AERODYNAMIC SIMULATION AND A TEST TECHNIQUE FOR INVESTIGATION OF A FLIGHT VEHICLE WITH JET ENGINE IN FRONT POSITION AND LATTICE FINS

**V.V. Voronin, V.V. Koudriavtsev, V.I. Lapygin, Yu.M. Lipnitsky,
K.A. Stekenius, P.V. Tretjakov, and V.N. Shmanenkov**

Central Research Institute of Machine Building,
141070 Korolev, Moscow region, Russia

A separated nose section of a launch vehicle with an emergency rescue system (ERS) is a flight vehicle (FV) with a jet engine (JE) in the front position and with honeycomb lattice fins (LF) in the base region. The flight vehicle configuration is illustrated in Fig. 1 above the *X*-axis, and a schematic of its scaled aerodynamic model is shown below the *X*-axis.

Determination of aerodynamic characteristics (AC) for that sort of flight vehicle is a complicated problem, which may be solved combining experimental techniques and theoretical calculations. Such work includes the following stages.

1. Approximate simulation of lattice fins

In case when it is necessary to fabricate aerodynamic model with scale not more than 1:10, it is impossible to keep geometrical similarity of thin-wall structure of the lattice fins. Taking into consideration results of particular investigations and also paper [1], the lattice fins may be approximately simulated basing on the following provisions: 1) in order to ensure similarity with respect to drag, it is necessary to keep relative washed surface $\overline{S}_{om}$ and blockage coefficient $k_b = sc/t$ close to their real values; 2) in order to simulate lift and side force it is necessary to provide similarity with respect to lift $\overline{S}_y$ and side $\overline{S}_z$ surfaces and relative step $\bar{t}$ of the lattice; 3) number of plans n of the model lattice fin is limited ($n \geq 7$) by condition of possibility to simulate lift property, and preferred variant of the model lattice fin when number of plans close to its real value; 4) blockage coefficient k_b is limited by the condition $k_{b\,model} \leq (2\ldots3)\,k_{b\,real}$, in order to exclude distortion of flow over the model lattice fin;

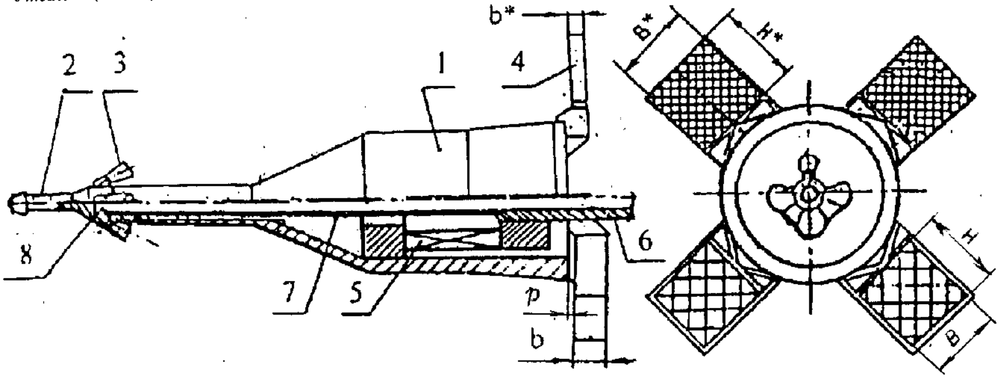

Fig. 1. The flight vehicle and a scheme of its jet-balance aerodynamic model.
1 – FV body; *2* – FV nose part; *3* – engine jets; *4* – lattice fins;
5 – strain-gage balance; *6* – sting; *7* – pipe; *8* – chamber

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5) the honeycomb lattice step *t* is chosen taking into account that numbers of the lattice site along its height *H* and width *B* are integer.

For experimental determination of aerodynamic characteristics with improved accuracy it is advisable to make the flight vehicle model with the lattice fins fabricated in two variants: the variant 1 corresponds to conditions of lifting capacity of the fins, and the second variant – conditions of drag simulation. In particular, when lifting capacity is simulated, reduced number of plans *n* is compensated by longer chord *b*.

