Near-Field Acoustical Characterization of Clustered Rocket Engines

Max Kandula[*]

Sierra Lobo, Inc. (USTDC), Kennedy Space Center, FL 32899

Bruce T. Vu[†]

NASA, John F. Kennedy Space Center, FL, USA

Halie K. Lindsay[3]

North Carolina Agricultural & Technical State University

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[7], wherein the flowfield from the clustered rockets is divided into two zones. Zone 1 contains the isolated nozzles which 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 of Eldred[5] 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 non-interfering jets. A graphics interface (Rocket Acoustic Prediction Tool) has been developed to take into account the effects of clustered nozzles and ground reflections.

Nomenclature

A_{e1} = total individual jet area

A_{e3} = exit area of individual nozzles

a = speed of sound, m/s

a_0 = speed of sound in the atmosphere, m/s

a_e = speed of sound in the flow at the nozzle exit, m/s

$DI(b, \theta)$ = directivity at the angle θ for the band centered at frequency b, dB

d_e = nozzle exit diameter

d_{eq} = equivalent nozzle exit diameter for a clustered nozzle, m

F = thrust of each engine, N

[*] Sr. Principal Investigator, Mail Stop ASRC-3, Kennedy Space Center, FL 32899, Associate Fellow AIAA.
[†] Lead, Launch Systems Testbed, Senior Member AIAA
[3] Graduate Student

1

f_p	=	peak frequency, Hz
Δf_b	=	bandwidth of the frequency band, Hz
$L_{w,b}$	=	sound power level in the band centered on frequency b, dB (re 10^{-12} W)
M_e	=	jet exit Mach number, U_e / a_e
m_t	=	nozzle mass flow rate, kg/s
n	=	number of nozzles
r	=	length of the radius line from the assumed position of the frequency source to the point on the vehicle
r_{e3}	=	exit radius of individual nozzles
St	=	Strouhal number, $f_p d_e / u_j$
St_x	=	axial Strouhal number, $f x a_e /(U_e a_e)$
T_{e1}	=	jet exit temperature, K
T_{e4}	=	temperature of combined jet, K
U_e	=	fully expanded exit velocity, m/s
U_{e1}	=	nozzle exit velocity, m/s
U_{e4}	=	maximum velocity of combined jet, m/s
W_m	=	mechanical power of jet, W
W_{OA}	=	overall acoustic power, W
$W(f,x)$	=	sound power per Hz per unit axial length at distance x along the flow axis, W/Hz/m
x	=	distance along the flow axis from the nozzle to the center of the slice, m
x_t	=	core length, m
Δx	=	length of plume slice, m

GREEK SYMBOLS

α	=	area ratio, A_{e1} / A_{e4}
β	=	temperature ratio, T_0 / T_{e1}
θ	=	angle between the flow centerline and r
γ	=	specific heat ratio

SUBSCRIPTS

0	=	ambient
1	=	jet exit

e =   jet exit

*   =   nozzle throat

I.   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. In order 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 (Lighthill[1,2]) for subsonic jet noise, and its extension to supersonic jets (Ffowcs Williams[3]; Tam[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 (Kandula and Vu[5]) provide an economical alternative for noise prediction from realistic rocket engine configurations for preliminary design purposes.

Currently the NASA SP-8072 method (Eldred[5]), 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 non-interfering jets (widely spaced nozzles). In the other extreme case of 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 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 flowfield significantly modifies the acoustic near-field (typically within 40 jet diameters, or about 300 ft. from the launch mount in a typical full scale) on account 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 (Potter and Crocker[6], Eldred[7]). As a consequence, the equivalent diameter approach does not hold. 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 an uncertainty of as much as about 10-15 dB noise level. 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[7] have been recently reported for the prediction of noise from coaxial jets (Fisher et al.[8,9]; Garrison et al.[10]). These pertain primarily to subsonic jets with application to commercial jet engines, while the present work is concerned primarily with application to rocket engines and launch acoustics.

In this report, 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.

II.   Analysis

A. Clustered Nozzle Interaction

For intermediate spacing of clustered nozzles, Eldred[7] presented a two-zone noise prediction method (Figs. 1a and 1b). In Fig. 1a, the longitudinal view shows two nozzles, although the cross sectional view indicates 4 nozzles

for illustration purposes. 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 together 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.

