

SEMIEMPIRICAL MODEL OF THE ACOUSTICS OF A SUPERSONIC JET UPON COLLISION WITH A PERPENDICULAR WALL

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ABSTRACT

This study presents a semiempirical model for estimating the acoustic loads generated by a supersonic jet colliding with a rigid perpendicular wall, expanding on traditional methodologies used to assess rocket jet acoustics near the launch structure. Unlike conventional approaches, the proposed model eliminates the need for additional algorithms to describe the flow-surface interaction zone. Instead, it reconfigures acoustic sources attributed to the free jet. Contributions from the undisturbed jet segment, the interaction zone, and acoustic reflection are compared as a function of the nozzle-wall distance. The simulation highlights the dominant role of reconfigured sources in increasing sound levels when the jet interacts with a nearby surface. This methodology is particularly relevant for modeling the acoustic environment during rocket lift-off and can support the engineering design of space vehicles.

Keywords

turbulence, supersonic jet, rocket noise, obstacle, acoustic loads.

1. INTRODUCTION

Large space launch vehicles rank among the most powerful man-made sound sources. In the initial flight interval, the noise generated by the rocket's hot supersonic jet reaches levels that may seriously affect the vehicle's structural elements, the environment, and the launch personnel. Often, however, it is the equipment or payload in the compartment under the fairing of the rocket head that is most susceptible to these severe acoustic loads. Therefore, accurately assessing and predicting the loads during lift-off is a critical procedure in developing new rocket systems.

The acoustic radiation produced by rocket engines is typically dominated by broadband mixing noises of a turbulent nature. Paradoxically, just a small portion of the kinetic energy of a supersonic jet is converted into generating such intense sound. This vast disparity in the power scales of gas-dynamic and acoustic processes is the

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Received 25.10.2024 • Revised 29.11.2024 • Accepted 02.12.2024

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main reason for the complexity of adequate computer simulation and analysis of rocket engine exhaust as a source of sound. Indeed, to capture the sound generation mechanisms, one needs to accurately reconstruct the fine details of various-scale non-stationary vortex structures formed during the laminar-turbulent transition in the jet periphery, mixing with atmospheric air [1,2]. Here the local Reynolds Numbers for the typical rocket nozzle diameters and exhaust velocities may exceed 10^6 , necessitating the use of cumbersome, sophisticated algorithms for the effective numerical modeling of such gas-dynamic turbulence. Even with state-of-the-art supercomputers, the computational cost of such detailed turbulence modeling remains extremely high [2,3].

Therefore, at the preliminary design stage, semiempirical methods are widely used to estimate the sound fields generated by a rocket flight. This approach is based on well-established spatial-frequency distributions of sound source characteristics known from experiments. It is undemanding in terms of computing power and provides accuracy acceptable for engineering purpose. However, in most cases, the semiempirical methodology uses information on the properties of free supersonic jets, whereas the actual launch scenario involves intense interaction of the exhaust trail of the rocket engine with the surface of the launch pad or gas deflector. This results in significant rescaling and spatial redistribution of the turbulent vortex structures and associated sound sources [4,5].

In this context, modeling the acoustic effects of a jet's collision with a rigid wall, as a function of the rocket's lift-off height, is of fundamental importance. Some researchers address this by introducing an additional acoustic source with special parameters located in the jet-wall interaction zone [6]. In our opinion, however, this procedure violates the core logic of the semiempirical methodology and causes complications in the computational schemes. To overcome these issues, in this paper we propose an alternative approach: constructing the new acoustic source directly on the rigid wall obstacle, due to the partial redistribution of the energy of the known free supersonic jet sources.

2. SELF-SIMILARITY OF ACOUSTIC PROPERTIES OF A SUPERSONIC JET

The semiempirical approach in rocket acoustics emerged in the 1960s, a period marked by rapid development in rocket and space programs. Its theoretical foundations were laid in classical studies by M. J. Lighthill and J. Ffowcs Williams on the generation of mixing noise by a supersonic jet [7,8]. As the Mach number increases for $M > 2$, the supersonic transportation of turbulent structures downstream causes the efficiency of acoustic radiation to increase, stabilizing at $M > 3$ and reaching an asymptotic value of 0.6%. In this process, the nature of acoustic sources gradually shifts from quadrupole to monopole. Moreover, due to the convective migration of the sources, the acoustic directivity pattern typical for rocket engine

sound emission arises, with a maximum inclined at an angle of $\theta \approx \arccos(1/M_c)$ to the main flow, where M_c is the convective Mach Number [7].

