High-Altitude Aerodynamics of the Clipper Spacecraft

M. Ivanov⋆*, P. Vashchenkov*⋆*, A. Dyadkin*⋆⋆*, and A. Krylov*⋆⋆
⋆*Institute of Theoretical and Applied Mechanics SB RAS*
Institutskaya 4/1, 630090, Novosibirsk, Russia
⋆⋆*Rocket Space corporation "Energia"*
Korolev, Moscow region, Russia

Abstract

The results of numerical investigations of the aerodynamic characteristics of the Clipper spacecraft during its de-orbiting to the Earth are presented. Free-molecular, transitional, and near-continuum regimes were considered. The computations were performed with engineering local-bridging methods and the Direct Statistical Monte Carlo method.

1. Introduction

The orbit of advanced space vehicles lies at altitudes of about 300-400 km. Entering the atmosphere, the vehicles are initially subject to the action of the free-molecular flow, then enter the transitional regime, and finally, beginning from an altitude of 80 km, descend in the continuum flow. For successful return of the vehicle to the Earth, it is necessary to know the behavior of its aerodynamic characteristics for all flow regimes. Computation of aerodynamic characteristics of reentry vehicles in the free-molecular flow does not involve many difficulties because theoretical approaches have been developed for simple shapes and the Test Particle Monte Carlo method can be readily used for more complicated shapes. Methods for computing aerodynamic characteristics in the continuum flow have also been adequately developed. The study of aerodynamic characteristics in the transitional flow regime ($0.001 < \mathrm{Kn} < 10$) is a rather complicated problem. The Navier-Stokes equations yield, strictly speaking, incorrect results in the transitional regime and require special modifications for taking into account flow slipping. The Direct Statistical Monte Carlo (DSMC) method provides rather accurate values of aerodynamic characteristics with allowance for physical and chemical processes but requires large amounts of computer memory and performance. Application of the software based on the DSMC method is unreasonably expensive at the initial stage of spacecraft design and trajectory analysis because it is necessary to compute a large number of variants for different angles of attack and sideslip (yaw) and for different flow parameters. A possible solution of this problem is the use of approximate engineering methods, which offer acceptable accuracy and a short computation time. For instance, the existing aerodynamic software system Ramses[2] includes an engineering method based on local bridging interpolation between the free-molecular and continuum flow regimes for obtaining local aerodynamic characteristics in the transitional regime. Accuracy evaluation of engineering methods is difficult because of the lack of experimental data on aerodynamic characteristics of modern spacecraft in the transitional regime. One possible way is a comparison with the complicated but accurate DSMC method. Using local bridging engineering methods, the aerodynamic characteristics of a promising reentry capsule Clipper were examined in the present paper.

2. Basics of Engineering methods

The basic criterion of flow rarefaction is the Knudsen number $\mathrm{Kn} = \lambda/l_c$, which is the ratio of the mean free path of particles and the reference size of the flow (body). For $\mathrm{Kn} \gtrsim 10$, the flow regime is free-molecular (particle collisions are so scarce that they do not affect aerodynamic characteristics); for $\mathrm{Kn} \lesssim 0.001$, the flow is described by the continuum model. There are many simple and fast methods for obtaining aerodynamic characteristics of complex-shaped bodies in the free-molecular flow. Based on Newton's theory, one can also readily calculate aerodynamic characteristics in a hypersonic continuum flow.

Obviously, using these two limits, one can perform interpolation and obtain aerodynamic characteristics in the transitional regime:

$$c_k = c_{k,FM} \cdot F(\mathrm{Kn}, S, \alpha, ...) + c_{k,Cont} \cdot (1 - F(\mathrm{Kn}, S, \alpha, ...)) \tag{1}$$

The function F was called the “bridging” function. In the general case, it depends on many parameters.

One should distinguish between the global bridging method with the use of global (drag, lift, pitching moment, etc.) coefficients of forces and moments c_k and the local bridging method where $c_{k,ds}$ (pressure, friction, etc.) are first calculated for elementary areas of the object surface, and then integration over the surface for obtaining of global aerodynamic coefficients is performed:

$$c_{k,ds} = c_{k,FM,ds} \cdot F(\mathrm{Kn}, S, \Theta, ...) + c_{k,Cont,ds} \cdot (1 - F(\mathrm{Kn}, S, \Theta, ...)) \quad (2)$$

$$c_k = \int^S c_{k,ds} \mathrm{d}S \quad (3)$$

Note, in this case, the local bridging function depends on the angle Θ to the normal to the elementary area where the flow is incident rather than on the angles of attack and sideslip.