2. Experimental determination of the flight vehicle body and model lattice fins aerodynamic characteristics

Principal similarity criteria for experimental determination of the flight vehicle body AC are Mach number M_∞ and Reynolds number $\mathrm{Re}_{\infty L}$ based on the body length *L* and undisturbed flow parameters. As examined flight vehicles is long (L~15 m), Reynolds number is high in real conditions ($\mathrm{Re}_{\infty L} = 10^7 \ldots 10^8$), and boundary layer on the most part of the flight vehicle is turbulent. At transonic and especially at subsonic velocity it is difficult to obtain real values of $\mathrm{Re}_{\infty L}$ in wind tunnels. With large enough scale of the models – about 1:30 – the values $\mathrm{Re}_{\infty L} \approx 10^7$ corresponded to the turbulent boundary layer are realized, and geometrical similarity of the flight vehicle is attainable.

For the lattice fins the similarity criteria with respect to compressibility and viscosity are local Mach number and Reynolds number Re_b (*b* – the plan chord length) in the flow in front of the fins.

The aerodynamic characteristics of the body and lattice fins for the model without jets are determined through balance tests using 6-component strain-gage balance [2]. During measurement of components of aerodynamic loads acted on the vehicle model it is advisable to “measure” also its nose part using another small balance. The flight vehicle models are basic ones for further determination of full-size flight vehicle characteristics.

Analyzing variation of the lattice fins characteristics in correlation with critical Mach numbers M_{k1}, M_{k2}, M_{k3}, (see [1]) and also calculating the lattice fins AC it is necessary to take into consideration local Mach number M_{LF} in a flow around the fins. For this purpose during the balance tests local total pressure $P_{\mathrm{t.LF}}$ and static pressure $P_{\mathrm{s.LF}}$ in front of the model LF were measured using microprobes placed among elements of the fin holder. Mach number M_{LF} was found basing on these measurements.

3. Theoretical determination of the lattice fins aerodynamic characteristics

A program for calculating aerodynamic characteristics of the lattice fins was elaborated basing on information from [1] and [3]. The aerodynamic characteristics obtained experimentally in item 2 were used for verification of computational technique. Along with the coefficients C_x and C_y, the coefficient of the center of pressure C_{db} is found in ratio to the chord length *b* during calculation of the aerodynamic characteristics of full-size and model lattice fins.

4. Experimental investigation of jet action on aerodynamic characteristics of the vehicle body and lattice fins

Simulation of hot gas jets of a small model in a wind tunnel is practically unrealized, but it is possible to simulate these jets approximately using cold air. Analyzing peculiarities of a flow around the flight vehicles with working jets from the point of view of integral aerodynamic characteristics, it is seen that similarity criteria have to reflect relationship between the jets energy and outside flow, and also relationship between dimensions of the jets (transverse dimension, in particular) and flight vehicle. These criteria are the following:

$$K = n \cdot (\gamma_j M_j^2 / \gamma_\infty M_\infty^2) \cdot (S_{j\Sigma} / S_m), \tag{1}$$

$$J^2 = n \cdot (\gamma_j M_j^2 / \gamma_\infty M_\infty^2) \cdot \sqrt{1 + 2(\gamma_j - 1)^{-1} M_j^{-2}}\ , \tag{2}$$

here n – jet pressure ratio, M_∞ and M_j, γ_∞ and γ_j – Mach number and adiabatic exponent in oncoming flow and the nozzle exit, correspondingly, S_m – midsection area (flight vehicle reference area), $S_{j\Sigma}$ – integral exit area of all nozzles.

The criterion (1) represents relation of momentum in jet and momentum in oncoming flow through their reference areas. The criterion (2) shows relation between the jet transverse dimension and vehicle/model reference size. This criterion is based on approach suggested in [4]. Similarity conditions $K = idem$, $J = idem$ permit to find Mach number M_j that is required designing model nozzles (γ_j=1.4) with exit area S_j, correspondent to condition $(S_j / S_m) = idem$. In this connection it is necessary to find such model value M_j^*, which meets both criteria K and J.

