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PREDICTION OF ROCKET JET NOISE BY EMPIRICAL AND NUMERICAL APPROACHES

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ABSTRACT

Intense sound waves are emitted from the highly energetic, supersonic, turbulent jet issuing from a rocket nozzle. Acoustic loads on the structural components like the payload, launch pad, rocket avionics, and so on, must, therefore, be studied carefully during design especially for the launch phase. In this paper, two approaches with different levels of fidelity are employed to predict the acoustic emission from a rocket jet. The first one is based on an empirical formulation stemming from the scaling laws for supersonic jet noise with well established data from the literature. On the other hand, the second approach strives to get direct numerical solutions to non-linear acoustics equations. A small, 2.8 Mach, experimental jet from the literature is investigated by the two approaches, and the overall sound pressure results obtained are compared. The noise levels predicted by the empirical approach agree well with the experimental data for large range of directions, and those obtained by the non-linear acoustic solver agree reasonably with the data at angles from jet axis to the peak radiation direction, while agreement is lost increasingly beyond the peak direction.

INTRODUCTION

Deployment of spacecraft from ground requires huge amounts of impulsive force. Such forces are generated by rocket engines accelerating propellant mass through their nozzles at very large quantities. The flow issuing from a rocket nozzle is, therefore, highly energetic and complex. Supersonically moving large turbulent structures themselves, and their strong interactions with forming shock/expansion waves in the jet are responsible for most of the radiated noise [Morris and Tam, 1977; Tam, 1991, 1995; Viswanathan, 2009]. The dominant directivity is a function of the supersonic convective Mach number and is about 40-60 degrees from the jet axis, as associated with the Mach wave radiation.

Due to quite dense turbulent structures existing in the jet, appreciable success in predicting supersonic jet noise has been possible only through large eddy simulation (LES) [Shur *et al.*, 2005; Viswanathan *et al.*, 2010; Nonomura, 2016; Brehm *et al.*, 2016], but its routine use is still quite expensive. On the other hand, empirical methods [Eldred, 1971; Varnier, 2001; Campos, 2005; Haynes and Kenny, 2009] based on theoretical scaling laws [Morfey *et al.*, 1978; Tam *et al.*, 1996; Kandula, 2008; Viswanathan,

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2009] and measurements from long time experimental investigations [Eldred, 1971; McLaughlin *et al.*, 1975; Seiner, 1984; Panda, 1999; Tam *et al.*, 2008] continue to serve as the most convenient tools in low-budget design and development activities [Varnier *et al.*, 2006; Casalino *et al.*, 2009; Smith, 2013; James *et al.*, 2016]. Eldred [1971] developed his own widely cited empirical approach in 1970's using measured data. In this approach the total sound power emitted from a rocket's jet plume was assumed to be about %0.5 of the jet mechanical power. This number in fact falls on the average of many measured rocket noise power data [Sutherland, 1993].

In this study, the empirical method originally developed by Eldred [1971], later improved with some length scale modifications [Varnier, 2001], and found recent use by Casalino *et al.* [2009]; Smith [2013]; Morshed *et al.* [2013]; James *et al.* [2016] is used for rapid noise prediction which can be used at preliminary design stage. Also, solutions to non-linear acoustics equations are carried out numerically to assess this more direct approach for rocket noise prediction.

Details of the two approaches are described in the next section. Then, a small experimental jet with 2.8 Mach from the literature is considered for evaluating the two methods.

JET NOISE PREDICTION METHODS

Empirical Jet Noise Prediction

A supersonic jet plume has quite complex flow structures. The length scales associated with turbulence, and thereby the emitted sound frequencies and power spectral densities vary along the jet. A noise prediction approach may then be based on a simple integration of the emitted sound power contributions, both over frequency and the jet volume, such that the total sound power fits to the commonly measured fraction of the jet mechanical power from previous rocket tests or launches. This is exactly what was done by Eldred [Eldred, 1971]. Following fundamentally his approach, many different researchers developed their own low fidelity but fast noise prediction tools [Casalino *et al.*, 2009].

Development of the empirical approach starts with sound pressure scaling for a given far-field observer position. This point is assumed to be contributed by concentrated, equivalent sources located at the centers of volume slices along the jet (see Figure 1). In addition to the local position of each jet slice from the nozzle exit and thereby the local length and time scales, the slice will also have different distance and orientation with respect to the observer. Hence, each slice contribution has distinct dominant frequency and directivity effects on the emitted sound which all must be accounted for.

