ACOUSTIC ENVIRONMENT OF LAUNCH VEHICLES AT LIFT-OFF

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Introduction

An acoustical environment generated by a main engine jets acoustical radiation and jet interaction with launch pad (LV) is one of principal sources of structural vibration and internal noise during launch vehicle (LV) at lift-off. For this reason a problem of acoustical field determination and noise sources investigation is arises during a design of expendable and reusable space transportation systems. Launch vehicle engine jets interaction with a launch pad in general is a very complicated gasdynamic problem and there is no reliable theoretical technique for its calculation. Much more it concerns theoretical calculations of acoustical field generated by such interaction.

The most reliable way to get acoustical field characteristics during design is to carry out experimental investigations with use of subscale models of a launch vehicle and a launch pad with sufficiently complete simulation of gasdynamic and thermodynamic parameters of engine jets. But this is in itself a very complicated and expensive task.

At preliminary stages of design it is acceptable to use semi-empirical techniques based on general theoretical considerations and a generalization of experimental data. Studies of 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 [2-4]. But such approach does not always agree with experimental data since, firstly, it does not take into consideration all regions of noise generation on the deflector and, secondly, there is a problem with an assignment of characteristic scales for acoustic sources distributions which represent noise generation regions [4, 5].

Another way to find an answer to a problem is to investigate jet interaction on typical elements of launch pads with subsequent using these results for estimations of acoustical fields generated jet engine interaction on real launch pads.

The semi-empirical technique for predicting broadband acoustic environment resulting from interaction of high temperature supersonic jet with a launch pad during launch vehicle take-off is presented in paper [6]. This technique is based on analysis of jet interaction with standard elements of a launch pad, extraction 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.

Different typical interactions have been studied: an interaction of a supersonic jet with a normal deflector, an interaction of a supersonic jet with single-slope and double-slope deflectors, an interaction of a supersonic jet with a normal deflector having a hole, an interaction of supersonic jet with a scoop-like deflector (open from the top) and so on. In each case main noise generation regions are selected and semi-empirical acoustic models are created for them.

The technique uses a superposition of contributions from different noise generation regions: a region of undisturbed jet, a region of strong interaction between jet and flow deflector, a region of a jet spreading over deflector surface, solid surfaces as a reflector or a shield for acoustic radiation. The contribution of each source of noise into integral acoustic field varies with a distance between a launch vehicle and a launch pad and with a transverse displacement of a launch vehicle. A system of independent acoustical sources with prescribed acoustic power and spectrum of acoustic radiation represent each noise generation region. Spectral characteristics of resultant acoustical field and overall sound pressure levels are determined by summation of inputs from each source using geometrical acoustics and taking in account possible shielding of some sources by elements of a launch pad. Reflection of noise radiation from launch pad elements is calculated by imaginary sources. Acoustic power of the sources, spectrum of radiation and directivity factor is defined basing on generalisation of manifold experimental data with a use of proper characteristic scales which takes into account jet thermogasdynamics and deflector geometry. Detailed analysis of noise generation regions in the case of jet interaction with a flat plate deflector and inclined deflector is given in papers [7, 8].

Typical interactions may be considered as “bricks”, which can be used for estimation of acoustical environment resulting from interaction LV engine jets with LP of real configuration.

This paper deals with making use of the technique for calculations of acoustic field generated at interaction of LV engine jets with real LP, with the analysis of peculiar properties of different noise generation regions and their input into generated acoustic field. It is shown that the technique allows to make reliable estimations of acoustical field characteristics as a function of geometrical and gasdynamic parameters of LV and LP.

Acoustic model of engine jet interaction with a deflector

Before analysis of calculated acoustic environment for different LV at lift-off we briefly present main assumption of the acoustic model.

