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Short Communication

Near-field acoustics of clustered rocket engines

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Abstract

This paper presents an approach for the prediction and characterization of the near-field acoustic levels from closely spaced clustered rocket engines. The calculations are based on the method proposed by Eldred wherein the flow field from the clustered rockets is divided into two zones. Zone 1 contains the isolated nozzles that produce noise independently and extends up to a distance where the individual flows completely mix to form an equivalent single nozzle flow. Zone 2 is occupied by the single mixed stream starting from the station where the jets merge. The acoustic fields from the two zones are computed separately on the basis of the NASA-SP method developed for a single equivalent nozzle. A summation of the spectra for the two zones yields the total effective sound pressure level for the clustered engines. Under certain conditions of nozzle spacing and flow parameters, the combined sound pressure level spectrum for the clustered nozzles displays a double peak. Test cases are presented here to demonstrate the importance of hydrodynamic interactions responsible for the double peak in the sound spectrum in the case of clustered rocket nozzles, and the role of ground reflections in the case of noninterfering jets.

1. Introduction

The acoustic levels in a launch vehicle environment arising from supersonic turbulent exhaust jets of rocket engines induce severe random structural vibrations of vehicle components, encapsulated payloads, and ground support structures and equipment in the immediate vicinity of the launch pad. To estimate the vibroacoustic stress levels during lift-off conditions, it is requisite to accurately determine the spectral sound power, overall sound power and its directivity, and spatial correlation.

Methods based on Lighthill's theory [1,2] for subsonic jet noise, and its extension to supersonic jets [3,4], seem to be rather cumbersome for application to complex configurations. Empirical or semi-empirical theories based on a wide range of test data and scaling laws [5,6] provide an economical alternative for noise prediction from realistic rocket engine configurations for preliminary design purposes.

Currently the NASA SP-8072 method by Eldred [7], developed on the basis of extensive rocket test data, appears to be the only documented semi-empirical method to predict noise from an isolated supersonic jet. Methods to estimate the noise produced by multiple rocket engines by the principle of superposition of individual jets work satisfactorily for noninterfering jets (widely spaced nozzles). In the other extreme case of

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very closely (tightly) spaced jets, the noise produced is occasioned primarily by the combined flow of a single equivalent nozzle. The effects of clustering, in such circumstances, are empirically taken into account by an equivalent diameter so that the NASA SP method can again be utilized. In both of these extreme cases, the spectral sound pressure level (SPL) is characterized by a single peak frequency, which is dependent on the characteristic nozzle diameter.

In the case of clustered rocket engines with intermediate spacing between the nozzles, the hydrodynamic interaction among the exhaust jets is such that the individual jets radiate noise independently in the initial stage but ultimately combine into a single effective stream. The resulting complexity of the flow field significantly modifies the acoustic near-field (typically within 40 jet diameters, or about 100 m from the launch mount in a typical full scale) because of the changes in the strength and distribution of the turbulent noise sources. Under such circumstances, the totality of the noise spectrum is due to both the individual jets and the combined flow [8,9]. As a consequence, the equivalent diameter approach does not hold for the entire region. A major limitation of this highly simplified method based on equivalent diameter is that it fails to predict the multiple-peaked spectrum of sound in the near-field, which can affect the resonant vibration modes of the nearby structures. Furthermore, it typically produces noise level uncertainty of as much as 10–15 dB. Thus it is imperative to develop an improved method to estimate the acoustic effects of clustered rocket thrusters.

Methods somewhat similar to that of Eldred [9] have been recently reported for the prediction of noise from coaxial jets [10–12]. These pertain primarily to subsonic jets with application to commercial jet engines, whereas the present work is concerned primarily with application to rocket engines and launch acoustics.

In this article derived primarily from Ref. [13], Eldred's two-zone model for the effect of clustered nozzle interaction is implemented and demonstrated. Also, the effect of ground reflection, important to launch vehicle environment, is assessed.