The jet model structure is illustrated in Fig. 1. During jet-balance tests the similarity criteria are provided by varying jet pressure ratio n and its required value is found from (1) with K = const.

Since exhausting jets make blockage of flow in the wind tunnel noticeably larger, a scale of jet model should be less (1:60) comparing the model without jets; and model lattice fins N3 are used, which correspond to compromise settlements from section 1. The model body 1 is mounted on the strain-gage balance 5, which is fixed on the sting 6. The tubular balance has central hole, and a pipe 7 is placed inside with no contact to the balance. Compressed air is going through the pipe to a chamber 8, and then flows out of the nozzle 3. Local flow parameters in front of the fins are detected using microprobes. In particular, a ratio is to be determined, $\bar{q}$, of local dynamic heads in front of the fins with and without jets. It is advisable to determine jet action on aerodynamic characteristics as "jet components", which are differences between the characteristics found with and without jets:

$$\Delta C_{xj} = C_{xj} - C_x,\ \ \Delta C_{yj} = C_{yj} - C_y,\ \ \Delta m_{zj} = m_{zj} - m_z. \tag{3}$$

5. **Determination of aerodynamic characteristics for full-size flight vehicle**

The aerodynamic characteristics of the full-size flight vehicle with working jets are found by summation of AC (from balance tests) with jet components (3) (from jet-balance tests), and also some other additions required to take into account certain factors. It is explained below at several typical examples.

Axial force coefficient of the full-size flight vehicle at zero incidence (α=0) is found by the formula:

$$C_{xo}^* = C_{xb} + \Delta C_{x.fr} + C_{x.LF}^* + \Delta C_{xj}^*\ \ , \tag{4}$$

here C_{xb} – the body axial force coefficient determined through experimental data (section 2), $\Delta C_{x.fr}$ – addition, which takes into account a difference in friction coefficients found for real conditions and model Reynolds number, calculated by the code [5]; $C_{x,LF}^*$ – axial force coefficient calculated for full-size lattice fins (section 3); ΔC_{xj}^* – jet addition, which takes into account variation of drag under action of jets of the body and lattice fins.

Jet addition C_{xj}^{*} is calculated in the following way:

$$C_{xj}^{*} = \Delta C_{xj}(1-\bar{q})(C_{x.LF}^{*} - C_{x.LF3}), \tag{5}$$

here ΔC_{xj} – jet component (3) determined through experimental data (Section 4), $C_{x,LF}^{*}$ and $C_{x.LF3}$ – drag coefficients of the full-size fin found by calculation (Section 3) and experimental data for jet-balance model with the lattice fins N3 without jets (Section 4), correspondingly; $\bar{q}$ – the ratio of local dynamic heads in front of the fins in tests with and without jets. The jet addition (5) takes into consideration a difference in drag of the full-size fin and model fin N3 with jets action. The coefficients related to the full-scale flight vehicle are marked by the superscript *.

The coefficient of the center of pressure is calculated by the next formula:

$$C_{d}^{*} = \bar{x}_{t} - m_{zt}^{*} / C_{y}^{*} \;, \tag{6}$$

here m_{zt}^{*} – pitch moment coefficient with respect to a reference point $C_t(\bar{x}_t,\ 0,\ 0)$ along the vehicle axis near probable location of its center of mass. The coefficient m_{zt}^{*} is calculated basing on the aerodynamic characteristics of the vehicle model with the lattice fins N1 with lifting capacities close to real ones.

It would be noticed that the fins N1 (the vehicle balance model) has the chord of lifting plan with relative length $\bar{b}_1 = 1.8\ \bar{b}^{*}$, $\bar{b}^{*}$ is related to the full-size fin. The length of LF N3 chord is even greater ($\bar{b}_3 = 1.8\ \bar{b}^{*}$). And relative distance $\bar{p}$ from the body base cut to the fin was the same for the model and full-size vehicle (see Fig. 1).