The universality of the mechanism shaping the acoustic properties of a supersonic flow made it possible to avoid detailed consideration of its turbulent structure. Instead, efforts were directed towards identifying self-similar relationships between the integral parameters of the rocket jet and the characteristics of the generated sound. The analysis of a vast amount of full-scale and model experimental data led to the discovery of such relationships, which were incorporated into the renowned NASA SP-8072 regulations for calculating acoustic loads from rocket engine jets [9]. Here, the energy, spatial, frequency, and directional properties of the sound from a free jet are preset. According to this methodology, the acoustic pressure at any arbitrary observation point outside the supersonic flow is expressed as the product of these independent factors.

2.1. OVERALL ACOUSTIC POWER

The starting point of calculations is the assessment of the overall sound power radiated by the gas-dynamic flow. In rocketry, the overall power W_{jet} of the jet is usually expressed in terms of the thrust N (driving force) and gas velocity v_e at the nozzle exit. Thus,

$$W_{OA} = \eta W_{\text{jet}} = \frac{\eta}{2} N v_e, \quad (1)$$

where η is the acoustic efficiency of the flow. As mentioned above, its theoretical limit is $\eta = 0.006$. However, its actual value may be somewhat lower because of the gradual deceleration of the peripheral turbulent structures carried downstream. Therefore, NASA regulations suggest adopting acoustic efficiency values within the limits of $\eta = 0.005 \pm 0.0022$ [9]. The authors of studies [10,11] tried to define η as a function of the gas-dynamic parameters of particular jets, but still, no significant progress was made. Here we adopt $\eta = 0.006$, which is close to a conservative estimate of the overall sound level radiated by the rocket jet.

The acoustic power is traditionally expressed in decibels (dB), using a logarithmic scale. So, the overall sound power level above the standard threshold 10^{-12} W is

$$L_w = 120 + 10 \lg W_{OA}. \quad (2)$$

2.2. AXIAL POWER DISTRIBUTION

Since the sound generated by the rocket jet is predominantly of turbulent origin, the longitudinal distribution of the radiated acoustic power depends on the natural spatial scale, namely the length s_L of the laminar core. Let s be the axial coordinate along the jet and let $s = 0$ stand for the nozzle exit, where the supersonic flow is almost laminar. Later, its periphery becomes turbulent due to the slowdown of

exhausted gases contacting the still quiescent ambient air in the mixing layer. As the flow moves downstream, the undisturbed laminar core degenerates, and the thickness of the mixing layer progressively increases due to the turbulence penetrating inside the jet, so it finally becomes turbulent across its full cross-section. In general, the laminar core is of a conical shape, with the distance $s = s_L$ from the nozzle to its top being the length of the core (see Fig. 1).

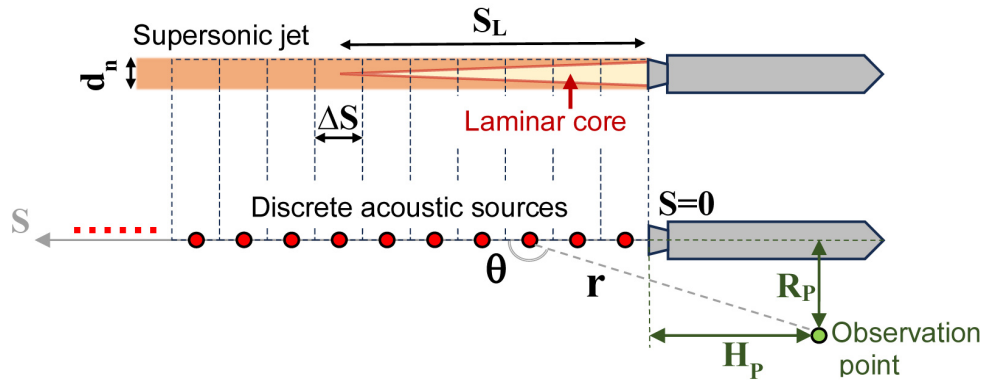


Fig. 1. Schematic representation of a free rocket jet, showing its principal dimensions and the distribution scheme of discrete acoustic sources along the jet's centerline.