2.1 Local bridging method (“Ramses”)

The bridging function

$$F = \frac{1}{2}\left[1 + erf\left(\frac{\sqrt{\pi}}{\Delta \mathrm{Kn}} \cdot \lg\left(\frac{\mathrm{Kn}_\infty}{\mathrm{Kn}_m}\right)\right)\right] \quad (4)$$

was used in Ref.[2] In eq. 4, Kn_m is the center of the transitional regime defined at $F = \frac{1}{2}$ and $\Delta\mathrm{Kn}$ is the logarithmic width of the transitional regime.

With varied rarefaction, the pressure and friction behave differently. In particular, the absence of friction forces is assumed in the continuum regime. Therefore, the coefficients of forces and moments over the elementary area can be divided into components related to pressure and friction, which gives rise to two different bridging functions in the “Ramses” system. The local bridging method offers more accurate allowance for pressure and friction redistributions over the body surface and, therefore, it is more accurate than the global bridging method.

2.2 Local bridging method (“Energia”).

A more complicated engineering local bridging semiempirical method “Energia”[3] employs the following formulas for determining the influence of the flow onto the elementary area:

$$P = P_0 + P_1 w_n + P_2 w_n^2 \qquad \tau = \tau_0 w_t + \tau_1 w_n w_t \quad (5)$$

Here P and τ are the pressure and friction coefficients of aerodynamic forces related to the dynamic pressure $q = \frac{\rho_\infty V_\infty^2}{2}$, $\vec{w}$ is the vector of the free-stream velocity direction, and w_n and w_t are the normal and tangential components of the velocity vector to the surface. The parameters P_0, P_1, P_2, τ_0, and τ_1 are calculated using the following formulas:

$$P_0 = P_0^{id} + (P_0^{fm} - P_0^{id})F_{P0} \qquad P_1 = P_1^{fm} F_{P2} \qquad P_2 = P_2^{id} + (P_2^{fm} - P_2^{id})F_{P2} \quad (6)$$

$$\tau_0 = \tau_0^{fm} F_{\tau 0} \qquad \tau_1 = \tau_1^{fm} F_{\tau 1} \quad (7)$$

($\vec{n}$ is the normal vector to the surface and $\vec{\tau}$ is the tangential vector). These vectors lie in one plane.

The bridging coefficients F_{P0}, F_{P1}, F_{P2}, $F_{\tau 1}$, and $F_{\tau 1}$ are used to take into account the influence of free-molecular or continuum flow regime under particular conditions.

2.3 Calculation of the bridging functions

The formulas for calculating the bridging functions F_P and F_τ were derived semi-empirically by V.M.Kotov, E.N. Lychkin, et al.[3] Here we give their final form:

$$F_{P0} = \frac{1}{a\sqrt{\mathrm{Re}_0} + \exp(-b\mathrm{Re}_0)}, \qquad \text{where} \quad (8)$$

$$a = \frac{(\gamma - 1)\sqrt{t_w} + \mathrm{M}^{-1}\sqrt{2(\gamma - 1)}}{(0.56 + 1.2t_w)(\mathrm{M} + 2.15)} \qquad b = 0.20 + 0.005\mathrm{M} \quad (9)$$

$$F_{P1} = F_{P2} = \exp\left(-(0.125 + 0.078t_w)\mathrm{Re}_0 \cdot 10^{-1.8(1-\sin\alpha_l)^2}\right) \quad (10)$$

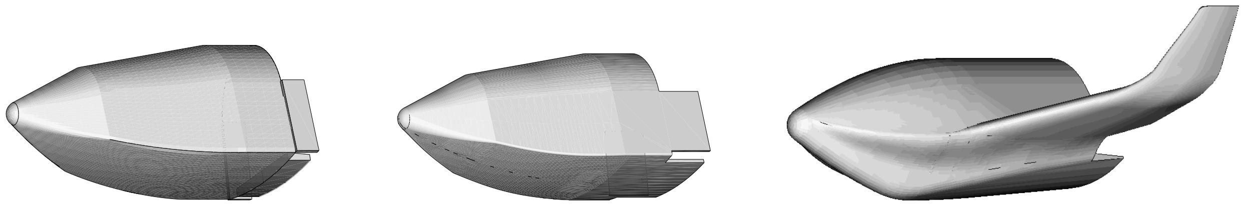

Figure 1: Clipper spacecraft geometries.