Based on observation, acoustic power $W_{\rm ac}$ is only a fraction of the the jet mechanical power W_m:

$$W_{ac} \quad = \eta W_m \tag{1}$$

where the factor η is correlated [Sutherland, 1993] to various jet parameters through

$$\eta = 0.0012 \frac{\gamma_j}{\gamma_a} \left(\frac{c_t}{c_a} \right)^3 \left(\frac{c_t}{V_e} \right)^2 \tag{2}$$

where γ is the ratio of specific heats, c is the sound speed, V is the gas velocity, and subscripts j, t and a correspond to the jet, throat, and ambient conditions, respectively. It should be noted at this point that depending on the rocket operation point the flow exiting the nozzle may be fully expanded (design point), underexpanded, or overexpanded. In the formulations, if otherwise is not expressed explicitly, jet conditions correspond to the fully expanded jet conditions signified by subscript j.

As distribution of the overall sound power is required over the entire frequency range and jet plume, a local curved coordinate s along it is defined. When the plume is split into segments, the sound power share (local, ℓ) of the k-th jet plume segment with coordinate s_k, denoted $w_\ell(s_k)$, will be dependent on the coordinate s_k due to the local length scales of the jet plume (see Figure 1). This power share is obtained from the observed data fit shown in Figure 2. The horizontal axis in this plot

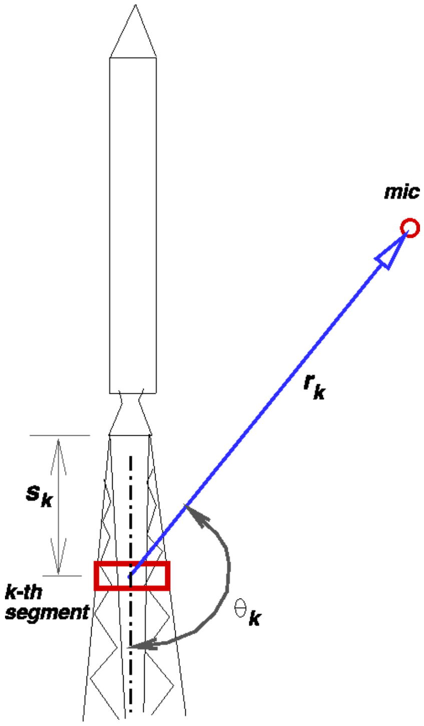


Figure 1: Configuration for empirical approach.

is $\bar{s} = s/L_{\rm ref}$ which is the normalized local coordinate with reference length $L_{\rm ref}$, and the vertical axis is $\bar{w}_\ell = w_\ell(s) L_{\rm ref}/W_{\rm ac}$ which is the normalized local power share of the segment at s.
The next step is to distribute the local power share $w_\ell(s)$ over the frequencies. Strouhal number St is scaled with normalized coordinate $\bar{s}$, and the jet ambient sound speed to jet sound speed ratio c_a/c_j. Then, $w_\ell(s)$ is split over this scaled Strouhal number based on scaling laws and measured data. Figure 3 shows the normalized local sound power density denoted $\bar{w}_{\ell,f}(s,f)$ and defined as

$$\bar{w}_{\ell,f}(s,\mathrm{St}) = \frac{w_{\ell,f}(s,f)}{w_\ell(s)} \frac{U_j}{s} \frac{c_a}{c_j} \tag{3}$$

Hence, the sound power level $\mathrm{PWL}_{k,i}$ for each segment located at s_k with segment length Δs_k and frequency interval Δf_i is [Casalino *et al.*, 2009]

$$\begin{aligned} \mathrm{PWL}_{k,i} &= 10\log_{10}[w_{\ell,f}(s_k,f_i)\Delta s_k \Delta f_i] \\ &= 10\log_{10}[\bar{w}_{\ell,f}(s_k,\mathrm{St}_i] + 10\log_{10}[\bar{w}_\ell(s_k)] + 10\log_{10}\left(\frac{W_{\rm ac}}{W_{\rm ref}}\right) \\ &+ 10\log_{10}(\Delta s_k/L_{\rm ref}) - 10\log_{10}\left(\frac{U_j}{s_k}\frac{c_a}{c_j}\right) + 10\log_{10}(\Delta f_i) \end{aligned} \tag{4}$$

The directivity effect for each segment and frequency interval is included by a directivity factor $\mathcal{D}$ which is plotted in Figure 4. Then, the sound pressure level SPL for each segment and frequency is

$$\mathrm{SPL}_{k,i} = \mathrm{PWL}_{k,i} - 10\log_{10}(r_k^2) + 10\log_{10}[\mathcal{D}(\theta_k,\mathrm{St}_i)] - 10\log_{10}\left(\frac{p_{\rm ref}^2 4\pi}{W_{\rm ref}\rho_a c_a}\right) \tag{5}$$

where r_k is the distance from the k-segment to the observer, θ_k is the angle from the jet axis at s_k to the observer, $p_{\rm ref} = 2\times10^{-5}$ Pa (ref. pressure for SPL calculation), and $W_{\rm ac} = 1\times10^{-12}$ W (ref. power for PWL calculation).

