Trade-off of aerodynamic configuration for a descent vehicle

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Abstract
Descent vehicle (DV) configurations are constructed with assumption that pressure on their surfaces is calculated by the tangent wedge method refined with computational results for ideal gas flow around typical configuration. A variational problem about configuration with maximal lift-to-drag ratio is stated; and this problem is solved with the help of the method of local variations. Results are illustrated for lifting body like DV "Clipper" optimal configurations. Application of the tangent wedge method for estimating the aerodynamic coefficients C_x, C_y, m_z, K of "lifting body" configurations is discussed.

Nomenclature

C_p – pressure coefficient
C_x – axial force coefficient
C_y – normal force coefficient
m_z – pitching moment coefficient
K – lift-to-drag ratio
C_f – friction coefficient
M – Mach number of oncoming flow
v – velocity of oncoming flow
γ – specific heat ratio
q_∞ – dynamic pressure of oncoming flow
α – angle of attack
δ – deflection angle of flap

1. Introduction

One of the problems in manned space exploration is creation of space vehicles, which provide a considerable lateral manoeuvre (~ 1000 km) and comfort crew conditions at space vehicle descent trajectory. In case of parachute landing, DV configuration is "lifting body" type, for example known project "Clipper"[1,2]. As a rule, aerodynamic configuration trade-off is based on a designer experience[1,2], or on analysis of a wide range of candidate shapes[3].

DV manoeuvre properties at descent trajectory are defined mainly by its maximal lift-to-drag ratio K_{max}, so the configuration trade-off can be executed by solving a variational problem about configuration with maximal lift-to-drag ratio. Obviously, the problem statement includes conditions imposed by required body volume, heat fluxes toward body surface, planform, etc.

A solution for such type variational problem with thin lifting configurations was suggested in the paper[4], and optimal configurations with ramjet were constructed in the paper[5].

While constructing the vehicle optimal configuration, restrictions imposed on heat fluxes toward body surface are stated by given shape of nose part bluntness that is constant in course of computations.

An algorithm for constructing an optimal "lifting body" configuration is presented below. Computational results are compared with DV "Clipper" parameters.

2. Problem statement

Let's examine a supersonic gas flow around a body, and flow velocity vector $\bar{v}$ makes an angle α with OX-axis of Cartesian coordinates OXYZ. Body surface is given by an equation *f(x,y,z)=0*. Since a variational method is used for solving the optimisation problem, a mathematical model of oncoming flow interaction with body surface should easy enough for quick approaching to a steady state. From the other hand, it is necessary to have the mathematical model adequate to real physical process, and appropriate accuracy of aerodynamic characteristics, K_{max} in particular, is required.

In this connection the aerodynamic characteristics are calculated by the local method of tangent wedge that is widely used in applied aerodynamic researches[6,7].

Pressure coefficient on body surface is calculated by equations [4,5] (1):

$$
\begin{aligned}
&C_p = k_1 \cos^2(\bar{n},\bar{v})\left\{\frac{\gamma+1}{4} + \left[\left(\frac{\gamma+1}{4}\right)^2 + \frac{1}{A^2}\right]^{1/2}\right\}, && \cos(\bar{n},\bar{v}) > 0 \\
&C_p = \frac{k_2}{\gamma\left(M^2-1\right)}\left[\left(1-\frac{\gamma-1}{2}A\right)^{\frac{2\gamma}{\gamma-1}} - 1\right], && \cos(\bar{n},\bar{v}) \le 0 \\
&C_p = -\frac{k_2}{\gamma(M^2-1)}, && 1-\frac{\gamma-1}{2}A < 0 \\
&A^2 = \left(M^2-1\right)\cos^2(\bar{n},\bar{v}), \quad A>0.
\end{aligned}
\tag{1}
$$

It is easy to derive that with $A \to \infty$ the dependencies (1) correspond to the Newtonian formula:

$$
C_p = \begin{cases} k_1(\gamma+1)\cos^2(\bar{n},\bar{v})/2, & \cos(\bar{n},\bar{v}) > 0 \\ 0, & \cos(\bar{n},\bar{v}) \le 0 \end{cases}
$$