2. Analysis

2.1. Clustered nozzle interaction

For intermediate spacing of clustered nozzles, Eldred [9] presented a two-zone noise prediction method (Fig. 1). In zone 1, the individual nozzles generate and radiate noise independently so that superposition holds. In zone 2, it is idealized that the jets combine to form an equivalent single jet. The distance at which the individual jets completely mix together and the effective size and properties (velocity, temperature, etc.) are deduced by considerations of mass, momentum, and energy balances. The transition region between zone 1 and zone 2 is removed from consideration in view of its complexity.

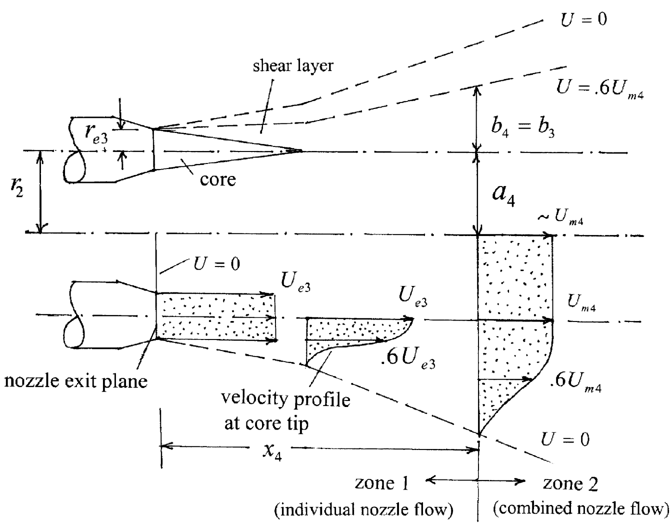

Fig. 1. Interaction of exhaust jets from peripheral tube nozzles, according to Eldred's model [9].

On the basis of mass, momentum and energy conservation considerations and some assumptions, the velocity ratio and temperature ratio of the combined stream are found to be [9]

$$\frac{U_{e4}}{U_{e1}} = f(\alpha,\beta) = \frac{1}{2}\left\{\alpha(1-\beta) \pm \sqrt{\alpha^2(1-\beta)^2 + 4\alpha\beta}\right\}, \tag{1a}$$

$$\frac{T_{e4}}{T_0} = \frac{1}{1-\alpha\left(U_{e1}/U_{e4}\right)(1-\beta)}, \tag{1b}$$

where U_{e4} is the maximum velocity of the combined jet, T_{e4} the temperature of the combined jet, U_{e1} the nozzle exit velocity, and T_0 the ambient temperature. The area ratio α and the temperature ratio β are defined by

$$\alpha = A_{e1}/A_{e4}, \quad \beta = T_0/T_{e1}. \tag{2a}$$

Here the quantity T_{e1} stands for the jet exit temperature, and $A_{e1}$and A_{e4}, respectively, represent the total individual jet area and the area of the combined jet. We thus have

$$A_{e1} = nA_{e3} = n\pi r_{e3}^2, \quad A_{e4} = \pi r_{e4}^2, \tag{2b}$$

where r_{e3} is the exit radius of the individual nozzle, A_{e3} the exit cross section of the individual nozzle, and n the number of nozzles. The quantity r_{e4} is expressed by

$$r_{e4} = a_4 + b_4 = r_2\left(1 - \frac{r_{e3}}{r_2}\right)\left(\frac{n^{1/2}}{n^{1/2}-1}\right), \quad a_4 \approx r_2 - r_{e3}. \tag{2c}$$

In Eq. (2c), a_4 is the width of the combined jet core. The distance $(a_4 + b_4)$ corresponds to a radial location where the local velocity is 0.6 times the maximum velocity (based on effective momentum). The quantity α can be shown to be related to the geometric parameters as

$$\alpha = \frac{\left(n^{1/2}-1\right)^2}{\left(r_2/r_{e3}-1\right)^2}. \tag{3}$$

Fig. 2 shows the variation of the velocity ratio as a function of the jet area ratio, with the temperature ratio as a parameter. Departures from the constant density jet ($T_0/T_{e1} = 1$) are seen to be important. A more comprehensive effect of the temperature is considered in Ref. [8].