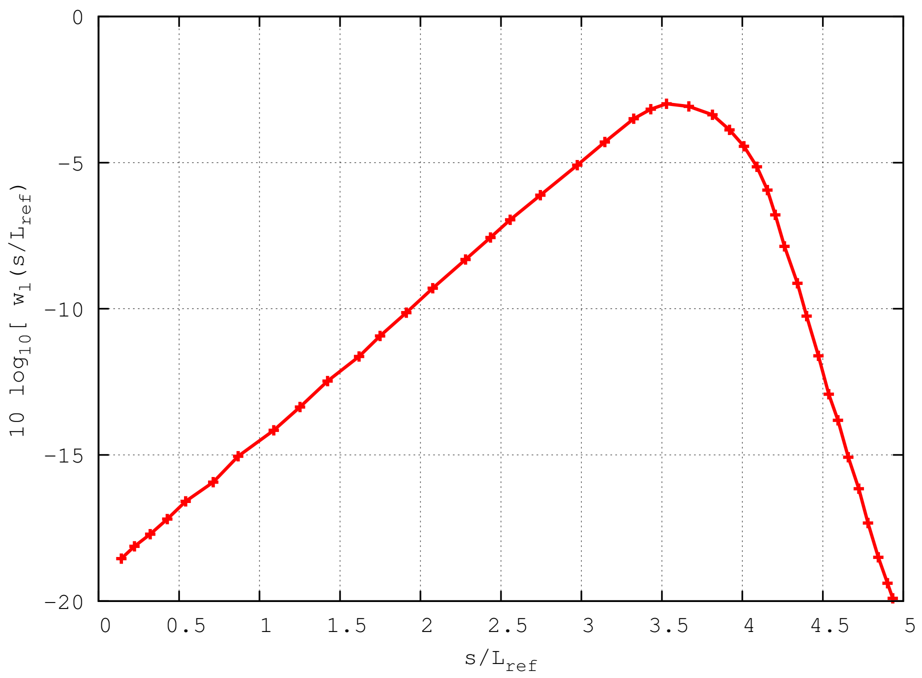


Figure 2: Normalized power shares along jet plume axis [Eldred, 1971; Casalino *et al.*, 2009].

In all these expressions, L_{ref} is taken as the reference length scale. It is calculated as [Varnier, 2001]

$$L_{\text{ref}} = 1.75D_j(1 + 0.38M_j)^2 \tag{6}$$

The fully developed jet Mach number, M_j, and the jet diameter D_j are calculated as

$$M_j = \left\{\frac{2}{\gamma_j - 1}\left[\left(1 + \frac{\gamma_j - 1}{2}M_e^2\right)\left(\frac{p_e}{p_a}\right)^{\frac{\gamma_j-1}{\gamma_j}} - 1\right]\right\}^{1/2} \tag{7}$$

$$D_j = \frac{2}{M_j}\sqrt{\frac{T}{\pi p_a \gamma_j}} \tag{8}$$

where T is the rocket thrust. The mechanical power W_m is given as:

$$W_m = TU_j \tag{9}$$

Finally the overall sound pressure level OASPL is computed by a double sum over the i and k indices:

$$\text{OASPL} \quad = 10\log_{10}\left(\sum_k \sum_i 10^{\text{SPL}_{k,i}/10}\right) \tag{10}$$

Numerical Jet Noise Prediction

Accurate simulation of supersonic jet noise numerically requires resolution of broad range of turbulent structures, shock/expansion waves and all of their interactions in the jet flow, as well as accurate propagation of the generated noise across the complex jet plume. Mesh resolution requirement is, therefore, quite high. Although theoretically Direct Numerical Simulation (DNS) approach, where grid resolution is equal to the Kolmogorov length scale, can be used to resolve all turbulent structures, the computational cost prohibits its usage in realistic applications. On the other hand, dominant scales