1. Real engine jet is substituted by an isoentropically fully expanded equivalent jet, having the same flow rate and enthalpy. Aerothermodynamic parameters of this equivalent jet are calculated by semi-empirical model described in paper [5]. The basic idea of jet aerodynamic model is a use of empirical similarity law for axial velocity distribution in the main

region of supersonic isobaric jet presented in paper [9]:

$$u_m/u_j = 1 - \exp[1.4/(1-2\xi)],\ \xi = x/x_m\ ,$$

where u_m – the velocity at the axis of fully expanded equivalent jet, u_j – nozzle exit velocity of fully expanded equivalent jet, x – distance along jet axis, x_m – a distance from nozzle exit to cross section where $u_m = 0.75u_j$. The quantity x_m may be calculated from experimental relation:

$$x_m/D_j = 6\left[1 + M_j^2(\gamma_j - 1)/2\right](1 + I_0/2) - \\ - M_j^2(\gamma_j - 1)/3 \quad (1)$$

where I_0 represents the ratio of ambient enthalpy to total enthalpy of the jet, D_j – exit diameter of fully expanded jet, M_j and γ_j – exit Mach number and specific heat ratio of fully expanded jet. As indicated in paper [9], the distance x_m corresponds to the location of the turbulence peak and to the maximum of axial velocity gradient in the jet. For acoustic model we assume that the turbulence peak location coincides with the sound power peak location in the jet. This quantity is used as a linear characteristic scale, which defines both the jet thermogasdynamic parameter distributions and sound power distribution for region of undisturbed jet and for spreading jet.

2. As distinct from "free jet deflection" model [1-3], numerous experimental investigations have revealed that there is an additional independent region of noise generation – a region of jet impingement with a deflector (region of strong interaction or "jet spot") [6-8]. By experimental data analysis a quantitative relationship between overall sound pressure level (OASPL) in outside acoustic field L_Σ and maximum root mean square level of pressure fluctuation in this "jet spot" on deflector surface $L_{\Sigma m}$ is determined. At that values of $L_{\Sigma m}$ depends on gasdynamic parameters of the jet, a distance from nozzle exit to deflector and geometrical parameters of the launch pad. One third octave spectra of acoustic pressure $L_{1/3}(f)$ induced in outside acoustic field by the region of strong interaction may be found from empirical relation $L_{1/3} - L_\Sigma = F_1(Sh_1)$, $Sh_1 = k(R/D_j, \varphi)\cdot(fD_j/M_jc_a)$. Here: f – frequency, c_a – speed of sound in ambient environment, (R,φ) – polar coordinates of observation point with the origin in critical point on deflector surface. In particular for heat shield region of LV we have $Sh_1 = 0.78(fD_j/M_jc_a)$ and for rear part of LV – $Sh_1 = 0.45(fD_j/M_jc_a)$.

3. The sound power density distribution, normalized by the overall acoustic power of free jet, for undisturbed portion of jet is set as empirical functions of normalized distance along jet axis $\xi = x/x_m$, with a maximal value around $\xi = 1$ (turbulence peak location in the jet) and a nil value beyond $\xi = 2{,}293$. The overall acoustic power is calculated through the free jet acoustic efficiency which is set as empirical dependence on u_j [6]. The same approach is used for determination of sound power density distribution for a jet spreading over flow deflector with some modifications to take into account changing of jet parameters connected with flow impingement.

4. OASPL L_Σ induced in outside acoustic field by each acoustic source representing undisturbed and spreading jet is determined through known sound power level of each source L_{Wi} by the relation $L_{\Sigma i} = L_{Wi} - 10\lg\Omega_i R_i$, R_i – distance from i-th source to observation point, Ω_i – solid angle of radiation for i-th source which depends on LP geometry.

5. One third octave spectra of acoustic pressure $L_{1/3}(f)$ induced in outside acoustic field by each acoustic source representing un-

disturbed and spreading jet is specified by empirical dependence $L_{1/3} - L_{\Sigma} = F_2(Sh_2)$. Here: $Sh_2 = Sh / Sh_{\max}$ - modified Strouhal number, which takes into account the distribution of characteristic frequency of sources (frequency of a maximum in spectrum generated by each source $f_{\max}$) along undisturbed and spreading jets, $Sh = fD_j / u_j$,

$$Sh_{\max} = f_{\max} D_j / u_j = K(T_j, \varphi, x_m)/\xi .$$

It is necessary to note that characteristic scales D_j and x_m are different for undisturbed and spreading jets [6].

6. Spectral characteristics of resultant acoustical field and overall sound pressure levels at given point of observation (R, φ) are determined by summation of inputs from each source and each noise generation region using geometrical acoustics and taking in account reflection of noise by LP elements and possible shielding of some sources by LP elements. Reflected noise is calculated using method of imaginary sources.

Integral acoustic power at jet interaction with a deflector

In our acoustic model of jet-deflector interaction parameters of acoustic sources are prescribed independently, and their values are defined by jet thermodynamics, the deflector geometry and a distance from the latter and the nozzle exit.