According to [9], the length of the laminar core is

$$s_L = 3.45d_n(1 + 0.38M_e)^2, \quad (3)$$

where M_e is the Mach Number of the jet at the nozzle exit. The normalizing dimension d_n is either the nozzle diameter (d_e), or the diameter of the perfectly expanded jet (d_j). The value of d_j is assessed from the basic gas-dynamic parameters of the rocket engine [12]. Usually, for engines of the first stages of space rockets, $d_j < d_e$, and the difference is less than 20%. Therefore, the choice between d_e and d_j in (Eqn. 3) is almost equivalent in engineering applications. Moreover, this is why the longitudinal variation of the jet's cross-section is not shown in Fig. 1.

The energy of jet turbulence and related sound is determined by two competing factors: the increasing fraction of the jet occupied by the vortex structures and the local rate of convective transfer, decreasing downstream due to flow deceleration. For practical purposes, the acoustically active segment of the jet is set within $0 \leq s \leq 5s_L$, with the maximum sound emission at $s \approx 1.5s_L$. In this zone the velocity of its periphery is still high, so the most intense turbulence in the mixing layer occurs [13,14]. Downstream, the turbulence energy in the mixing zone gradually decays.

The universal longitudinal distribution of the normalized sound power level:

$$L^*\left(\frac{s}{s_L}\right) = 10 \lg \left(\frac{s_L W(s)}{W_{OA}} \right)$$

is shown in Fig. 2. It was noticed quite a long time ago that the use of the traditional distribution [9] (dashed curve) leads to an erroneous overestimation of the contribution of the remote part of the jet to the induced acoustic field [15]. In the early 2000s, the short laminar core theory was developed to correct this imbalance [13]. Later, it was criticized for apparent non-conformity with the experimental data [14,16], and Eldred's normalization was rehabilitated.

In this study, we instead opt to use another corrected longitudinal energy distribution [15,17], combined with the classic estimate of the length of the laminar core (Eqn. 3). It suggests more than half of sound energy be emitted by the sources located at $s/s_L < 1.5$ from the rocket nozzle, see Fig. 2, solid curve. We approximate this dependence with the following piecewise polynomial:

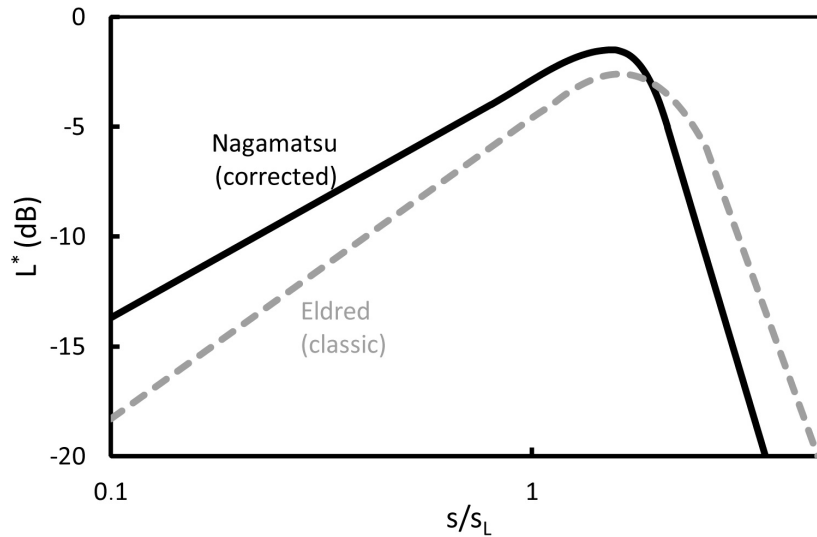


Fig. 2. The universal distribution of the acoustic power along the supersonic jet.

$$L^*(s^*) = \begin{cases} 10.75 \lg s^* - 2.95, & s^* < 0.8; \\ -80.8 \lg(s^*/1.55)^3 - 53.5 \lg(s^*/1.55)^2 - 1.5, & 0.8 \leq s^* \leq 1.55; \\ -646.6 \lg(s^*/1.55)^3 - 116 \lg(s^*/1.55)^2 - 1.5, & 1.55 \leq s^* \leq 2.1; \\ -64.35 \lg s^* + 15.7, & s^* > 2.1, \end{cases} \quad (4)$$

where $s^* = s/s_L$.

