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ACOUSTIC ENVIRONMENT AT JET INTERACTION WITH A PLATE

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ABSTRACT
In connection with the acoustic environment of launch vehicles at lift-off this paper presents results from experimental studies of unsteady surface pressures and outer broadband acoustic field produced by strongly supersonic cold and hot jets impinging normal to a large flat surface. It is shown that at relatively small distances between nozzle exit and flat deflector the region of direct jet impingement (region of strong interaction) is a main source of very intensive acoustic radiation upstream. Based on test data analysis empirical dependencies for intensity, spectrum and directivity of this source are derived. The semi-empirical technique for predicting a broadband acoustic field at launch vehicle lift-off, which uses a superposition of contributions from different independent noise generation regions, is discussed.

1 - INTRODUCTION
Studies on acoustic environment resulting from subsonic and supersonic jets interaction with a deflector have been carried out during many years. Paper [1] contains a thorough review and bibliography on early investigations and includes a semi-empirical method for predicting acoustic environment resulting from supersonic jet interaction with a deflector based on a model of "free jet deflection". The jet itself (from a nozzle exit to the deflector), jet spreading over the deflector (it has the same characteristics as free jet), and noise reflection from the deflector are considered to be sources of noise generation. Analysis of later works on this subject and refinement of the above model are presented in paper [2]. But such approach does not always agree with experimental data since it does not take into consideration all sources of noise generation on the deflector.

For the first time the fact that the region of strong interaction of supersonic jet with a plate at distances between nozzle exit and plate $H<10-15$ jet diameter is the main source of broadband noise towards the nozzle body was noted in the work [3]. Analogous phenomenon for subsonic jet interaction with the deflector was noticed in paper [4]. Basing on the results of investigation [3] carried out in the seventies and also on results of more later investigations in a wider range of jet parameters and gas deflector geometry, the semi-empirical technique was elaborated for predicting broadband acoustic environment resulting from interaction of high temperature supersonic jet with a launch pad during take-off [5]. This technique is based on analysis of jet interaction with standard elements of a launch pad, selection of characteristic noise generation regions and substitution of each region of noise generation by a system of independent acoustic sources with prescribed acoustic power and spectrum of acoustic radiation. Acoustic power of the sources, spectrum of radiation and directivity factor are defined basing on generalisation of manifold experimental data.

This paper deals with the analysis and generalization of experimental data on broadband acoustic environment for generic case of jet interaction with launch pad: jet impingement on a flat deflector (plate). On the one hand this relatively simple case of interaction manifests all main features of noise generation during lift-off and on the other this interaction occurs at some moments during lift-off from any launch pad. It must be noted that this paper do not touch upon self-exited flow oscillations resulting in radiation of intense pure tone which can arise at some conditions.

It is shown that at least three independent regions of noise generation for the system "jet + flat deflector" exist: region of undisturbed jet between nozzle exit and deflector, strong interaction region and the deflector as a reflector of acoustic radiation. As concern acoustic radiation from spreading jet experimental data show that for this particular case it can be neglected due to very quick decay of this wall radial jet.

2 - EXPERIMENTAL RESULTS ANALYSIS

Fig. 1 illustrates variation of overall sound level at the nozzle body for air jet and solid propellant (SP) combustion products jet in the point M1 located at the distance about $0.5D_a$ upstream nozzle exit. A difference $\Delta L_\Sigma = L_\Sigma\left(\bar{H}\right) - L_\Sigma\left(\bar{H} = \infty\right)$ is plotted against $\bar{H} = H/D_a$.

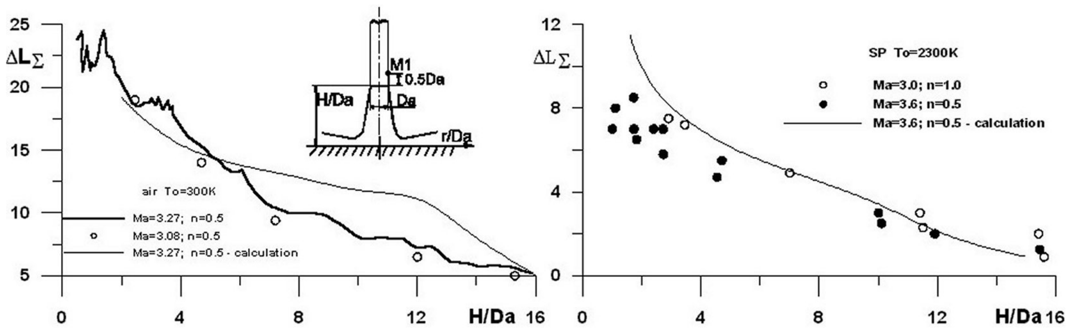

Figure 1: OASPL variation with a distance between nozzle and deflector.