From the above reasoning it follows that pitch moment coefficient is represented in the form:

$$M_{zt}^{*} = (m_{zt1} + \Delta m_{z.LF1}) + (\Delta m_{ztj} + \Delta m_{z.LF3}) \tag{7}$$

here m_{zt1} – pitch moment coefficient of the model with LF N1 (Section 2), $\Delta m_{z.LF}$ – addition due to difference of chord length $\bar{b}_1$ and $\bar{b}^{*}$, Δm_{ztj} – jet component (Section 4), $\Delta m_{z.LF3}$ - addition due to difference of chord length $\bar{b}_3$ and $\bar{b}^{*}$. The addition $\Delta m_{z.LF}$ is calculated by the next formula:

$$\Delta m_{z.LF} = (1+\bar{p}-\bar{x}_t)(C_{y.LF1} - C_{y.LF}^{*}) + (C_{y.LF} C_{db1} \bar{b}_1 - C_{y.LF}^{*} C_{db}^{*} \bar{b}^{*}) \,. \tag{8}$$

The addition $\Delta m_{z.LF3}$ is calculated by the analogous formula:

$$\Delta m_{z.LF3} = (1+\bar{p}-\bar{x}_t)(C_{y.LF3j} - C_{y.LFj}^{*}) + (C_{y.LF3j} C_{db3} \bar{b}_3 - C_{y.LFj}^{*} C_{db}^{*} \bar{b}^{*}) \,, \tag{9}$$

here $C_{y.LFj}^{*}, C_{y.LF3j}$ – normal force coefficients of full-size and model Lattice fin N3 in case with working jets.

Calculation results on aerodynamic characteristics of the full-size flight vehicle, using formulas (4) – (9), for cases with and without working jets are presented in Fig. 2.

Presence of jets at zero angle of attack causes increase of drag coefficient C_{x}^{*} (Fig. 2a) at subsonic velocity ($M_\infty \approx 0.4$), when jets momentum is much greater than momentum of undisturbed oncoming flow. In the range $M_\infty \approx 0.6 - 1.0$ jet action causes a small additional rise