2.3. FREQUENCY SPECTRUM

The frequency spectrum $W(f, s)$ of the sound radiated by the supersonic jet in its cross-section s depends on the modified Strouhal Number $St'_s = St_s c_e / c_a$:

$$L^{**}(St'_s) = 10 \lg \left[\frac{W(f, s) v_e c_a}{W(s) s c_e} \right],$$

where f is frequency, $St_s = fs/v_e$ is the axial Strouhal Number, c_e and c_a are the sound speeds in rocket exhaust and atmospheric air, respectively. According to [18],

$$L^{**}(St'_s) = \begin{cases} 10 \lg St'_s - 7, & St'_s < 0.8; \\ -12 \lg (St'_s / 1.5)^3 - 18 \lg (St'_s / 1.5)^2 - 6.7, & 0.8 \leq St'_s \leq 3.55; \\ -23 \lg St'_s + 2.5, & St'_s > 3.55. \end{cases} \quad (5)$$

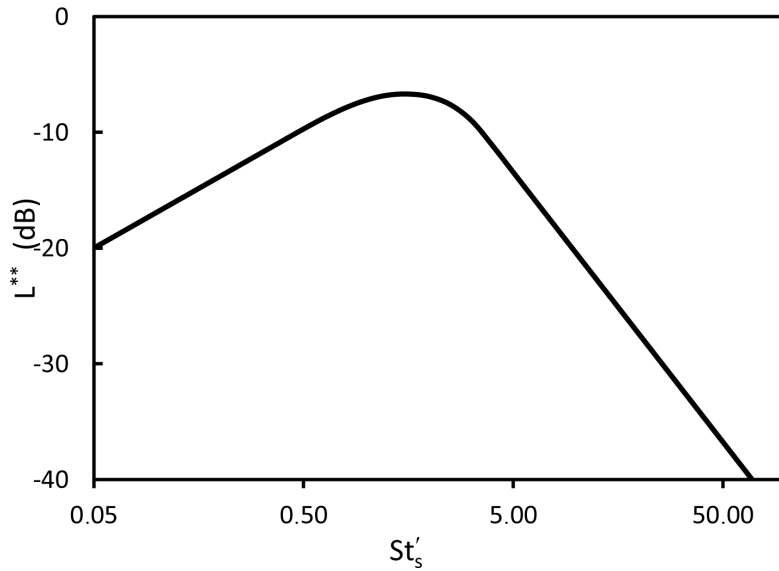


Fig. 3. The universal frequency distribution of the acoustic power for the s -th jet cross-section.

The graph of $L^{**}(St'_s)$ is shown in Fig. 3 [9,18]. As self-similarity is observed for the product of $fs = \text{const}$, the further downstream, the lower the frequencies that are generated. Such a tendency conforms with the physical nature of turbulence in the jet. Namely, the larger-scale vortex structures that correspond to the low-frequency part of the spectrum develop at greater distances [1].

2.4. DIRECTIVITY INDEX

A complete description of the acoustic field generated by the rocket jet requires consideration of its directivity index. Although several variants of directional diagrams depending on the Strouhal number $St_d = fd_n/v_e$ have been proposed, there is still no agreement on this matter [4,9,11]. In general, a well-defined emission maximum usually lies in the direction of the order of $\theta \approx 50^\circ$, but a frequency

dependence is also observed. To address this, an interesting approach to calculating the modified apparent axial source locations was proposed in [19].

Here we use the model [11], employing the suitable approximation formula [18]:

$$DI(St_d, \theta) = 10 \lg \frac{0.37(1 + \cos^4 \theta_e)}{((1 - 0.75 \cos \theta_e)^2 + 0.16875)^{2.5} (1 + 310 \exp(-9\theta_e))} - (7) \\ - 0.698 \cdot \lg St_d - 1.67.$$

In (Eqn. 6), $\theta_e = \theta - 9.61 \cdot \lg(St_d/0.01515)$. Note that the true angle θ should be set in degrees, but the value of θ_e is read in radians. Unlike the frequency spectrum, the directivity is controlled by the Strouhal number scaled by the nozzle diameter, which is constant for the particular rocket engine.