1. *Air Entrainment*

The velocity ratio and temperature ratio of the combined stream are found to be

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

$$\frac{T_{e4}}{T_0} = \frac{U_{e4}}{U_{e4} - \alpha U_e(1-\beta)} \tag{1b}$$

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

$$A_{e1} = nA_{e3} = n\pi r_{e3}^2, \quad A_4 = \pi r_{e4}^2$$

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

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

Here 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)

Mass, momentum and energy considerations show that the values of α and β can be deduced from

$$\alpha = \frac{\left(n^{1/2} - 1\right)^2}{\left(r_2 / r_{e3} - 1\right)^2}, \quad \beta = \frac{U_{e4}T_0}{U_{e4} - \alpha U_e(1-\beta)} \tag{3}$$

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 ($T_0 / T_e = 1$) are seen to be important. A more comprehensive effect of the temperature is considered by Potter and Crocker[6].

2. *Length of Mixing Region*

The axial location x_4 where zone 1 and zone 2 are separated is expressed by the following relation:

$$\frac{x_4}{x_t} = \begin{cases} \dfrac{2(r_2 / r_{e3} - 1)}{n^{1/2} - 1} & x > x_t \\[4mm] \dfrac{(r_2 / r_{e3} - 1)}{n^{1/2} - 1} & x < x_t \end{cases} \qquad (4)$$

It is pointed out by Eldred[7] 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.

B. Effect of Reflections

1. Ground Reflections

Ground refection increases the OASPL on the vehicle by 3 to 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, while the direction RB the reflected sound path.

2. Vehicle and Surface Reflections

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 SPL of as much as 6 dB (relative to that predicted for the free field) is possible, depending on the angle of incidence (Eldred[5]). 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 from 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.

III.   Rocket Acoustic Prediction Tool (RAPT) Development

On the basis of Eldred's clustered nozzle mode, a Rocket Acoustic Prediction Tool (RAPT), with a user-friendly graphic-user interface (GUI), is developed. The GUI is accomplished with the aid of Visual Basics. In addition, the dynamic link library (DLL) from the main prediction program, coded in C++ or Fortran, is called from the GUI, to eliminate all the command-line options.

Different input parameters needed for the acoustic estimation can be interactively specified. This feature as it would enable design engineers to conduct parametric studies on acoustic loads produced by different rocket engine configurations. The present version of RAPT also includes ground reflection effects.

Figure 4a shows a typical plot of SPL vs. frequency. The input menu, composed of various flow and geometric parameters is displayed in Fig. 4b.

Results and Comparison

A. Clustered Nozzle Effect
A sample case is presented here in order 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 identical nozzles is chosen for this purpose. The procedure of Eldred[7] for clustered nozzles is considered to predict the acoustic levels. Figure 5 shows the calculated spectrum, which signifies the existence of two peaks. While 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.

B. Ground Reflection Effect

A second sample test case is chosen to illustrate the role of ground reflections on the acoustic levels. Figure 6 displays the results for a large rocket cluster, for which jet interaction effects are not appreciable. Predictions based on the Eldred's model[5] 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

V. 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 role of hydrodynamic interactions between the neighboring jets, and also the ground effects. It is shown that the ground reflections 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 respectively to the isolated zone (non-interfering jets) and the mixed zone. Satisfactory agreement is noted between the predictions and the data in the assessment of effects due to jet interaction and ground reflections.

Acknowledgments

References

[1] Lighthill, M.J., On sound generated aerodynamically, I. General Theory, Proc. Roy. Soc. A, 211, 564-587, 1952.

[2] Lighthill, M.J., On sound generated aerodynamically, II. Turbulence as a source of sound, Proc. Roy. Soc., A, 222, 1-32, 1954.

[3] Ffowcs Williams, The noise from turbulence convected at high speed, Proc. Roy. Soc., A, 255, 469, 1963.

[4] Tam, C.K.W., On the noise of a nearly ideally expanded supersonic jet, J. Fluid Mechanics, Vol. 51, Part I, pp. 69-95, 1972.