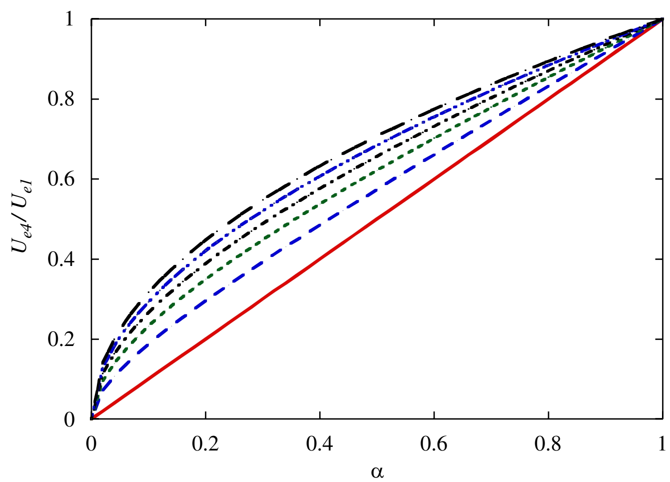

Fig. 2. Dependence of the velocity of the combined jet on jet area ratio for various values of jet temperature ratio. —— $\beta = 0$, – – – – $\beta = 0.2$, ----- $\beta = 0.4$, -·-·- $\beta = 0.6$, ········ $\beta = 0.8$ and — —— $\beta = 1.0$.

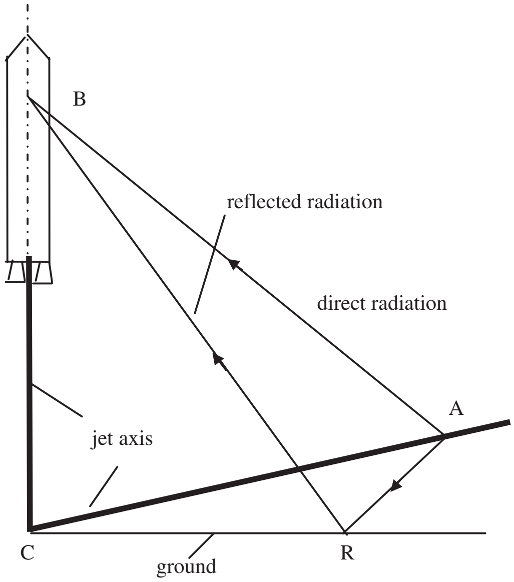

Fig. 3. Schematic of the ground reflection effect.

The axial location from the nozzle exit x_4 where zones 1 and 2 are separated is expressed by the following relation:

$$\frac{x_4}{x_t} = \begin{cases} \dfrac{2\left(r_2/r_{e3} - 1\right)}{n^{1/2} - 1} - 1, & x_4 > x_t, \\ \dfrac{\left(r_2/r_{e3} - 1\right)}{n^{1/2} - 1}, & x_4 < x_t. \end{cases} \tag{4}$$

It is pointed out by Eldred [9] that when the individual nozzles are in close proximity, their total acoustic power generation in zone 1 (initial mixing region) can be considerably less, because only the peripheral mixing zone is of major importance in the noise generation.

2.2. Effect of ground reflections

Ground refection increases the overall sound pressure level (OASPL) on the vehicle by 3–6 dB. A value of 0.5 is usually considered in the overall effective reflectivity. A schematic of the reflected path of the radiation emanating from the jet is depicted in Fig. 3. Considering that A is the axial source, and B the point on the vehicle, the direction AB represents the direct sound path, whereas the direction RB represents the reflected sound path.

Reflections from the surface of the launch vehicle can also be significant. On the surface of the vehicle facing the exhaust flow, a local increase in the SPL of as much as 6 dB (relative to that predicted for the free field) is possible, depending on the angle of incidence [6]. Near the sides of the vehicle, the reflection effect is not significant, and the SPL is close to that in the free field. On the side of the vehicle opposite the flow, the shielding of the vehicle will diminish the SPL relative to the free field. The effect of large reflecting surfaces such as launch stand walls should also be considered in estimating the acoustic levels.