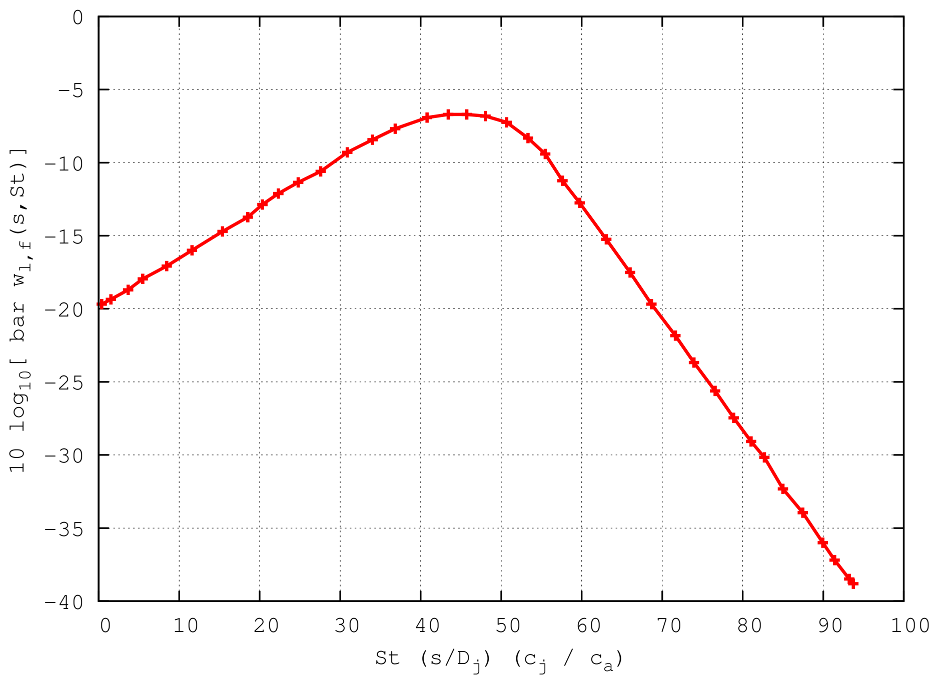


Figure 3: Normalized local power density as a function of scaled Strouhal number [Eldred, 1971; Casalino *et al.*, 2009].

of turbulent structures related to noise generation can be solved by using LES approach. Although many studies related to hot, supersonic jet noise have appeared using LES [Viswanathan *et al.*, 2010; Nonomura, 2016; Brehm *et al.*, 2016], its frequent use is still very expensive. To decrease computational cost of noise prediction simulations, usage of the non-linear disturbance equations as the governing equations was proposed and coded in Metacomp Technologies' Non-Linear Acoustics Solver (NLAS) module [Batten *et al.*, 2004]. In this paper we utilize this solver as a rather more direct, numerical rocket noise prediction tool. This solver is a high-resolution pre-conditioned solver for propagation of pressure disturbances. It calculates noise generation and transmission from turbulent flows. A mean flow and the statistical turbulence data need to be computed through Reynolds-Averaged Navier-Stokes (RANS) computations a priori so that the required sources to the non-linear disturbance equations can be formed. A cubic $k-\varepsilon$ model [Palaniswamy *et al.*, 2001] which incorporates anisotropies in turbulence is used in NLAS.

The governing equations of the acoustic part of NLAS are based on splitting the flow variables into mean and fluctuating components. With this approach the Navier-Stokes equations are put in the form

$$\frac{\partial Q'}{\partial t} + \frac{\partial F_i'}{\partial x_i} - \frac{\partial (F_i^v)'}{\partial x_i} = -\frac{\partial \overline{Q}}{\partial t} - \frac{\partial \overline{F_i}}{\partial x_i} + \frac{\partial \overline{F}_i^v}{\partial x_i} \tag{11}$$

$$\overline{Q} = \begin{bmatrix} \overline{\rho} \\ \overline{\rho u_j} \\ \overline{e} \end{bmatrix}, \quad \overline{F}_i = \begin{bmatrix} \overline{\rho u_i} \\ \overline{\rho u_i u_j} + \overline{p}\delta_i j \\ \overline{u_i}(\overline{e} + \overline{p}) \end{bmatrix}, \quad \overline{F}_i^v = \begin{bmatrix} 0 \\ \overline{\tau_{ij}} \\ -\overline{\theta}_i + \overline{u}_k \overline{\tau}_{ki} \end{bmatrix} \tag{12}$$

$$Q' = \begin{bmatrix} \rho' \\ \overline{\rho} u_j{}' + \rho' \overline{u_i} + \rho' u_j{}' \\ e' \end{bmatrix}, \quad (F_i^v)' = \begin{bmatrix} 0 \\ \tau_{ij}' \\ -\theta_i' + u_k' \overline{\tau}_{ki} + \overline{u}_k \tau_{ki}' \end{bmatrix} \tag{13}$$