[5] Kandula, M., and Vu, B., On the scaling laws for jet noise in subsonic and supersonic flow, AIAA-2003-3288, 9th AIAA/CEAS Aeroacoustics Conference, Hilton Head, South Carolina, May 2003.

[5] Eldred, K.M., Acoustic loads generated by the rocket propulsion system, NASA SP-8072, June 1971.

[6] Potter, R.C., and Crocker, M.J., Acoustic prediction methods for rocket engines, including the effects of clustered engines and deflected exhaust flow, NASA CR-566, 1966.

[7] Eldred, K., Mann, M., White, R.W., and Cottas, M., Suppression of jet noise with emphasis on the near field, ASD-TDR-62-578, Wright Patterson AFB, Ohio, Feb. 1963.

[8] Fisher, M.J., Preston, G.A., and Bryce, W.D., A modeling of the noise from simple coaxial jets, Part I: with unheated primary flow, J. Sound and Vibration, Vol. 209, No. 3, pp. 385-403, 1998.

[9] Fisher, M.J., Preston, G.A., and Bryce, W.D., A modeling of the noise from simple coaxial jets, Part II: with heated primary flow, J. Sound and Vibration, Vol. 209, No. 3, pp. 405-417, 1998.

[10] Garrison, L.A., Dalton, W.N., Lyrintzis, A.S., and Blaisdell, G.A., An investigation of the extension of the four-source method for predicting the noise from jets with internal forced mixers, AIAA 2003-3165, 9th AIAA/CEAS Aeroacoustics Conference, Hilton Head, South Carolina, May 2003.
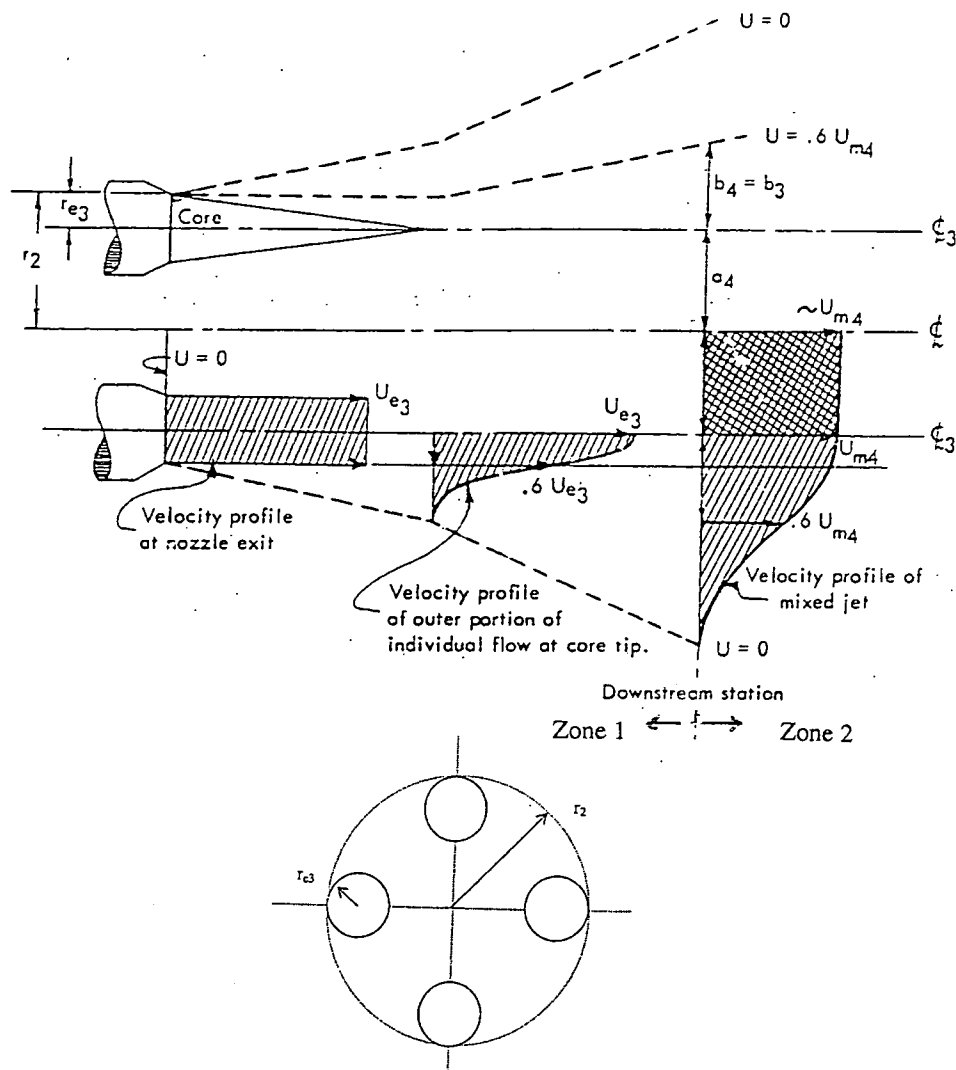
Figure 1a: Interaction of exhaust jets from peripheral tube nozzles, according to Eldred's model[7].
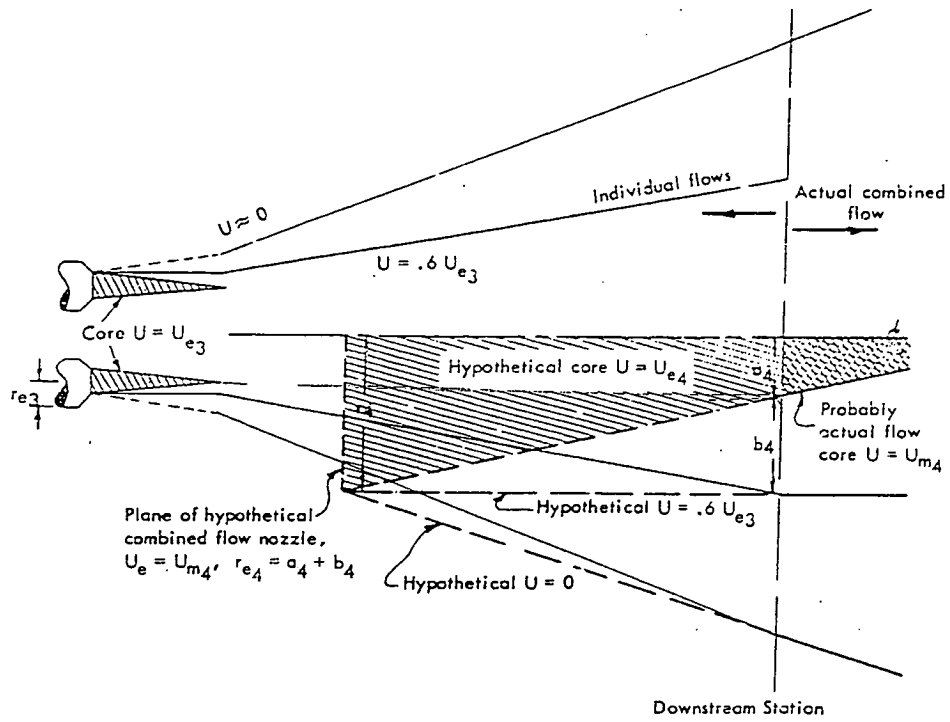
American Institute of Aeronautics and Astronautics

Figure 1b: The superposition of hypothetical nozzle for the downstream combined flow (from Eldred[7]).