$$F_{\tau 0} = \left[a_1 \mathrm{Re}_0 + \exp\left(-b_1 \mathrm{Re}_0\right)\right]^{-3/4}, \qquad \text{where} \tag{11}$$

$$a_1 = \frac{\gamma - 1}{2}\left[\sqrt{\frac{\pi\gamma}{2}}\mathrm{M}(0.208 + 0.341 t_w)\right]^{-4/3} \qquad b_1 = 0.213 - 0.133 t_w \tag{12}$$

$$F_{\tau 1} = \left[0.145R + \exp\left(7.2 \cdot 10^{-3} R - 1.6 \cdot 10^{-5} R^2\right)\right]^{-1/2}, \qquad \text{where} \tag{13}$$

$$R = (0.75 t_w + 0.25)^{-2/3}\, \mathrm{Re}_0 \cdot 10^{-0.24(1-\sin\alpha_l)^3} \tag{14}$$

2.4 DSMC computations

The accuracy of the engineering method in the transitional and near-continuum flow regimes was analyzed by means of comparisons with the aerodynamic characteristics of the Clipper space vehicles computed by the DSMC method.

The DSMC computations were produced using the SMILE software system[1], which is general purposes code for analysis of rarefied atmospheric flows with non-equlibrium thermal relaxation and chemical reactions involved. The number of collisions was calculated by the majorant frequency technique. The collisions of molecules were computed using the variable hard sphere (VHS) model. The internal degrees of freedom were taken into account by the Larsen-Borgnakke model. For rather high Knudsen numbers (approximately $\mathrm{Kn} > 0.1$), computations were performed on single-processor computers. In problems with a rather dense incoming flow, it is necessary to introduce a large number of model particles and divide the computational domain into many cells (on the average, about 10^6 of cells and $5 \cdot 10^6$ model particles). Such flows around the capsules were simulated by the parallel version of the SMILE code. The geometric size of the computational domain was varied for different degrees of rarefaction of the free-stream flow. The reason is that the influence of the body on the external flow at high Knudsen numbers is extended to a greater distance than in the case of a denser flow with the same other parameters of the free-stream flow. The total number of cells in the computational domain was also variable to ensure the necessary spatial resolution.

2.5 Geometrical models and flow parameters

The wingless model of the Clipper vehicle is shaped as a lifting body that provides an effective aerodynamic lifting force during the reentry into the atmosphere. As a result, unlike a traditional reentry capsule, the vehicle is able to perform side maneuvering during its return to the Earth. Two variants of the wingless model of Clipper were computed in the present work: with short air brakes and balance flaps and with a doubled size of the air brakes and balance flaps. In addition, for the geometry with large air brakes and balance flaps, three positions of balance flaps of 0, 10°, and 20° were considered.

A model with wings was also considered. It is expected to ensure better maneuverability and lower overloading during its reentry.

The geometric models of space vehicles in computations were formed of a set of triangular panels. The total number of panels was about 20,000. The aerodynamic characteristics of reentry capsules were computed by the DSMC method along the initial part of the reentry trajectory to an altitude of about 80 km and by the engineering methods to an altitude of 50 km. Depending on the degree of rarefaction of the ambient flow, the number of molecules simulating the flow in DSMC computations around the capsules was varied from 10^5 up to $80 \cdot 10^6$. For gas-surface interaction, the diffuse reflection model with complete energy accommodation was used. The aerodynamic characteristics of the Clipper capsule were examined for angles of attack equal to 0, 30°, and 40°.