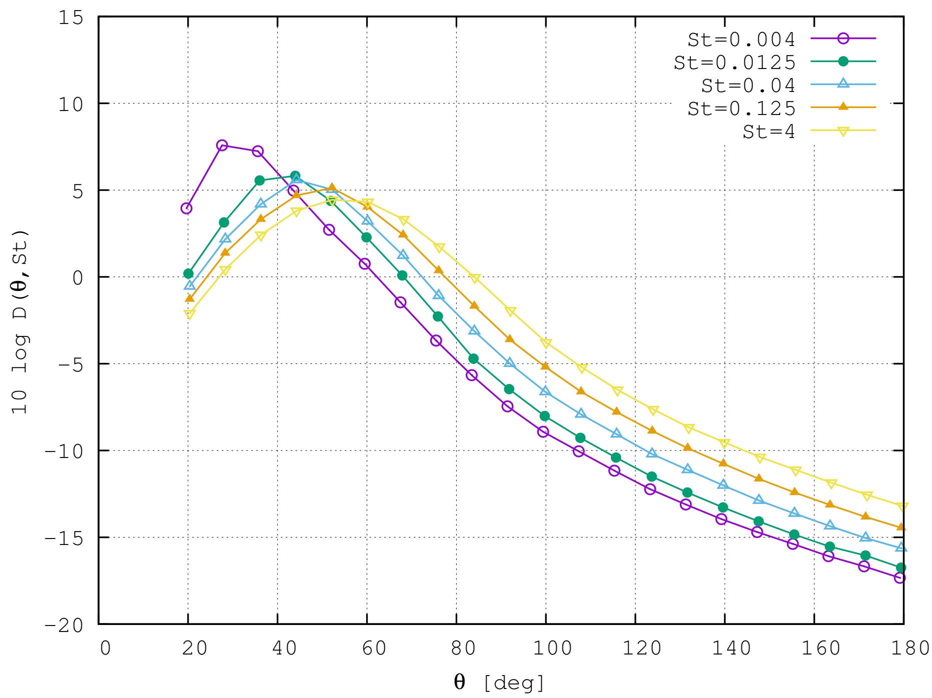


Figure 4: Directivity factor for supersonic jet noise [Eldred, 1971; Casalino *et al.*, 2009].

$$F_i' = \begin{bmatrix} \overline{\rho} u_i' + \rho' \overline{u_i} \\ \rho' \overline{u_i u_j} + \overline{\rho u_i} u_j{}' + \overline{\rho} u_i{}' \overline{u_j} + p' \delta_{ij} \\ u_i{}'(\overline{e} + \overline{p}) + \overline{u_i}(e' + p') \end{bmatrix} + \begin{bmatrix} \rho' u_i' \\ \overline{\rho} u_i{}' u_j{}' + \rho' u_i{}' \overline{u_j} + \rho' \overline{u_i} u_j{}' + \rho' u_i{}' u_j{}' \\ u_i{}'(e' + p') \end{bmatrix} \tag{14}$$

Neglecting density fluctuations and taking time averages gives :

$$\overline{LHS} = \overline{RHS} = \frac{\partial R_i}{\partial x_i} \tag{15}$$

where residual R_i may be written as :

$$R_i = \begin{bmatrix} 0 \\ \overline{\rho} \overline{u_i{}' u_j{}'} \\ c_p \overline{\rho} \overline{T' u_i{}'} + \overline{\rho} \overline{u_i{}' u_k{}'} \overline{u_k} + \frac{1}{2} \overline{\rho} \overline{u_k{}' u_k{}' u_i{}'} + \overline{\tau_{ki}' u_k'} \end{bmatrix} \tag{16}$$

The unknown Reynolds-stress tensor and turbulent heat fluxes in above equation are obtained by a prior RANS simulation. By constructing source terms from RANS simulation, time-dependent acoustic computations can be carried out with NLAS. The far-field noise predictions are calculated using the Ffowcs Williams–Hawkings (FW-H) integral equation [Ffowcs Williams and Hawkings, 1969].

RESULTS AND DISCUSSION

For evaluation and comparison of the two methods employed in this study, the Jet IV experimental configuration of Varnier [2001] is used. The jet is composed of combustion gases of hydrogen-air mixture. However, they are treated as single ideal gas with a specific heat ratio of 1.32 and gas constant of 302 J/kg.K [Varnier and Raguenet, 2002]. The experimental and geometrical parameters related to Jet IV are given in Table 1.

Table 1: Varnier [2001] Jet IV experimental parameters.

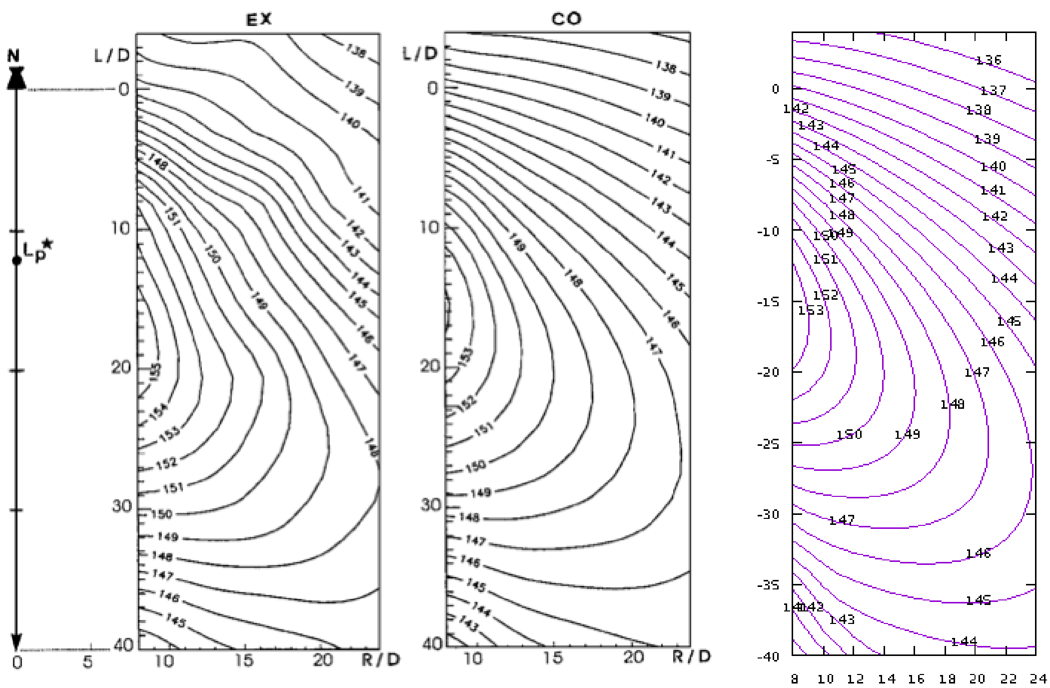
Parameter	Value	Unit
chamber pressure, p_{tot}	30	bar
chamber temperature, T_{tot}	1040	K
nozzle mass flow rate, $\dot{m}_t$	1.71	kg/s
nozzle exit diameter, D_e	6	cm
nozzle exit Mach number, M_e	3.3	-
nozzle exit velocity, U_e	1270	m/s
nozzle exit pressure, p_e	0.5	bar