Thus integral acoustic power of noise radiated by the system “jet-deflector”, inputs of different regions of noise generation into the integral acoustic power, and, by analogy with acoustics of free jets, acoustic efficiency of the system have been calculated for three theoretical supersonic jets interacting with normal plate and with double-slope deflector mounted on the flat plate.

Variation of acoustic efficiency for the system “jet–deflector” $\eta = W_a / W_{mech}$ with a distance between nozzle exit and deflector is shown in Fig. 1 (W_a – integral acoustic power of noise radiated by the system, W_{mech} – mechanical power of free jet, H/D_j – distance between the nozzle exit and deflector).

Input of different region of noise generation into integral acoustic power of the system is illustrated by calculation results presented in Fig. 2. Here: W_j – acoustic power of noise generated by undisturbed jet region including reflections, W_{sj} – acoustic power of noise gen-

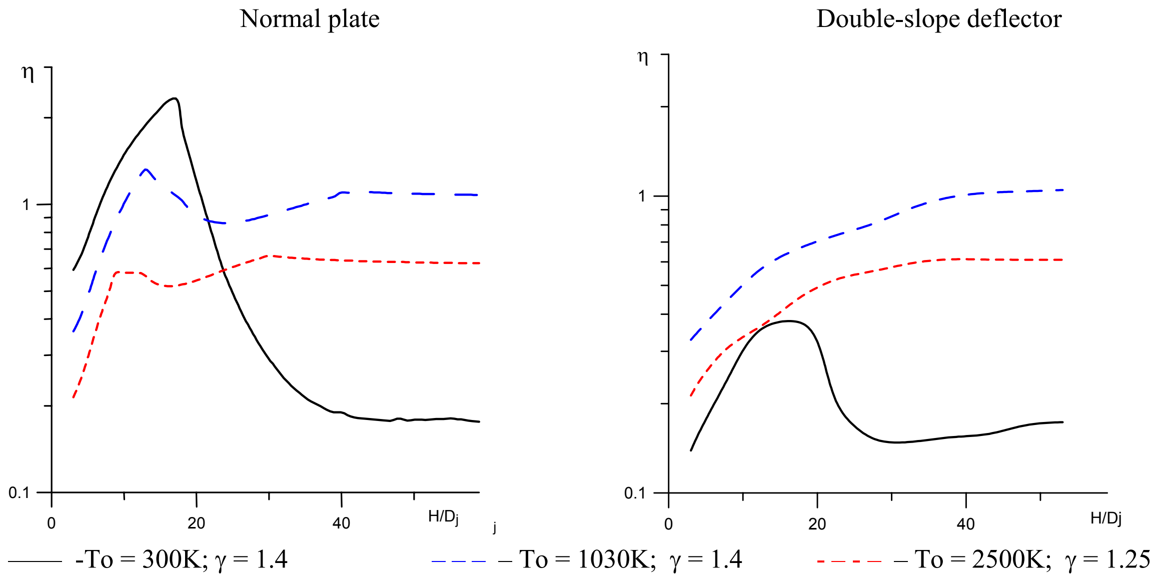

Fig. 1 Acoustic efficiency of the system “jet-deflector” (*Mj*=3.0)