Here: H is a distance between the nozzle exit and the plate, $\bar{H} = \infty$ corresponds to free jet (there is no plate), M_a − Mach number at the nozzle exit, n − a ratio of static pressure at nozzle exit to ambient pressure, D_a − nozzle exit diameter. Maximum OASPL L_Σ is observed when the nozzle is positioned near the plate, with increased distance OASPL falls and tends to a limit − OASPL in case of corresponding free jet. Since acoustic radiation from free jet portion between the nozzle and plate is relatively small at small $\overline{H}$, so considerable rise of noise with presence of a plate cannot be explained by sound reflection and it is connected with noise generation in flow directly near the plate.

A comparison of integral acoustic power radiated by a system "jet + deflector" and integral acoustic power radiated by free jet were conducted by a comparison of OASPL measurements in diffuse field of reverberation chamber. Fig. 2 shows results of such measurements as a difference $\Delta L^r_\Sigma = L^r_\Sigma\left(\bar{H}\right) - L^r_\Sigma\left(\bar{H} = \infty\right)$, L^r_Σ - overall sound level measured in diffuse field of reverberation chamber at corresponding distance between the nozzle and plate.

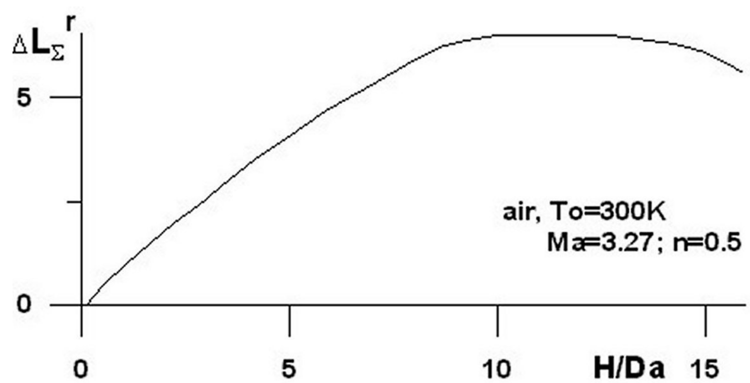

Figure 2: Estimation of integral acoustic power.

Seeming paradox takes place: OASPL in outside acoustic field is maximum with minimum integral acoustic power radiated by the system "jet + deflector".

Two main flow regions on the plate may be distinguished when supersonic jet impinges on normal plate: a zone of direct jet interaction (the region of strong interaction), where pressure fluctuation on the plate is very high, and a zone of spreading wall jet which is characterised by rapid reduction of velocity (in proportion with r^2) and relatively low pressure fluctuation.

Typical distributions of rms levels of pressure fluctuations on the plate L_Σ in radial direction ($\bar{r} = r/D_a$) and 1/3-octave spectra of fluctuations $L_{1/3}(f)$ are shown in Figs. 3 and 4. Double-humped curve for L_Σ

in Fig. 3 is typical for $\bar{H} < 10$, and at $\bar{H} > 10$ the distribution is usually single-humped. Moving from the jet axis, rms levels of pressure fluctuations fall quickly, and the maximum in pressure fluctuation spectra on the plate shifts to more lower frequencies (Fig. 4).

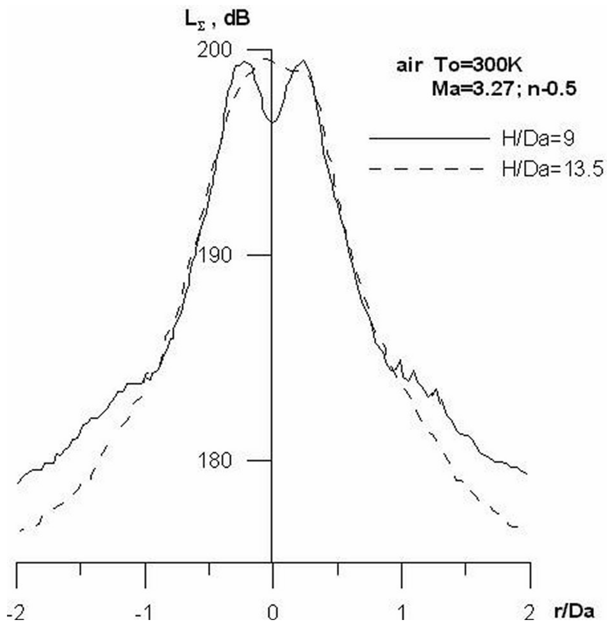

Figure 3: Radial distribution of rms levels of pressure fluctuations on the plate.