Examples of the directivity index approximated by (Eqn. 6) are shown in Fig. 4. Due to the actual spatial jet's divergence, only the sector of $\theta > 20^\circ$ should be considered. For typical space rockets, the chosen range of St_d from 0.05 to 5 is wide enough to cover most of the frequency band of rocket jet noise. While these dependencies resemble the curves from [9], the predicted levels for $\theta > 90^\circ$ and $St_d \gg 0.1$ may differ for 2 to 5 dB.

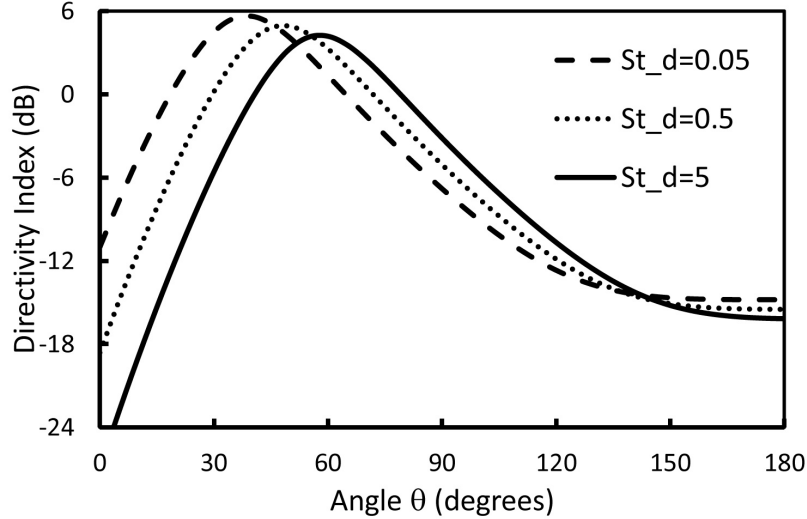


Fig. 4. The directivity index of the supersonic jet according to [11,18].

3. DISCRETE SOURCE METHOD

3.1. FREE SUPERSONIC JET

Knowing the spatial-frequency distributions of the radiated acoustic power, one can represent a supersonic jet as a continuous linear sound source. Still, in practice,

it is usually approximated as a discrete set of point sources, each corresponding to a sufficiently short jet cross-sections Δs (see Fig. 1). From the point of view of wave acoustics, Δs should be chosen to be smaller than the wavelength for the upper limit of the studied frequency range. However, the uncorrelated nature of the mixing noise and the phase stochasticity of the jet-generated sound field allows it to be described in terms of intensity, without considering any diffraction effects. On the one hand, we can relax the requirements for the value of Δs . On the other hand, the sound pressure level at any arbitrary observation point P outside the jet may be assessed using the simplified approach of geometrical acoustics. In engineering practice, the frequency range is typically divided into octave or suboctave bands with the central frequencies f_b and widths Δf_b .

Taking the above into account, one can readily show that the level of the acoustic pressure (in dB) generated by the s -th sound source at point P is given by:

$$L_{s,b,P} = L_W + L^* \left(\frac{s}{s_L} \right) + L^{**}(\text{St}'_s) + \text{DI}(\text{St}_d, \theta) + 10 \lg \left(\text{St}'_s \frac{\Delta s}{s_L} \frac{\Delta f_b}{f_b} \right) - 10 \lg(4\pi r^2). \quad (8)$$

Here, r is the distance from the source to point P , θ is the angle between the flow direction and the direction to point P . The last term in (Eqn. 8) stands for the spherical divergence of sound energy.

The logarithmic summation of the contributions of all sources to the observation point yields the sound level $L_{b,P}$ in the band with the central frequency f_b . The summation of all frequency band levels yields the overall sound level $L_{OA,P}$ at point P :

$$L_{b,P} = 10 \lg \left[\sum_s 10^{L_{s,b,P}/10} \right], \quad L_{OA,P} = 10 \lg \left[\sum_b 10^{L_{b,P}/10} \right]. \quad (9)$$

3.2. SUPERSONIC JET IN NORMAL COLLISION WITH A WALL

Having established an applied theory for the acoustics of a free rocket jet, we now proceed to model the specifics of sound generation upon supersonic jet collision with a rigid wall. Such an interaction inevitably leads to a critical loss of the jet's longitudinal momentum. Note that the supersonic flow never reflects, but always spreads over the surface. This scenario is valid even for the collision inside the laminar core, immediately destroying its structure. In all cases, rapid flow turbulization around the interaction zone is always observed.