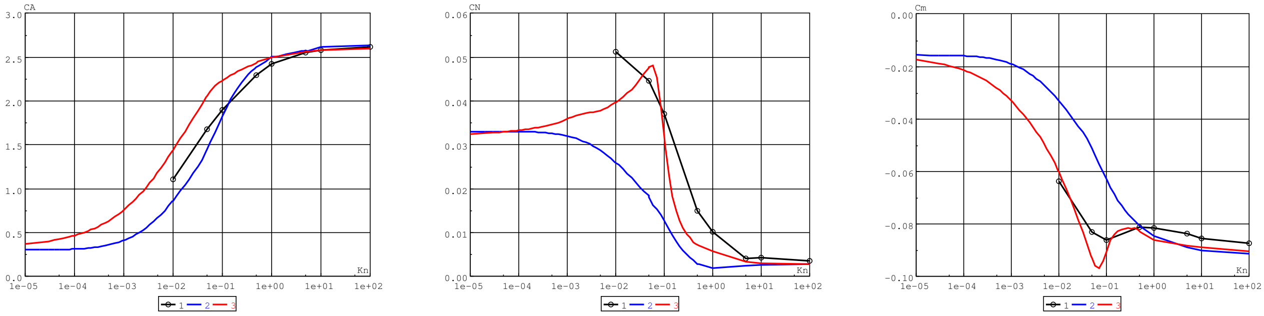

Figure 2: Aerodynamic characteristics of the Clipper vehicle with short flaps versus the Knudsen number of the flow. Angle of attack 0°. Curve 1 shows the DSMC results; curves 2 and 3 show the computations by the "Ramses" and "Energia" local bridging methods, respectively

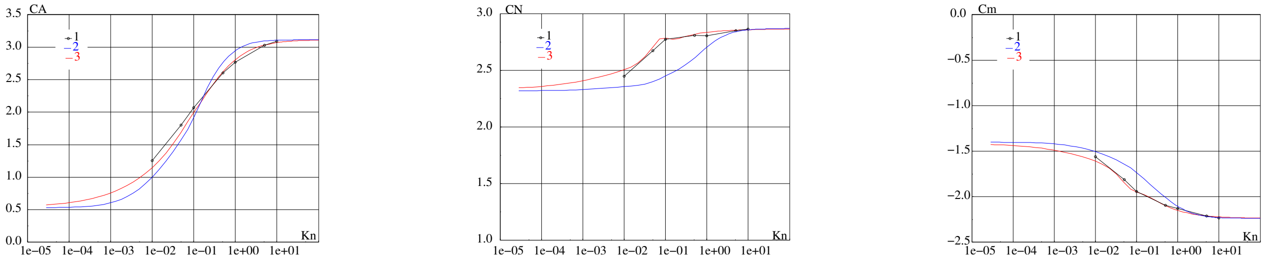

Figure 3: Aerodynamic characteristics of the Clipper vehicle with short flaps versus the Knudsen number of the flow. Angle of attack 40°. 1 – the DSMC results, 2 and 3 – the computations by the "Ramses" and "Energia" methods, respectively

3. Results of computations

3.1 Wingless model

Clipper is a vehicle of the lifting body type. For such a vehicle, it is necessary to know not only the drag force but also the lift force and moment characteristics. Figure 2 shows the behavior of the aerodynamic coefficients C_A, C_N, and C_m of the Clipper capsule at zero incidence as functions of the free-stream Knudsen number, which were calculated by the DSMC method and two local bridging methods ("Ramses" and "Energia"). The distribution C_A(Kn) predicted by "Energia" method has approximately the same error as that of the "Ramses" method, but the results of computations of the normal force C_N(Kn) and pitching moment C_m(Kn) display much better agreement with the DSMC results. The "Ramses" local bridging method does not predict the nonmonotonic behavior of the curve C_m given by the DSMC method and the "Energia" engineering method. Figure 3 shows the results computed for an angle of attack of 40°. The curves obtained by the "Energia" method for the flow at an angle of attack gives also smaller errors than curves of the "Ramses" method, which is clearly seen.

The qualitative difference at low Knudsen numbers can be attributed to the fact that the engineering method ignores the history of variation of flow parameters. The flow reaches the rear part of the spacecraft with parameters different from the free-stream parameters. These changes are caused not only by the jump in gas parameters in the bow shock wave but also by the change in flow velocity and temperature in the boundary layer. Clearly, the larger the distance of a spacecraft element from the stagnation point, the greater the difference between the parameters of the flow acting on this element and the free-stream parameters. The DSMC method captures these changes, while the engineering local bridging method ignores them and takes into account only the panel temperature, accommodation coefficients, and the angle of panel inclination to the undisturbed flow. This fact can explain the difference in the error of results obtained by the approximate method for the same geometry with different angles of attack.

Let us see effect of flap deflection on aerodynamic characteristics of the Clipper vehicle with long flaps at angle of attack 30°. The results are plotted in Fig. 4.