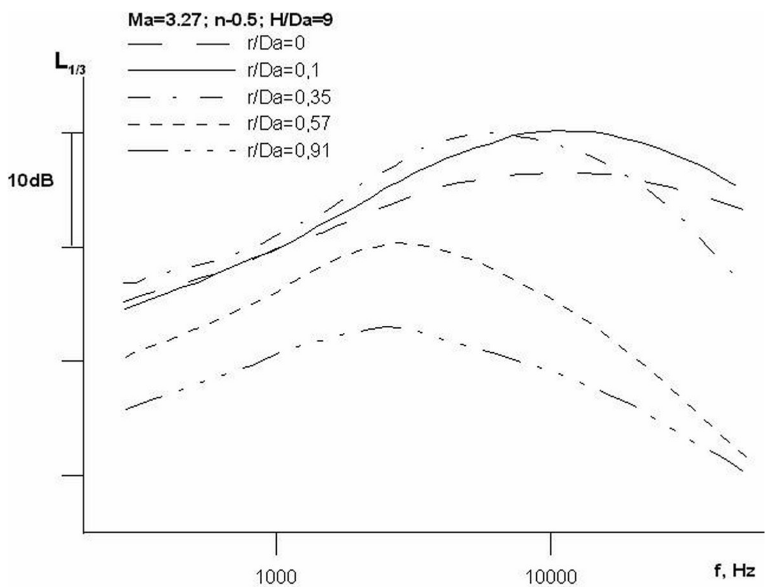

Figure 4: 1/3 octave spectra of pressure fluctuations at different points of the plate.

Now consider results of experimental evaluation of contribution of flow regions on the plate into acoustic field generated. Fig. 5 presents results of investigations on shielding of acoustic field generated by spreading jet by an open screen with the same size as the plate and having apertures with different diameters. The jet flows freely through an aperture. At $D/D_a \geq 3.0$ 1/3-octave spectrum of noise on the nozzle body with shielding is practically the same as without shield.

Noticeably more strong influence on sound levels in outside acoustic field was observed in experiments when a supersonic jet interacts with an open plate having aperture with diameter $D \approx D_a$, and a part of jet flow rate (or total jet flow rate) is withdrawn from the region of direct jet impingement (Fig. 6). Gas is withdrawn through a duct in such manner that a noise generated inside the duct and at the duct exit does not influence significantly on the outer acoustic field.

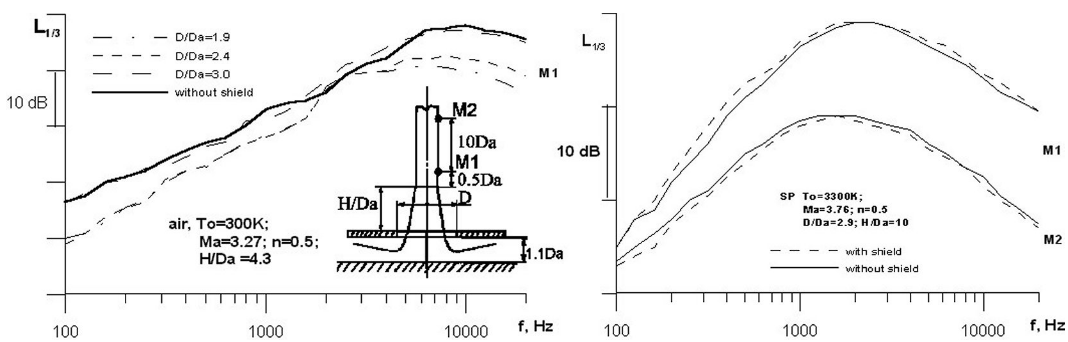

Figure 5: Evaluation of spreading jet input into generated acoustic field.

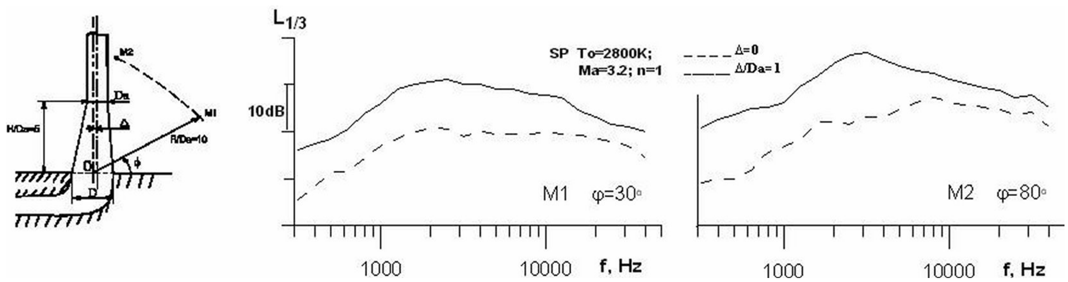

Figure 6: Evaluation of direct jet impingement region input into generated acoustic field.