For the empirical calculations, the fully expanded jet parameters are used. They are given in Table 2. The computed OASPL distribution of Jet IV by using empirical approach and the experimental and computational results Varnier [2001] are compared altogether in Figure 5. As evident from the figure, the present calculated results are in reasonable agreement with the experimental results and are in good overall agreement with the computational results of Varnier [2001].

Table 2: Varnier [2001] Jet IV fully expanded jet parameters.

Parameter	Value	Unit
jet diameter, D_j	4.8	cm
jet Mach number, M_j	2.8	-
jet velocity, U_j	1200	m/s
jet pressure, p_j	1.0	bar

The second set of calculations is based on use of NLAS described above. Calculations are started from the exit of the nozzle with supersonic inlet boundary conditions using the data given in Table 2. First a 2-D axisymmetric simulation is performed to obtain the mean flow as well as to form initial sources for the NLAS procedure which is subsequently carried out entirely in 3-D. The Mach number contours of the Jet IV configuration obtained from the steady state simulation are shown in Figure 6, while Q-criterion iso-surfaces colored with velocity are displayed from the time-accurate calculations in Figure 7. These results demonstrate highly turbulent structures exist in the jet. Strong Mach wave emission is expected due to the supersonic convection speeds these structures have. Figure 8 shows the dominance of the Mach wave radiation in a direction slightly above 40 degrees from the jet axis, indicated by the instantaneous pressure fluctuations. The radiation direction and OASPLs found from the NLAS computations are in consistency with those of the empirical predictions presented above, as well as those of Varnier [2001] Upton the peak radiation direction from the axis. This is better observed in the OASPL curves along the $r/D_e = 8$ line parallel to the jet axis in Figure 9. The empirical and experimental OASPL peak levels agree quite well, while the NLAS captured the peak about 2 dB lower than the others. However, the main radiation direction appears to be predicted better by NLAS than the empirical approach by a few degrees. It is worth noting though that the NLAS significantly underpredicts OASPL for higher radiation directions, where the main contributions to the noise come from shock associated interactions and fine scale turbulent structures.



(a) Left : Varnier's experiment, Right : Varnier's computation [Varnier, 2001]

(b) present empirical results

Figure 5: Empirically computed OASPL distributions of Varnier [2001] Jet IV experimental configuration.

CONCLUSIONS

The objective of the paper is to investigate two different approaches for rocket jet noise prediction. The first is based on an empirical approach which utilizes formulations from the jet noise scaling laws with usage of data obtained from previous rocket tests and launches; and therefore, it is a fast noise prediction method. Results obtained by this approach for a small experimental supersonic jet for which data is available in literature indicated good agreement with the measured data for large range of directions. The second approach the paper deals with is based on a commercial non-linear acoustic solver. This solver is based on reformulating the Navier-Stokes equations for the perturbed flow states. It requires an initial steady flow calculation and a subsequent unsteady calculation. The NLAS results captured the dominant noise generating structures reasonably, and yielded sufficiently accurate peak radiation direction, with the peak OASPL predicted only about 2 dB lower than the measured peak OASPL. The comparisons along the $r/D_e = 8$ line parallel to the jet axis indicated though, the NLAS significantly underpredicts OASPL values for higher radiation directions.