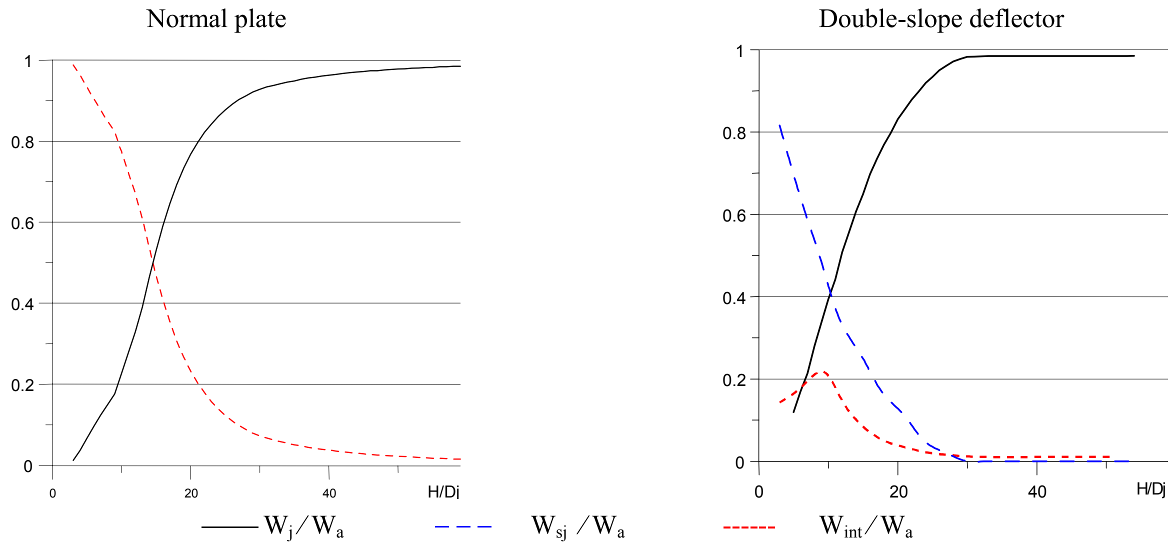

Fig. 2. Input of different regions of noise generation (T_o = 2500K; γ = 1.25; Mj = 3.0)

erated by the jet spreading over the obstacle including reflections, W_{int} – acoustic power of noise generated by strong interaction region, W_a – integral acoustic power of the system.

From presented data it follows that for discussed acoustic model of interaction the noise generated by the system "jet-deflector" depends significantly on the jet parameters, the distance between the nozzle exit and deflector and the deflector geometry.

Use of the technique for calculations of acoustic field generated at interaction of LV engine jets with real LP

The technique was used for estimating acoustic environment arising during take-off of operated and newly creating launch vehicles. Analysis of calculation results, flight data, geometrical and gasdynamic parameters of launch vehicles and launch pads has shown that the technique may be successfully used for prediction of acoustic field generated at LV take-off. In such prediction the main problem is to find a proper reference linear dimension for acoustic sources that defines maximum frequency for sound pressure spectra. Many LV have engines with single nozzle or four-nozzle scheme. Recall that for single jet (in general case non-perfectly expanded) we take the diameter of fully expanded equivalent jet D_j, having the same flow rate and enthalpy.

For clustered engine with dense arrangement of nozzles, when ratio of a distance between axes of adjacent nozzles to nozzle exit diameter does not exceed two, the jets interact strongly at initial (gasdynamic) zone. It causes significant transformation of jets with corresponding changing of jet propagation and acoustic radiation. In this case for reference linear dimension, which defines maximum frequency, diameter of equivalent jet having the total flow rate and enthalpy as interacting jets has to be chosen.

For non compact arrangement of clustered nozzles, as a rule, calculation is conducted for each individual jet with subsequent summation of spectra in examined point.

There are some designs, for example Saturn V, Ariane 4, with five-nozzle arrangement. This scheme of nozzles may be considered as intermediate: peripheral jets do not interact between each other, but each of them interacts with the central jet and appropriate choice is diameter of single jet.

In some cases compactness of nozzles is not only criterion for choosing reference linear dimension of acoustic source. A configuration and geometrical parameters of a launch pad (number of gas-escape trays and their depth) are other affecting factors.

This usually takes place for shallow gas-escape trays and dense or intermediate arrangements. When the gas-escape tray depth is less then x_m, determined by relation (1), significant input into sound pressure is given by gas jets spreading over the trays. Appropriate choice for the reference linear dimension may be a value proportional to diameter of a jet passing through each gas-escape tray with flow rate equal to one. In particular, such situation is realized for LV "Proton" with six nozzles arranged in annular configuration. We have intermediate nozzle arrangement with $x_m \approx 12$, and depth of double slope gas-escape tray equals $\approx$ 8.5m.

For this case the diameter of single fully expanded equivalent jet D_j multiplied by $\sqrt{3}$ (3 – number of jets passing through each gas-escape tray) chosen as reference linear dimension of acoustic sources gives a good correlation between calculation and experimental data. Example of such correlation at the beginning of lift-off for LV head fairing zone is shown in Fig. 3 as dependence of $L_{1/3}(f) - L_\Sigma$ on $f / f_{\max}$, $f_{\max}$ - maximum frequency in one third octave sound pressure spectra.