Optical investigations have shown that there is an intensive acoustic radiation from the region of strong interaction. At distances about 3−5 D_a from the critical point this radiation may be considered as spherical [3], [5].

Large values of space-time correlation coefficient between pressure fluctuations on the plate in a region of their maximum and acoustic noise in outside field were obtained during correlation measurements, at that time lag of the correlation coefficient maximum is equal to the time which is necessary for sound disturbance to travel between observation points [3], [5]. It was found that a value of correlation coefficient between pressure fluctuations in the critical point and fluctuations in different points on the plate is negligible when a distance between them is $\bar{r} \geq 1$.

3 - IMPINGING JET ACOUSTIC MODEL

It follows from the above data that the main source of acoustic radiation in a flow directly near the plate is lumped in the region of strong interaction having a size about jet diameter in the interaction cross section. Starting with a distance $\bar{R} = R/D_a > 3 - 5$ this source may be considered as a point source with spherical directivity.

Based on the results of numerous tests with both air cold jets and hot jets of combustion products with various composition, a quantitative relationship was found between OASPL in outside acoustic field L_Σ and maximum rms level of pressure fluctuations on the plate L_{Σ_S}:

$$L_\Sigma = 0.7 L_{\Sigma_S} - 20\lg\bar{R} + 38$$

Obviously, the value $L_\Sigma + 20\lg\bar{R}$ is proportional to specific acoustic power of sound source located on the plate. For off-design jets $\bar{R} = R/D_j$, where D_j - diameter of isentropically fully expanded equivalent jet.

Analysis and generalisation of experimental data with $\bar{H} < 10 - 15$ has allowed to define 1/3-octave spectra of acoustic pressure $L_{1/3}(f)$ induced in the outside acoustic field by the region of strong interaction with the dependency $L_{1/3} - L_\Sigma = F_1(Sh_1)$ shown in Fig. 7. Here: $Sh_1 = \frac{fD_j}{M_j C_\infty} \frac{1}{k_1(\varphi)} \frac{1}{k_2(\bar{R})}$, where f - frequency, M_j - Mach number of isentropically fully expanded equivalent jet, C_∞ - ambient speed of sound, $k_2(\bar{R}) = 1 + \frac{1}{0.5 + 0.025\bar{R}^2}$, $k_1(\varphi)$ is determined by the following way: $k_1(\varphi) = 1$ at $15^o \leq \varphi < 35^o$, $k_1(\varphi) = 0.025\varphi + 0.125$ at $35^o \leq \varphi < 45^o$, $k_1(\varphi) = 1.25$ at $45^o \leq \varphi < 90^o$, $k_1(\varphi) = k_1(180 - \varphi)$ at $90^o \leq \varphi < 165^o$.

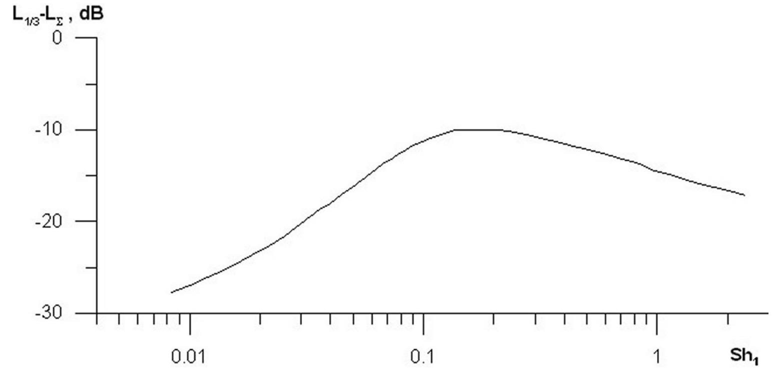

Figure 7: Spectrum of noise generated by strong interaction region.