Based on these curves, it is possible to determine the influence of balance-flap deflection on axial and lift forces, and pitching moment of the spacecraft. The figure also contains points corresponding to results obtained by the DSMC method. The engineering method represents correctly the effect of the balance flap deflections on the aerodynamic characteristics. The greatest error (about 22%) is observed in computing the drag coefficient for the configuration with

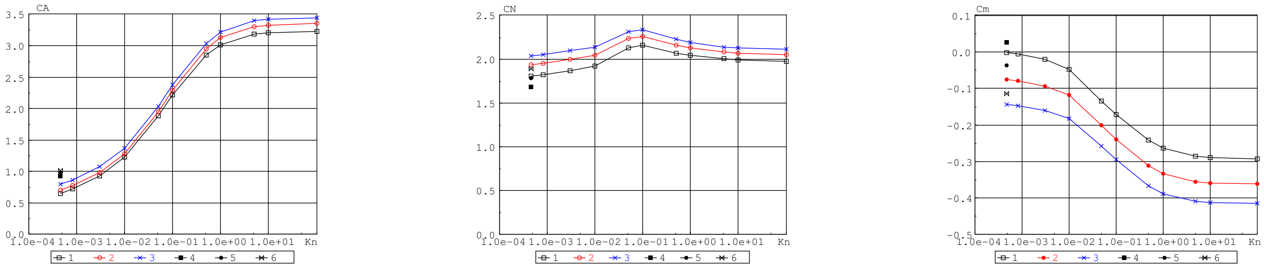

Figure 4: Aerodynamic characteristics of the Clipper vehicle with long air brakes and balance flaps vs the Knudsen number. The angle of attack is 30°. Curves 1-3 are the computations by the "Energia" local bridging method for an angle of deflection of the flaps 0°, 10°, and 20°, respectively; curves 4-6 are the DSMC computations for an angle of deflection of the flaps 0°, 10°, and 20°, respectively

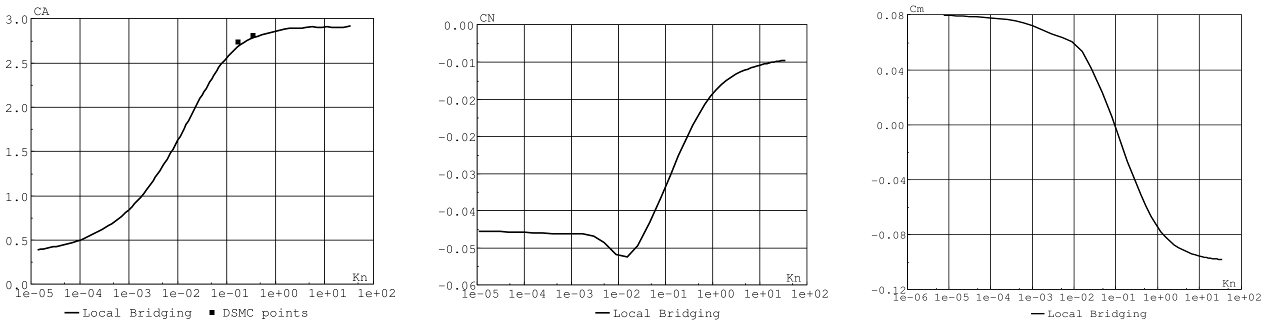

Figure 5: Aerodynamic characteristics of the winged Clipper vehicle versus the Knudsen number of the flow. Angle of attack 0. Computations performed by the "Energia" method

a non-deflected flap. Another factor responsible for such a significant error is the neglect of chemical reactions in the engineering method.

The aerodynamic characteristics for two configurations of the wingless model of the Clipper vehicle for different angles of deflection of the balance flap, which were obtained by the DSMC method, are listed in Table 1.

Table 1: Aerodynamic characteristics of two configurations for different angles of deflection (φ) of the balance flap. Altitude 80 km; angle of attack 30°. DSMC computations.