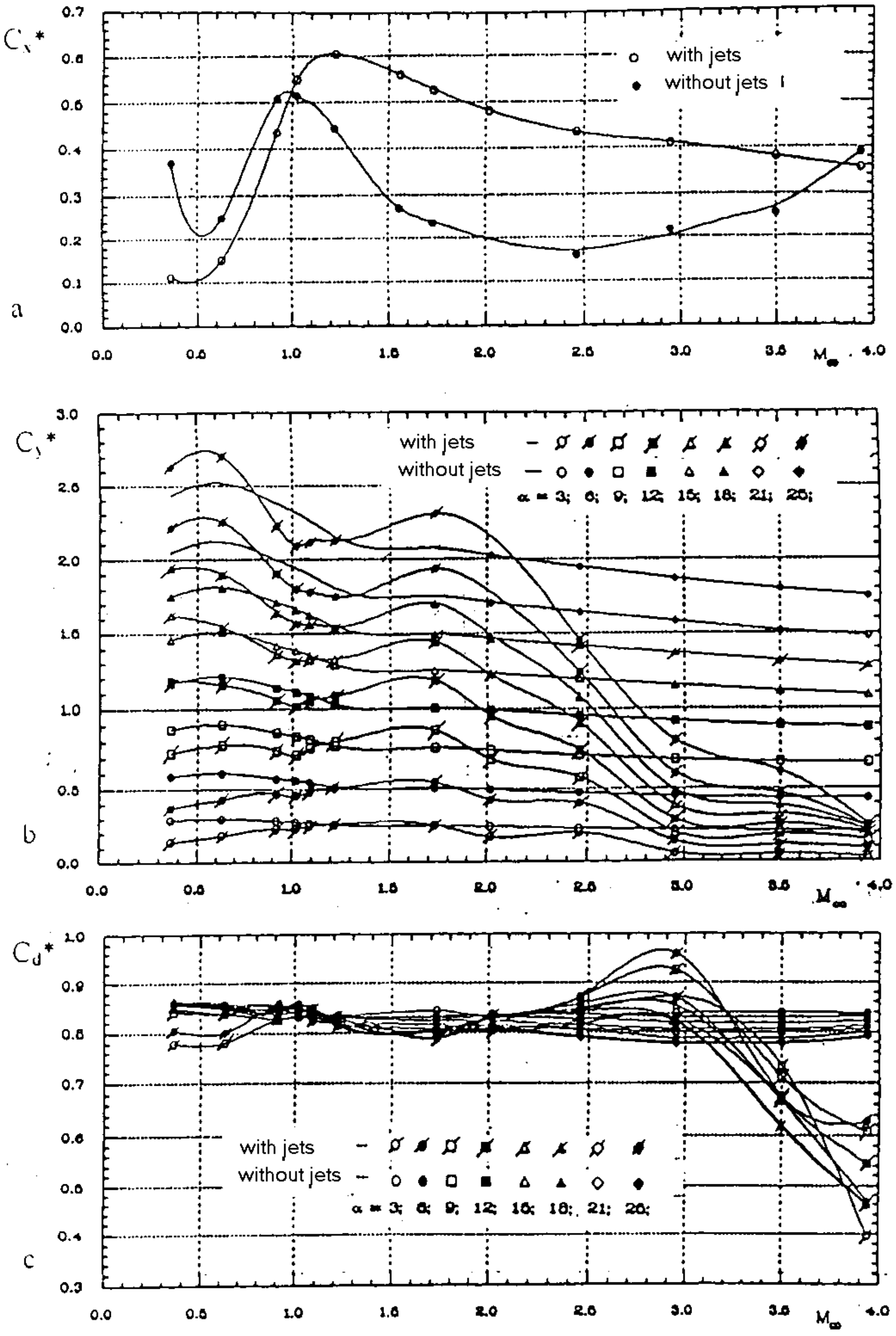

Fig. 2. The flight vehicle aerodynamic characteristics in real conditions.

of C_x^*, and vice versa in the range $1 \leq M_\infty \leq 2.5$ it causes its significant decrease. When Mach number is increasing from 2.5 to 4.0 that is accompanied by rise of jet pressure ratio due to rise of the altitude, the drag coefficient rises.

The normal force coefficient C_y^* (Fig. 2b) in the range $M_\infty = 0.4 - 2.0$ varies slightly with appearing of jets, but with further increase of Mach number it falls essentially and reaches values comparable with the coefficient C_{yn} of the flight nose part. It is caused by the fact that with increased flight altitude and corresponding rise of jet pressure ratio, the jets transverse size increase so much that the jets, with the higher energy than the outside flow, shadow the vehicle body and lattice fins from the flow effect.

The jets flow influences comparatively weakly on the position of the vehicle center of pressure at $M_\infty \leq 2.5$ (Fig. 2c). With Mach number increased to $M_\infty \sim 3$ and corresponding rise of the similarity criterion J the jets shadow the body conical part (see Fig. 1), and in this case a role of the lattice fins increases. Therefore the center of pressure moves a bit towards the base (C_d coefficient rises). With further increase of Mach number the center of pressure moves noticeably forward, because the jets shadow the whole body of the vehicle and the lattice fins from the outside flow. In this case unshielded nose stage of the vehicle gives significant input into the moment characteristics $m_{zt(\alpha)}$ and $m_{yt(\beta)}$, it has the coefficient $C_{dn} \approx 0.2$ (see Fig. 2c).

The displacement of the center of pressure towards the nose due to shielding of the vehicle by the front jets is very important in practice, because it may cause loss of the vehicle static stability during its flight.

The problems of aerodynamic simulation are discussed in present paper, the technique for determining aerodynamic characteristics of the flight vehicle with front engine jets and lattice fins is elaborated, and peculiarities of aerodynamics for such type of vehicles are discovered.

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