3. Results and comparison

3.1. Clustered nozzle effect

A sample case is presented here to highlight the characteristics of clustered nozzles with significant interaction effects. A typical configuration for the expendable launch vehicle (ELV) with a cluster of four

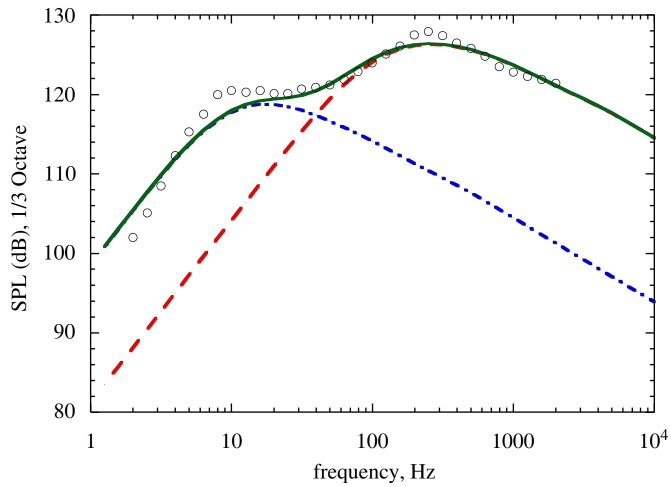

Fig. 4. Comparison of the predicted sound pressure level spectrum with data for a clustered rocket engine. ----- theory (isolated zone), -·-·- theory (mixed zone), —— theory (total) and ○ data.

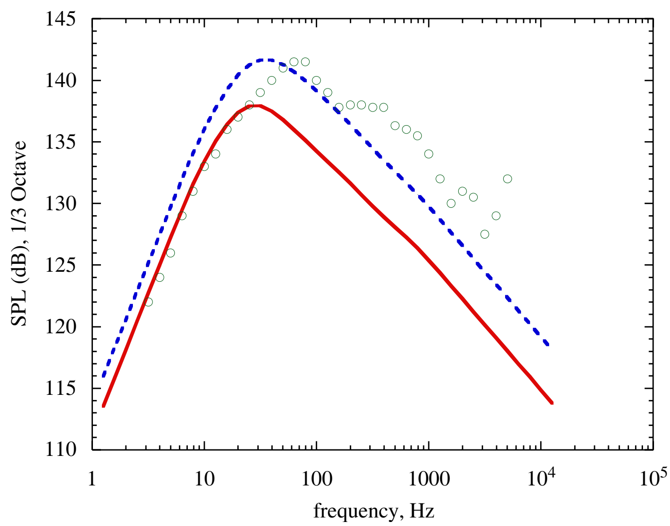

Fig. 5. Comparison of the theory with data for the effect of ground reflection on the sound pressure level spectrum. —— prediction (no ground reflection), ----- prediction (with ground reflection) and ○ data.

identical nozzles is chosen for this purpose. Eldred's model [9] for clustered nozzles is considered to predict the acoustic levels. Fig. 4 shows the calculated spectrum, which signifies the existence of two peaks. Whereas the high frequency corresponds to the length scale associated with isolated nozzles in zone 1, the low frequency is characteristic of the length scale corresponding to the combined flow.

3.2. Ground reflection effect

A second sample test case is chosen to illustrate the role of ground reflections on the acoustic levels. Fig. 5 displays the results for a large rocket cluster, for which jet interaction effects are not appreciable. Predictions based on NASA SP-8072 for the acoustic levels at a particular position on the vehicle are shown with and without the ground effects. A sound reflection coefficient of 0.5 is chosen. The results show that ground reflections enhance the SPL by as much as 5 dB and enable a closer agreement with the test data. Both the calculations and the data yield a single peak frequency, with the ground reflections improving the prediction of the peak frequency. The reason for the minor oscillations in the data beyond the peak frequency is not clear.

4. Conclusion

A calculation procedure has been implemented for the prediction of acoustic levels from large clustered rockets. Test cases have been identified to signify the ground effects and the role of hydrodynamic interactions between the neighboring jets. It is shown that the ground reflections enhance the acoustic levels by as much as 5 dB and that the ground reflections seem to increase the peak frequency. For intermediate spacing of clustered rockets, the manifestation of two peak frequencies in the sound spectrum is evident, which correspond to the isolated zone (noninterfering jets) and the mixed zone. Satisfactory agreement is noted between the predictions and the data in the assessment of the effects of jet interaction and ground reflections.

Acknowledgments

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