	Geometry with long flaps				Geometry with short flaps			
φ	C_A	C_N	C_m	C_{ya}/C_{xa}	C_A	C_N	C_m	C_{ya}/C_{xa}
0°	0.934	1.683	0.0246	0.6	0.835	1.593	-1.686	0.633
10°	0.980	1.780	-0.036	0.605				
20°	1.016	1.890	-0.115	0.618				

3.2 Winged model of the Clipper spacecraft

The computed aerodynamic characteristics of the winged model of the Clipper spacecraft are plotted in Fig. 5. Note that the axial force coefficient computed by the "Energia" local bridging method is in reasonably good agreement with the result obtained in DSMC simulations (see Fig. 5). The difference from the DSMC results is substantially greater for the coefficients of the normal force C_N and pitching moment C_m. Apparently, this difference is caused by much greater area (than that of wingless models) of the vehicle surface, for which the local angle between the normal to the surface and the free-stream vector is close to $\pi/2$. In this case, the local engineering method yields a considerable error in computing the normal force and, hence, the pitching moment.

Flowfields of pressure and density and surface distribution of the heat transfer coefficent are presented in Fig. 6 and 7.

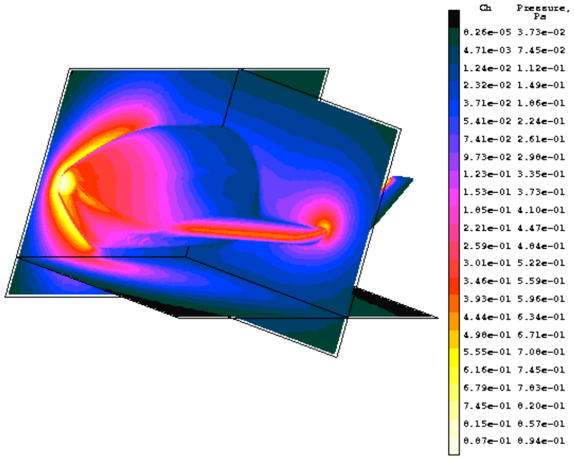

Figure 6: Pressure flowfields and heat transfer coefficient distribution at altitude 120 km.

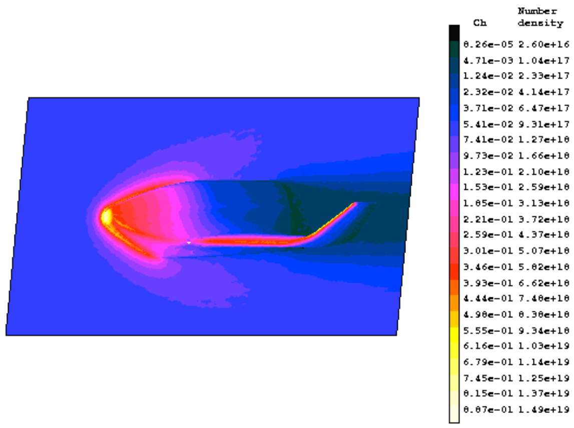

Figure 7: Density flowfield and heat transfer coefficient distribution on altitude 115 km.

Table 2: Clipper aerodynamic parameters with chemically reacting and non-reacting flow

	Altitude 90 km				Altitude 80 km			
Chemically reacting	0.859	0.055	0.055	0.150	0.805	0.055	0.049	0.095
Chemically non-reacting	0.852	0.051	0.054	0.154	0.817	0.056	0.055	0.134

4. Real gas effects on aerothermodynamic characteristics

As the engineering method ignores chemical reactions, it is necessary to find out at which altitude the real properties of air start to be noticeably manifested. For this purpose, additional computations for the Clipper capsule with short flaps were performed by the DSMC method with allowance for chemical reactions at altitudes of 90 and 80 km. The results are presented in Table 2. They show that the values of aerodynamic parameters remain almost unaffected if chemical reactions are taken into account for this altitudes. Thus, we can conclude that the engineering method ensures acceptable accuracy of aerodynamic characteristics for a rather wide range of Knudsen numbers.

5. Conclusions

Results of using two engineering methods for approximate computations of aerodynamic characteristics of reentry vehicles in a hypersonic flow are presented. Comparisons with results obtained by a complicated and expensive DSMC method prove the adequacy of results of aerodynamic forces computation. It is shown that the “Energia” method can reproduce some flow details inaccessible for the engineering “Ramses” method. It can be reasonably used at the initial stage of design of spacecraft of the lifting-body type for approximate estimates of a large number of different geometries or flow parameters, selection of the optimal spacecraft configuration, and other aerodynamic problems. It is necessary, however, to study more details of the area of applicability and errors of the ”Energia“ local bridging method in computing bodies with a large aspect ratio at angles of attack close to zero.

5.1 Acknowledgements

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