Maximum overall levels of pressure fluctuations on the flat deflector L_{Σ_S} are determined by an empirical relation $\sigma_{\Sigma_S}/\left(p_S - p_\infty\right) = F_2\left(\bar{H}\right)$ shown in Fig. 8. Here: p_S - maximum static pressure on normal flat deflector, p_∞ - pressure in ambient atmosphere, $L_{\Sigma S} = 20\lg\frac{\sigma_{\Sigma S}}{2\cdot 10^{-5}Pa}$, $\bar{H}_j = H/D_j$. The model, which assumes that the region of jet between the nozzle exit and flow deflector is represented by a system of continuously distributed statistically independent radiating sources with prescribed acoustic power and spectrum of acoustic radiation, is used for calculation of the input from undisturbed jet region. In contrast to [1], [2], these distributions are specified with use of jet reference length x_m - a distance from the nozzle exit to cross section where the velocity on the axis of isentropically fully expanded equivalent jet U_m equals 0.75 U_j. A value of x_m may by found from aerothermodynamics calculations for given turbulent jet. Details of the calculation procedure are described in paper [5] together with calculation of noise reflection. Two aspects should be noted: an empirical directivity factor for the system "jet + flat deflector" as a whole (not for each noise generation region or noise source) is used and it is assumed that there is no essential acoustic radiation from spreading jet. The last is valid for normal flat deflector. If a jet interacts with inclined deflector, especially for real angles of interaction about 20°−40, it is necessary to separate the region of jet impingement with the deflector (the region of strong interaction) and the jet spreading over the deflector and flat plate surface [5].

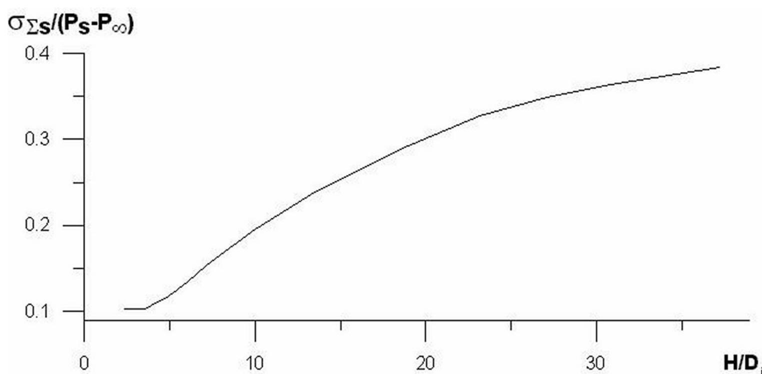

Figure 8: Maximum values of pressure fluctuation in the region of strong interaction.

4 - SIMULATION RESULTS

Consider some results of acoustic field simulation with the above model. Calculated variations of OASPL at the rear part on the nozzle body with a distance between nozzle exit and the plate are shown in Fig. 1. In general there is a quite good correspondence of measured and calculated data. It is necessary to keep in mind that according to the model the acoustic power of strong interaction region and region of undisturbed jet independently vary with $\bar{H} = H/D_a$ and simultaneously the point of observation moves away from regions of noise generation.

Data in Fig. 9 illustrate spectra similarity used in the model under conditions when acoustic radiation from strong interaction region dominates. Measurements and calculations have been conducted at points located along radius with origin at stagnation point on the plate and having angle φ=80° with the plate

(Fig. 6). There is a shift of maximum in experimental and calculated spectra towards low frequencies with $\overline{R}$ increasing.

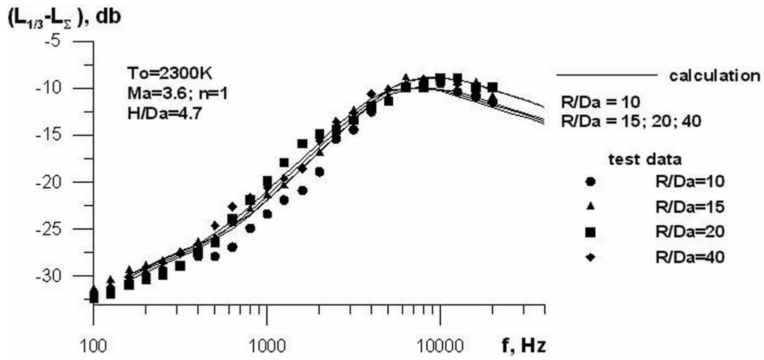

Figure 9: Comparison of experimental and calculated data near nozzle body.

5 - CONCLUSION

By experimental evidences it is shown that the region of direct jet impingement on a deflector is an independent source of very intensive acoustic radiation which dominates at relatively small distances between nozzle and deflector. Based on test data analysis empirical dependencies for intensity, spectrum and directivity of this source are derived and included into impinging jet acoustic model for generic case of jet interaction with a launch pad: jet impingement on a flat deflector.

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