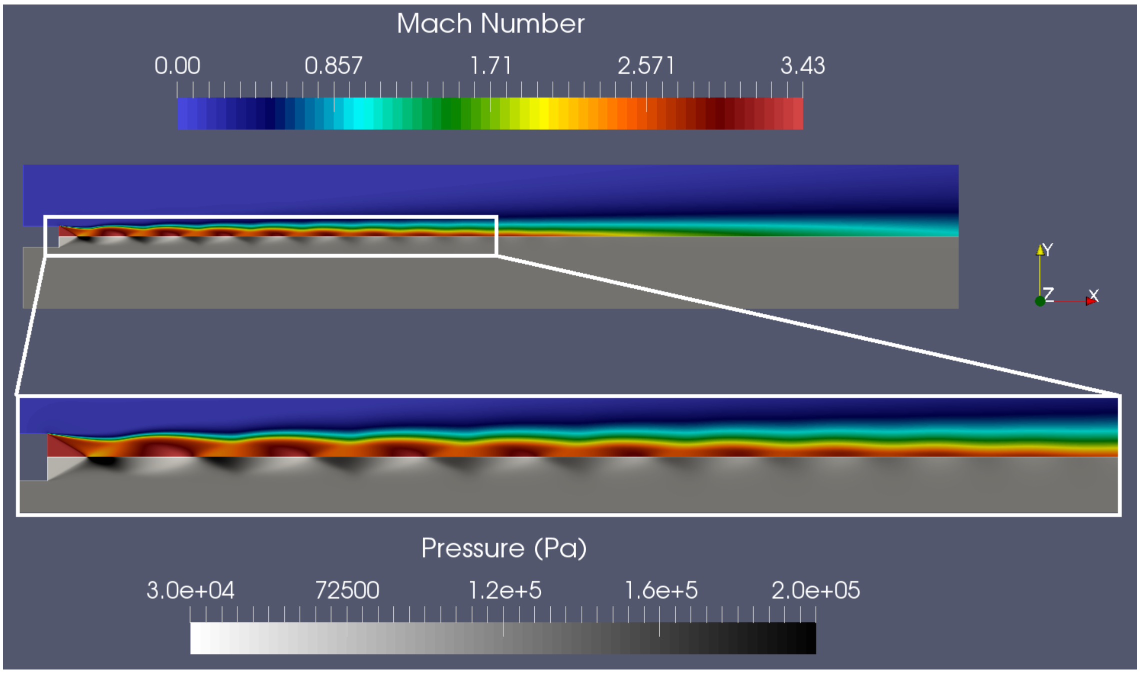


Figure 6: Mach number and pressure contours of Varnier's Jet IV.

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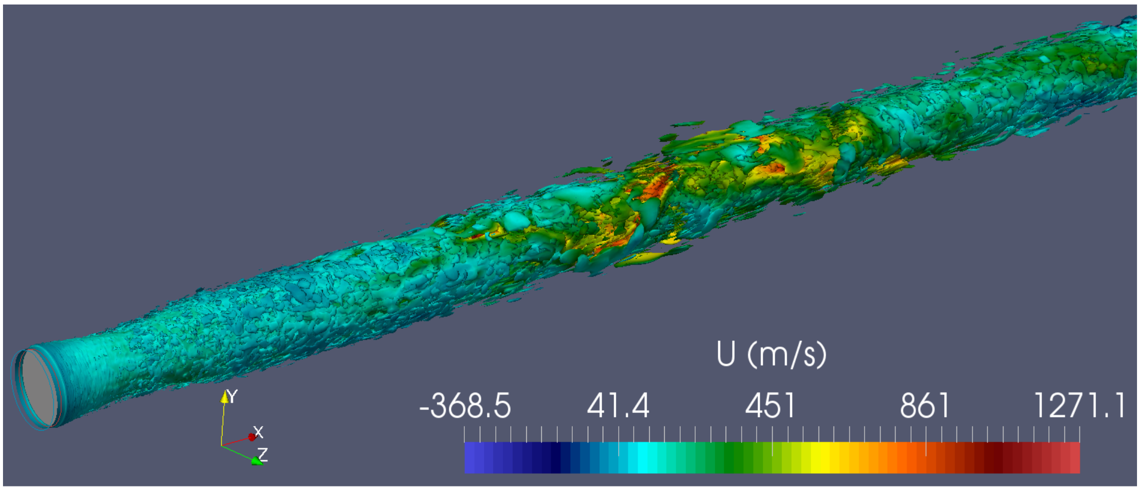

Figure 7: Iso-Q criterion (1×10^5) surfaces colored with instantaneous velocity.

