporate anisotropic effects and P_y is a calibration constant. ρ is the flow density. l_s, l_{sy} and l_{sz} are the lengthscales in the three directions of a Cartesian system, and τ_s is the timescale, all of which can be calculated based on the turbulence kinetic energy k and its dissipation rate ε supplied by the RANS simulation as in classical acoustic analogies:

$$l_s = l_c \frac{k^{1.5}}{\varepsilon} \tag{3}$$

$$\tau_s = \tau_c \frac{k}{\varepsilon} \tag{4}$$

The terms F_t, M_t and N_t represent farfield, midfield and nearfield contributions, which are functions of the observer coordinates and scale with the distance to the observer as -2, -4 and -6, respectively. At this point it is worth mentioning that Miller's model can be applied to midfield and farfield noise predictions as well, according to the relative importance of each term. The double volumetric integrals over $\boldsymbol{\eta}(\xi,\eta,\zeta)$ must be evaluated numerically. For further details refer to the work of [6].

As previously mentioned, the three model constants must be calibrated based on either LES or experimental PSDs. Initially, this has been done using data from the Doak Laboratory at the Institute of Sound and Vibration Research, Southampton using only one spectrum from a round, 38.1-mm diameter nozzle at two jet diameters axially downstream and 1 jet diameter radially from the jet centerline. Only results for jet Mach number 0.6 are presented in this paper. For this case the specific values of the model parameters were: $P_y = 66.45$, $l_c = 2.5$ and $\tau_c = 0.5$.

Once the model has been tuned using as many reference nearfield spectra as available, the whole process for calculating the JSI noise at a given farfield position can be synthesized as follows. Since the jet nearfield is assumed not to be affected by the presence of the surface by Liu and Dowling's model, only one simulation of the isolated jet is necessary, and the results are saved for further use. Upon running a RANS simulation using the standard $k-\varepsilon$ turbulence model, the values of the turbulence quantities, axial velocity and density are saved and read in by the nearfield code. The nearfield PSD is then computed, preferably at the trailing edge position of the wing, and used as input to the JSI code. The model for JSI noise is classical and can be found in the literature [5]. In its simplest form, it can be understood as a transfer function from the nearfield to the farfield, due to the scattering effect of the wing trailing edge. The whole process takes a few minutes (not including the isolated jet RANS), including the expensive double integration over the CFD domain where sources are, which makes it suitable for use in MDO processes and quick preliminary design estimates. The standard $k-\varepsilon$ turbulence model has been chosen because of its capability to better capture the velocity and turbulence kinetic energy variations along the jet plume as compared to other RANS models. The mesh resolution was approximately 3 million hexahedra, no symmetry boundary conditions applied, which provided mesh-independent results. The turbulence intensity and the length scale at the nozzle exit were prescribed as 5% of the exit velocity and 10% of the nozzle diameter, respectively. Enhanced wall treatment was applied rather than the standard wall functions, although tests showed results not to be sensitive to such a choice. The CPU time for the RANS simulation amounts to less than one hour running on 20 dual 2-GHz Intel Skylake CPUs.

3. RESULTS AND DISCUSSION

Fig. 1 compares the experimental nearfield PSD, measured at the Doak Laboratory, with the one calculated using the method described above, at a distance of two nozzle diameters downstream and one diameter above the jet axis. The results show good agreement, which is not surprising given the initial calibration using an experimental probe at the same location. It is important to note that the model accurately reproduces the trends in the frequency range of interest (0.02<St<1).

Fig. 2 provides a more detailed analysis of the contributions of each term (nearfield, midfield, and farfield) to the PSD. The results show that the nearfield term is more significant at very low frequencies, while the midfield and farfield terms are important at intermediate and higher frequencies, respectively. These findings are useful for understanding the physical mechanisms involved in the generation and propagation of the sound field.