Clearly, interaction with an obstacle cannot increase the jet's kinetic energy. Another reasonable assumption is that the total level of flow turbulization will not considerably change. Note that for subsonic turbulent flows, the occurrence of a rigid

wall leads to a transition from the quadrupole to the dipole model of sound radiation, significantly increasing its efficiency. In contrast, in a free supersonic flow with $M > 3$ all turbulent sources have already transformed into monopoles [7,8], i.e., their efficiency is as high as possible. Therefore, one can conclude that the acoustic efficiencies of the bounded and the free jets should be similar, namely, $\eta = 0.006$.

Therefore, the main reason for discrepancies in the acoustic fields generated in these two cases should be the wall-induced spatial redistribution of the sources characteristic of a free jet. This reasoning forms the basis for studying the acoustic effects that emerge from the interaction of the rocket jet with a launch pad construction using the NASA SP-8072 methodology and its derivatives. Note that the possibility of source reconfiguration on the gas deflector was mentioned in the original document [9]. However, the most important efforts to adapt the semiempirical methodology to deflected jet conditions were made much later [4].

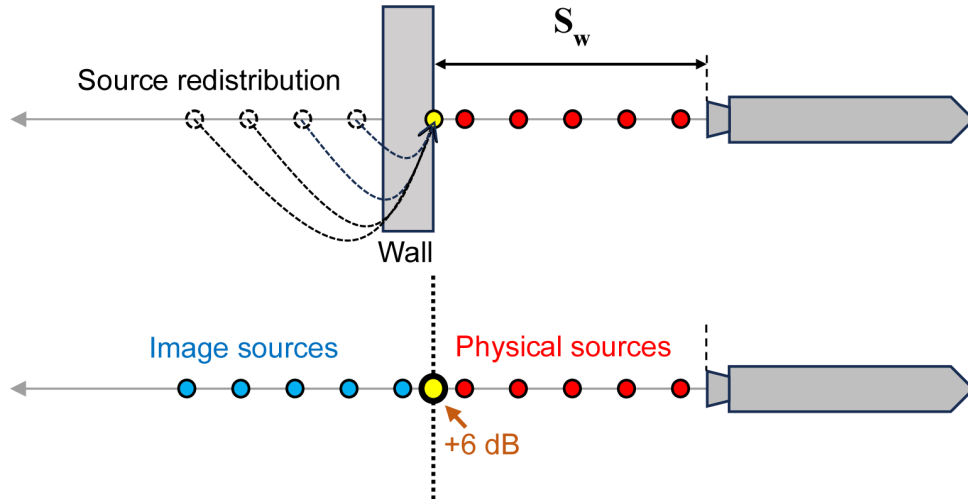


Fig. 5. Redistribution of discrete acoustic sources in a jet bounded by a normal wall (top) and modeling of acoustic reflection (bottom).

Let $s_w > 0$ be the distance from the nozzle exit to an obstacle. The segment $s < s_w$ of the jet remains undisturbed, so the sources located there “do not feel” the changes in flow conditions downstream. In the case of a normal collision with a wall, the rest of the sources that were initially located at distances $s \geq s_w$ move to the point $s = s_w$ (see the top part of Fig. 5). To fulfill the law of energy conservation, we set the power of the newly formed source equal to the sum of the powers of all “far” sources of the free jet. However, the frequency distribution of acoustic energy in it should be assessed by referring to the limiting value of the axial Strouhal number, $St_s|_{s_w} = fs_w/v_e$. Indeed, from the physical point of view, the occurrence of the wall cuts off the large-scale vortices associated with the most low-frequency spectral components.

When setting the angle θ_w for assessing the directional properties of the source on the wall, the spreading of the jet trail along the obstacle should be considered. Although no predominant direction can be indicated at the normal impingement, it is reasonable to assume that the deflected flow has turned by 90° .

We then complete the model by fulfilling the standard acoustic condition: the normal velocity component on a rigid wall should be zero. For this purpose, match each physical point source with an identical in-phase image source mirrored relative to the wall (see the bottom part of Fig. 5). In the limiting case of placing the emitter on the wall, the physical and image sources coincide. This is equivalent to the well-known doubling of the sound pressure amplitude when reflected from such a surface (+6 dB according to the logarithmic scale).