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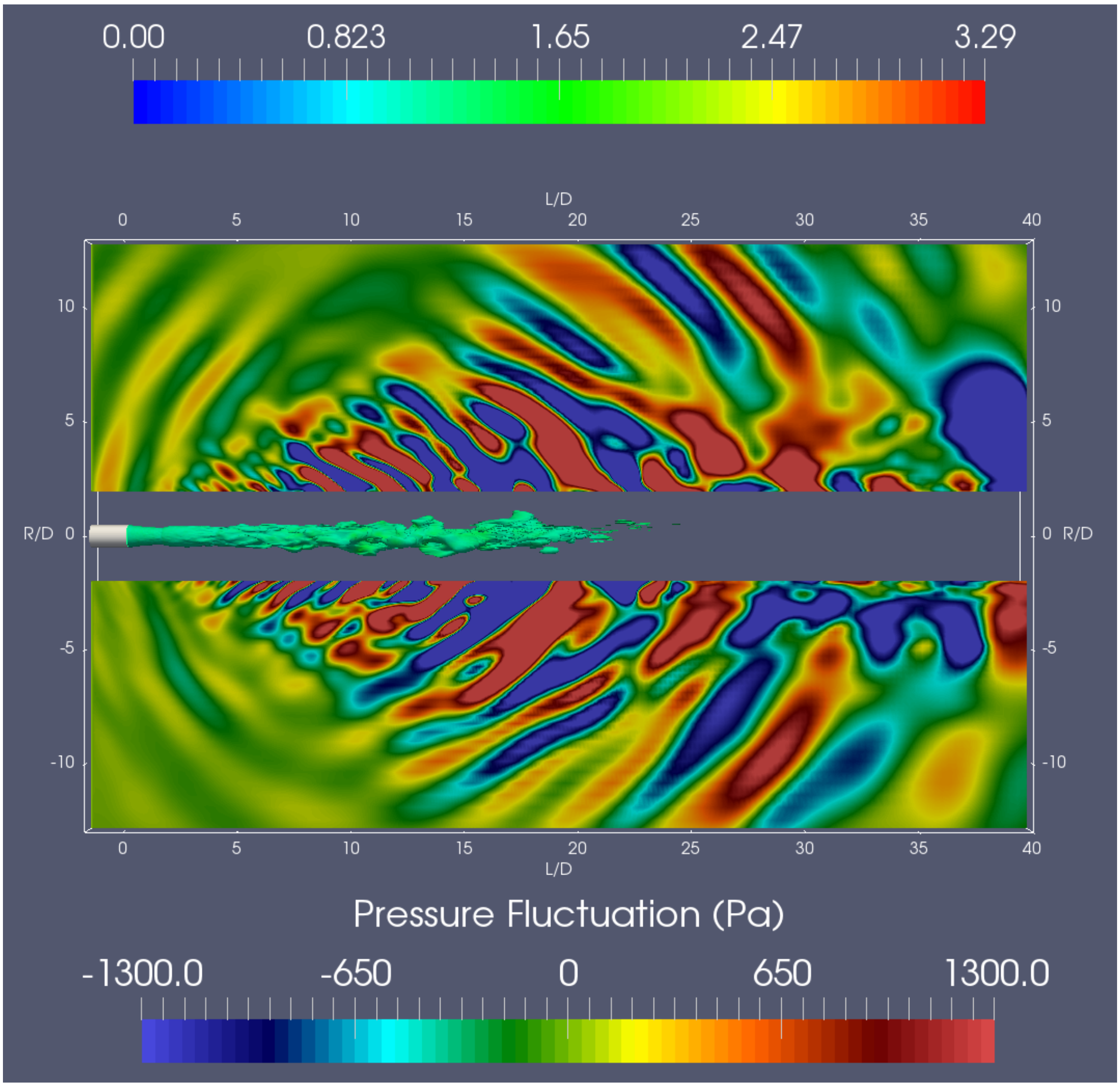

Figure 8: Turbulent jet plume and an instantaneous pressure fluctuation field from it.

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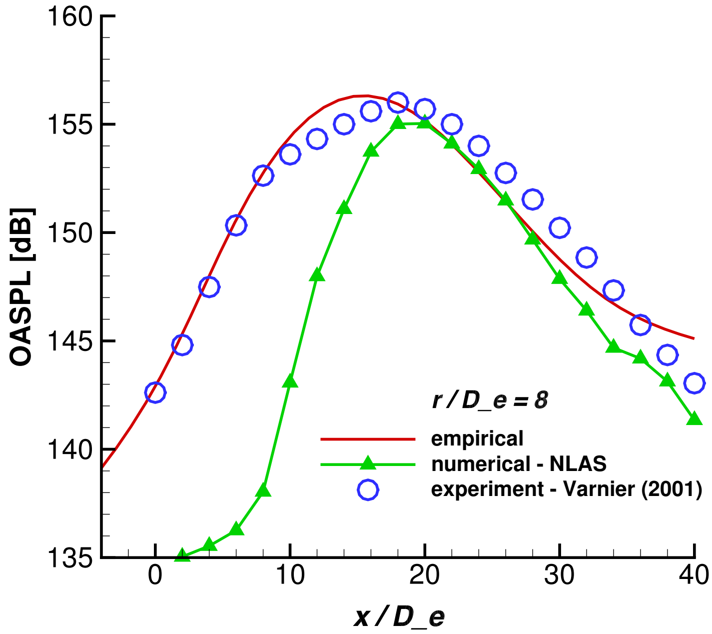

Figure 9: Comparison of the OASPL variations along $r/D_e = 8$ line from the empirical and numerical predictions, and experiment of Varnier Varnier [2001].

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