American Institute of Aeronautics and Astronautics
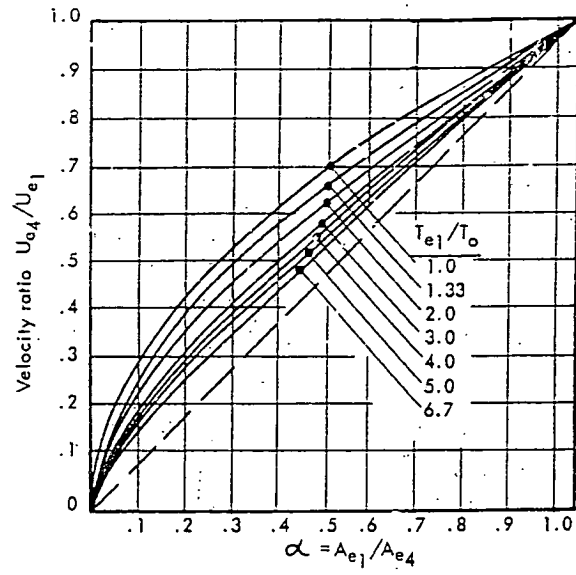
Figure 2: Dependence of the velocity of the combined jet on jet area ratio for various values of jet temperature ratio (Eldred, 1963).
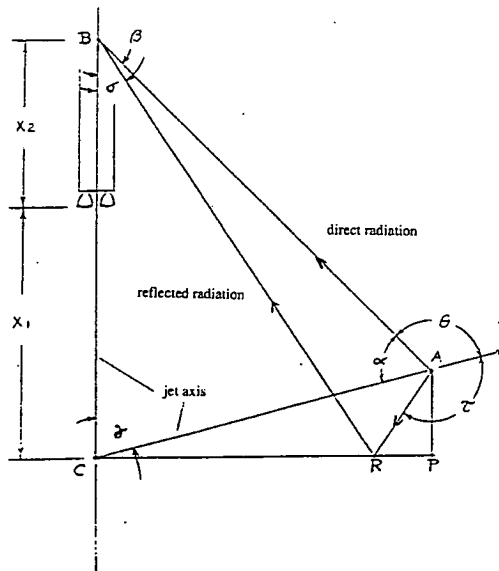
Figure 3: Schematic of the ground reflection effect.

Figure 4a: Spectral Sound Pressure Level from RAPT   Figure 4b: Input Parameters in RAPT

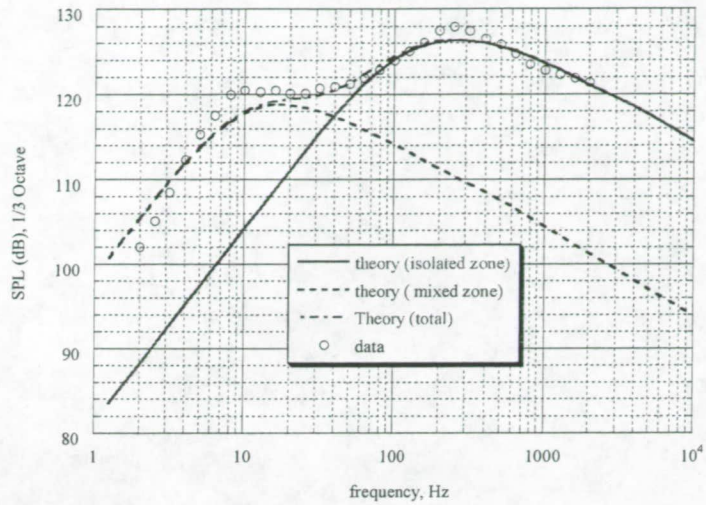American Institute of Aeronautics and Astronautics

Figure 5: Comparison of the predicted sound power level with data for a clustered rocket engine.
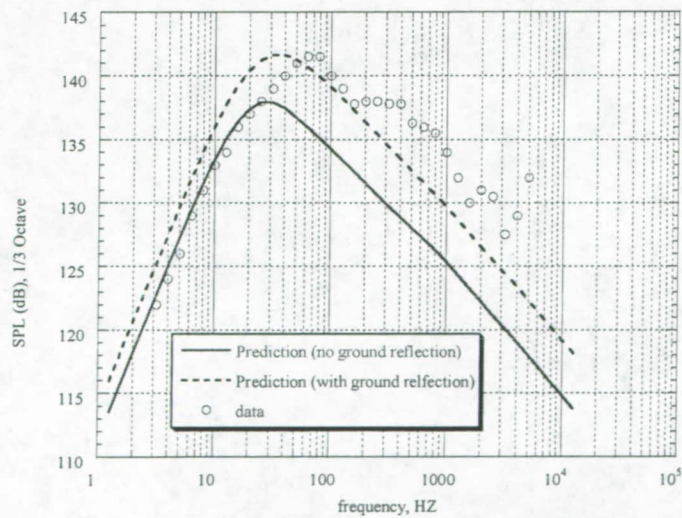

Figure 6: Comparison of theory with data for the effect of ground reflection on the spectral sound power distribution.