Taking the above considerations into account, the free jet methodology can be readily adapted to the case of a jet falling on a plane wall.

4. RESULTS AND DISCUSSION

Before analyzing the results obtained using the proposed model, let us specify the main parameters of the system: constant thrust $N = 2000$ kN, nozzle-exit velocity $v_e = 2600$ m/s, and nozzle-exit Mach number $M_e = 3.3$. Let the diameter of the nozzle exit $d_e = 1$ m be the length scale ($d_n = d_e$). As the sound speeds in the air and the gas at the nozzle exit, let us adopt $c_a = 340$ m/s and $c_e = 790$ m/s respectively. Most of these values are close to the corresponding characteristics of space rocket engines. According to (Eqn. 3), the laminar core of such a rocket jet is about $s_L = 17.5$ m.

Fig. 6 shows the dependence of the acoustic loads on the distance between the nozzle and the wall. It was computed for observation point P chosen at $H_P = 10d_n$ upstream from the nozzle exit and $R_P = 10d_n$ from the jet axis. Note that though the particular values of acoustic levels vary from point to point, the general trend is retained almost everywhere.

The solid red curve depicts the overall level of acoustic loads. The other curves show the components generated by the undisturbed jet segment (in green), the image sources (reflected field – in blue), and the special source at the wall (in black). All these values are normalized to the level produced by the free jet, which with the selected input parameters was estimated at 139 dB. As expected, the source formed at the wall predominates across a wide range of s_w . For example, an +18 dB increase of the acoustic loads is observed at $s_w/s_L = 0.5$, which corresponds to roughly an eightfold increase in sound pressure amplitude. This result is in fairly good correlation with the data from paper [6], presenting an experimental study of acoustic effects from the interaction of a supersonic jet with a plate.

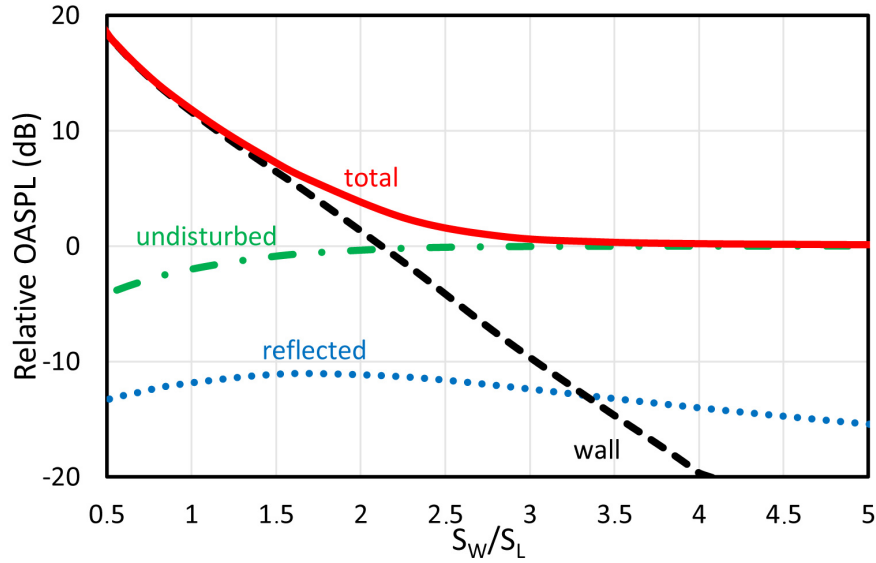


Fig. 6. The overall level of acoustic loads and the substantial components contributing to it, plotted with respect to the distance between the nozzle and the wall.

Some overestimation of predicted sound levels may stem from certain model simplifications. For example, we omitted some gas-dynamic features of the flow transformation on the wall when the distance s_w is too short. Moreover, the concentric divergence of the jet along the surface was neglected.

The significance of the wall acoustic source diminishes with the increasing distance and almost levels off at $s_w/s_L \gg 2$. In parallel, the contribution from the elongating undisturbed jet segment progressively increases. The contribution of the reflected field is less significant. At $s_w/s_L = 0.5$ its level is 9 dB lower than that of the undisturbed part, and this difference progressively increases with s_w . For $s_L \geq 3$, the overall level of generated sound approaches the value typical for the free jet.