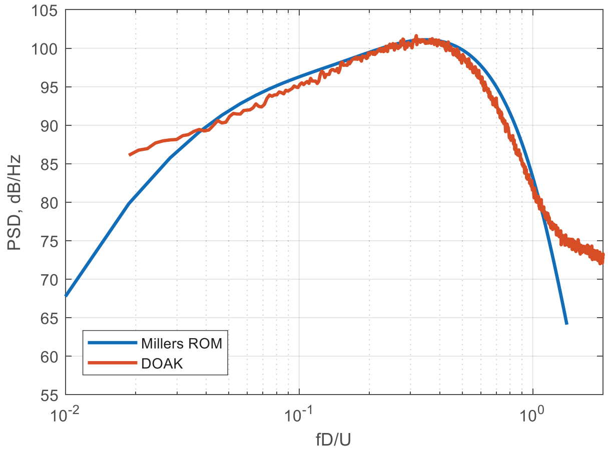

Figure 1. Comparison between the predicted nearfield PSD and experimental nearfield for a round nozzle (D=38.1 mm) at x/D=2, y/D=1, Mach number=0.6.

The calibrated nearfield model can now be used as input to Lyu and Dowling's model, which will in turn predict the jet-surface interaction noise. In order to assess the quality of the prediction, measurements of an installed round nozzle obtained at the Doak Laboratory are used as a reference. The testcase corresponds to a 38.1-mm nozzle placed four diameters upstream and 0.67 diameters below a 0.762-m flat plate's trailing edge (i.e., L/D=4, H/D=0.67).

Fig. 3 shows the JSI noise predicted by the above-described procedure at a polar angle of 90 deg and at a distance of 50 nozzle diameters from the nozzle exit, against the experimentally data measured at the Doak Laboratory. Also, the JSI noise predicted by Lyu and Dowling's model using the nearfield PSD obtained by a LES [3] instead is included. Both experimental and LES total PSDs can be decomposed azimuthally, but only the total PSDs are considered in this assessment. It should be noted that considering the azimuthal modes can lead to better agreement with the experiments than using the total PSD, especially for non-axisymmetric nozzle geometries. These initial results are promising and suggest that the RANS-based nearfield model can be used to produce quantitatively meaningful JSI predictions.

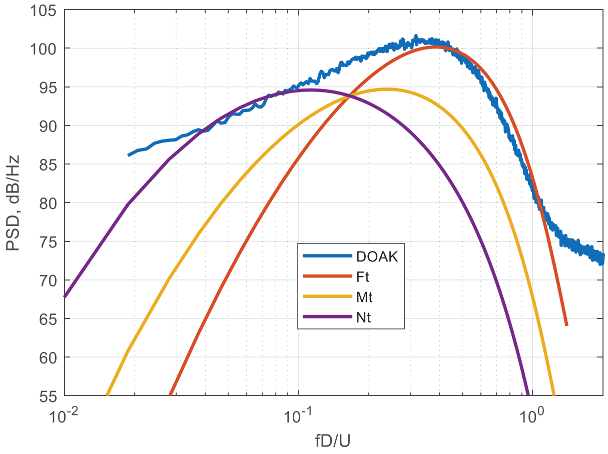

Figure 2. Breakdown of the different term contributions to the predicted nearfield PSD at x/D=2, y/D=1, Mach number=0.6.

The nearfield input PSD for Lyu and Dowling's model need not necessarily be supplied at the same H/D as the surface trailing edge, but it should be at the correct L/D position. Therefore, an important robustness test for Miller's model accuracy is to predict the pressure nearfield across the streamwise direction. This has been carried out by calibrating the model constants using four experimental nearfield spectra of the isolated jet, at x/D=1, 2, 3 and 4, rather than just at one location. An optimization procedure was set up in MATLAB using genetic algorithms (GA) in order to minimize the least square sum of the deviations between the predictions and experimental values of the PSD. Other methods have been used as well (particle swarm), but GA proved to be the most efficient.

Unfortunately, further attempts to calibrate Miller's model have demonstrated that it is unable to represent the nearfield features accurately for arbitrary positions, as depicted in Fig. 4. The predicted magnitude is seemingly insensitive to the probe location for Strouhal numbers above 0.5. Furthermore, the model did not capture the shift between the spectra frequency.