Comparison of calculated and measured one third octave sound pressure spectra for head fairing zone and for rear part of LV "Soyuz" at the beginning of lift-off is presented in Fig. 4.

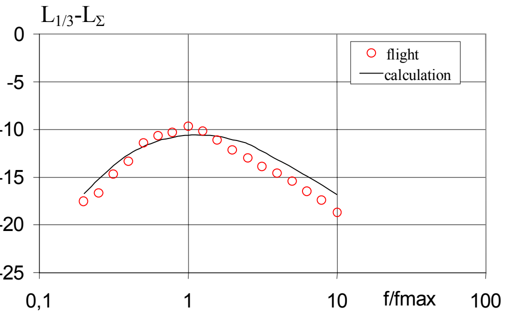

Fig.3. Comparison of flight and calculated noise spectra on head fairing at LV "Proton" lift-off

At lift-off LV "Soyuz" consists of the central core and four side units with the same clustered engines having 4-nozzle dense arrangement. Standard launch pad for this vehicle has a single slope deflector with wide enough and sufficiently long gas-escape tray; maximal depth of the tray is about 28m. At calculations the following model has been assumed: four jets from each LV unit are substituted by single equivalent jet with subsequent summation of inputs from five individual equivalent jets interacting with single slope deflector. Close fit calculated and experimental data is rather evident. It must be noted that flight data presented in Fig. 3 and Fig. 4 constitute data averaged over several LV flights.

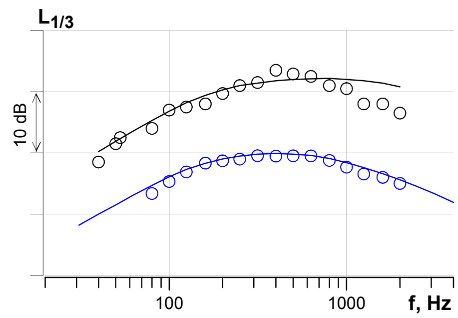

Fig.4. Comparison of calculated (solid lines) and flight (circles) data for noise spectra on head fairing (lower data) and rear part (upper data) at LV "Soyuz" lift-off

Calculation technique verification with a use of experimental data, in particular with the data gained at LV "Soyuz" launchings from standard Russian LP, allowed to estimate influence of construction features of LP for LV "Soyuz-ST", creating in the frame of "Soyuz en Guyane" project, on acoustic loading of the vehicle. Initial design of LP in Guyane differed from Russian prototype by geometry of gas-escape tray (with the same depth) and by presence of fixed service tower just near launch vehicle and the tray. Comparison of calculated OASPL L_Σ as function of LV altitude H for two locations along LV is presented in Fig.5.

At small altitudes increasing of acoustic loading is stipulated by a difference in gas-

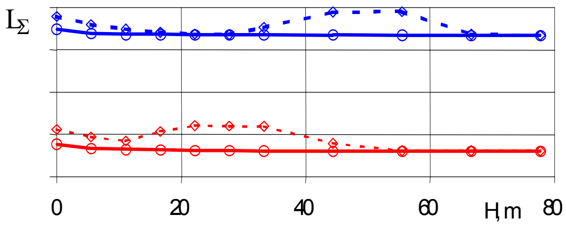

Fig.5. OASPL levels on head fairing (upper curves) and rear part (lower curves) at Soyuz (circles) and Soyuz-ST (rhombs) lift-off (L_Σ scale interval equals 5 dB)

escape tray geometry, at larger altitudes – by noise reflection from fixed service tower. Obtained data are critical by the terms of providing acoustic environment under head fairing and LV vibration. As a result it has been decided to use mobile service tower, which is removed before lift-off, and to approach geometry of gas-escape tray as much as possible to Russian prototype.

It follows that before application of standard techniques for evaluation of complicated configurations it is necessary to analyze arrangement and geometrical parameters of the launch vehicle and launch pad in order to find appropriate reference linear dimension of sources of acoustic radiation. In any case with the help of the technique it is possible to get conservative estimation of effect of acoustic radiation on the launch vehicle by ordinary enumeration of possible variants for the reference length.

Conclusions

Comparisons of calculated results with experimental data indicate that the technique allows to make reliable estimations of acoustical field characteristics as a function of geometrical and gasdynamic parameters of LV and LP, to analyze inputs of different noise generation regions and, consequently, to analyze means for reduction of acoustic loading at lift-off.

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