Understanding the frequency content of acoustic loads is also important in practice. The octave-band spectra for three different distances from the nozzle exit to the wall are shown in Fig. 7. In addition to a general trend of decreasing levels, one can easily mention the relative decrease of the low-frequency components at $s_w < 1$. This effect is related to scale limitation for sound-generating vortex structures and quickly diminishes as distance from the wall increases.

In particular, an upward shift in the maximum octave level is observed. Fig. 3 suggests that the peak of the universal spectral distribution corresponds to the modified Strouhal Number of $St'_s \approx 1.5$. Therefore, for small values of s_L , one can expect the sound emission maximum to migrate towards $f_w \approx 1.5(v_e/s_w)(c_a/c_e)$, although the computed octave-band spectral maxima are located 35% higher. This apparent discrepancy is explained by the progressive widening of the octave or suboctave bands with increasing central frequencies. As a result, high-frequency bands always accumulate more acoustic energy. When the ordinary frequency spectra

with uniform distribution of the levels (dB/Hz) are considered, the peak occurs near the frequency f_w .

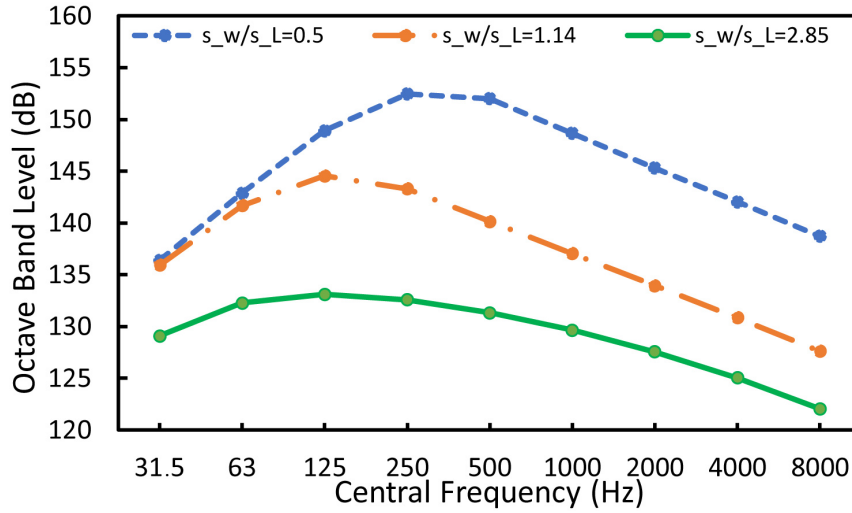


Fig. 7. The octave spectra of acoustic loads for different distances from the wall.

In the simplest case of a normal jet collision, we can neglect the possible shortening of the jet laminar core for $s_w < s_L$, as the axis of the disturbed part is projected into a single point $s = s_w$. At an inclined fall on the surface, the relation s_w/s_L is an important factor controlling source locations in the deflected flow along the wall [4,5].

The presented estimates are qualitatively consistent with most rocket launch observations and model experiments. A detailed quantitative analysis of their results is planned in subsequent publications.

5. CONCLUSION

This paper has presented an original semiempirical model for estimating the sound levels generated when a supersonic jet impacts a flat, rigid wall. The model assumes that the acoustic properties of such a system arise from the redistribution of the sound sources associated with a free jet. The acoustic properties of these sources can be determined using the self-similar laws suggested by regulations NASA SP-8072 [9].

The collision of the rocket engine exhaust with a rigid surface leads to a dramatic increase in the acoustic loads, as compared to those of a free jet. Analysis of the spectral-frequency distribution of acoustic loads reveals that, at small distances between the nozzle and the wall, the radiation maximum shifts to higher frequencies due to the degradation of low-frequency components. The reason for this maximum increase is the destruction of large-scale vortex structures in the flow by the wall.

The proposed model can be considered a first approximation for simulating the acoustic effects from the interaction of rocket engine supersonic jets with launch structure components. A number of the model's limitations, however, present opportunities for further refinement. First, the model does not account for specific thermodynamic phenomena occurring when the gas jet collides with the wall. Second, it overlooks the concentric divergence of the flow over the wall surface, where the distant turbulent sources are better represented as being distributed in circles of increasing radii rather than concentrated in a single point. These considerations provide a basis for further improvements of the model.

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