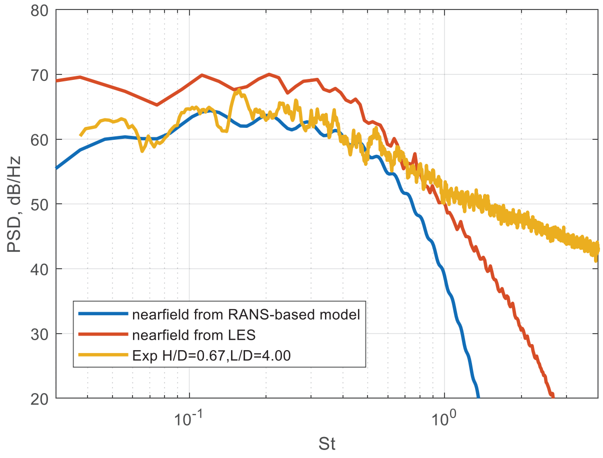

Figure 3. Prediction of installation noise by Lyu and Dowling's model based on two inputs – LES and nearfield model as compared to the experimental results. The nozzle is positioned at H/D=0.67 and L/D=4 relative to the flat plate. Mach number is 0.6.

The reason for such poor predictions is not clear at this stage. As the installation noise model relies on accurate nearfield pressure, of particular concern is the insensitivity to Strouhal number, which severely impacts subsequent farfield installation noise predictions. In his original paper, Miller [6] reports predictions in good agreement with experimental references at several observer locations, mostly in the midfield and farfield. Yet, it should be highlighted that his jet source model was based on an empirical, unidimensional fit, in lieu of a full 3D CFD model. The dependence of the model on Strouhal number is represented not only through A_{ijlm} (Eq. (2)), but also via modification of jet sources, whereas the latter is not included in the version used in this paper. This is expected to explain, at least in part, the discrepancies observed in Fig. 4.

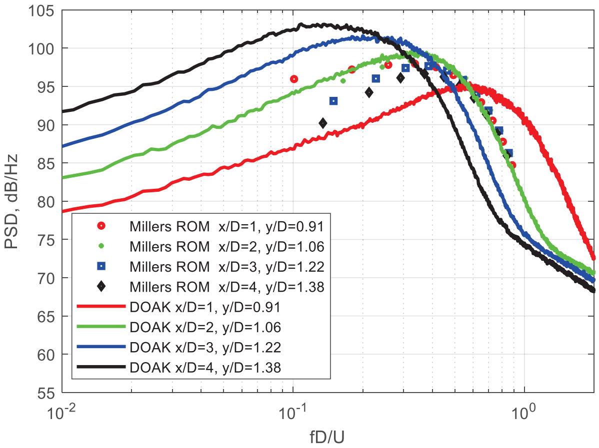

Figure 4. Prediction of pressure nearfield at different locations by Miller's reduced-order model (symbols) against experiments carried out at the Doak Lab (ISVR). Jet diameter is 38.1 mm and Mach number is 0.6.

4. CONCLUSIONS

In this work, a reduced-order approach for predicting farfield jet-surface noise based on RANS was assessed. In summary, it combines the nearfield pressure prediction by Miller's model with the farfield JSI model proposed by Lyu and Dowling. While the latter is known to produce accurate results as long as the accurate nearfield pressure is input, the reasons for the inaccurate prediction of the nearfield itself by Miller's model are still unclear. Further investigations are underway, mainly focusing on the model dependence on Strouhal number.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] R. Head and M. Fisher: "Jet/surface interaction noise - Analysis of farfield low frequency augmentations of jet noise due to the presence of a solid shield", in *Proc. of the 3rd Aeroacoustics Conference*, (Palo Alto, USA), pp. 1-12, 1976.

[2] R. Amiet: "Noise due to turbulent flow past a trailing edge". *Journal of Sound and Vibration*, vol. 47, no. 3, pp. 387–393, 1976.

[3] Z. Wang, A. Proenca, J. Lawrence, P. Tucker and R. Self: "Large-eddy-simulation prediction of an installed jet flow and noise with experimental validation". *AIAA Journal*, vol. 58, no. 6, pp. 2494-2503, 2020.

[4] H. Abid, A. Markesteijn, V. Gryazev, S. Karabasov, H. Jawahar and M. Azarpeyvand, "Jet Installation Noise Modelling Informed by GPU LES", in *Proc. of 28th AIAA/CEAS Aeroacoustics 2022 Conference*, (Southampton, UK), pp. 1-18, 2022.

[5] B. Lyu, A. P. Dowling, and I. Naqavi: "Prediction of installed jet noise", *Journal of Fluid Mechanics*, vol. 811, pp. 234-268, 2017.

[6] S. Miller: "Prediction of Near-Field Jet Cross Spectra". *Journal of Aircraft*, vol. 53, no. 8, pp. 2130-2150, 2015.