At low supersonic speeds $A \to 0$, and the dependencies (1) correspond to formulas of the linear theory of supersonic flow:

$$
C_p = \begin{cases} k_1 \cos(\bar{n},\bar{v})\left(M^2-1\right)^{-1/2}, & \cos(\bar{n},\bar{v}) > 0 \\ -k_2 \cos(\bar{n},\bar{v})\left(M^2-1\right)^{-1/2}, & \cos(\bar{n},\bar{v}) \le 0 \end{cases}
$$

and with $k_1=k_2=2$ they are the Akkeret formula for a flat plate in small incidence $\alpha = \arcsin(\cos(\bar{n},\bar{v}))$.

k_1, k_2 values depend on shape of examined bodies, and for some family of bodies they can be found from comparison of aerodynamic coefficients C_x, C_y, m_z calculated by the formulas (1) and through numerical integration of the equations of ideal gas motion. For thin wings with large aspect ratio $k_1=k_2=2$, and values of C_x, C_y, m_z coefficients calculated by the formulas (1) and by numerical integration of the Euler equations are close[4]. "Lifting body" configuration is a rather blunted body with significant pressure gradients at transition from windward side to lee-side, and with substantially three-dimensional flow structure.

The coefficients k_1, k_2 for "Clipper" type configuration were estimated by numerical simulation of supersonic ideal gas flow basing on a procedure described in paper[8]. Aerodynamic coefficients values C_x, C_y, m_z calculated by the formulas (1) and by numerical simulation were compared, and k_1, k_2 values were found that correspond to maximal proximity of these calculations. As an example, Table 1 presents "Clipper" aerodynamic coefficients with M=6 for $k_1=k_2=2$ and $k_1=1.5$; $k_2=0.1$ that illustrate accuracy of approximate estimations. Reference area is planform area, body length equals unity, and moment is calculated with respect to body nosetip.

It follows from these results that variation of k_1, k_2 values allows enhancing the accuracy of examined configuration aerodynamic coefficients, and $K(\alpha)$values are close regardless of the mathematical model used.

Thus, with known k_1, k_2 values for a definite body family and using dependencies (1) for estimation of pressure on body surface is possible to find C_x, C_y, m_z, K coefficients with appropriate in practise accuracy.

Table 1

Model	**Euler equations**		$k_1 = k_2 = 2$		$k_1 = 1.5$; $k_2 = 0.1$	
α, degr.	20	35	20	35	20	35
K	1.129	0.825	1.183	0.862	1.151	0.846
C_x	0.184	0.239	0.236	0.309	0.178	0.236
C_y	0.468	0.864	0.640	1.219	0.465	0.892
m_z	-0.237	-0.474	-0.338	-0.689	-0.243	-0.502

For determining C_x, C_y, m_z coefficients the body surface is divided into small triangular elements where pressure is defined by orientation of local normal to oncoming flow velocity vector.

Friction coefficient C_f is constant on the body surface, and base pressure coefficient C_{pb} is estimated by the simplest formula $C_{pb} = -2/\gamma M^2$ that can be refined if necessary.

Denote C_{x0}, C_{y0}, - aerodynamic coefficients of aerodynamic configuration elements (flaps, protrusions, etc.), that are not varied during optimisation procedure, then C_x, C_y are found from the following relations:

$$
\begin{aligned}
SC_x &= \sum_i \left(C_p \cos(\bar{n},\bar{x}) + C_f \cos(\bar{\tau},\bar{x}) \right)_i \Delta S_i - C_{pb} S_b + C_{xo} S_0, \\
SC_y &= \sum_i \left(C_p \cos(\bar{n},\bar{y}) + C_f \cos(\bar{\tau},\bar{y}) \right)_i \Delta S_i + C_{yo} S_0, \\
K &= (C_y \cos\alpha - C_x \sin\alpha) / (C_y \sin\alpha + C_x \cos\alpha),
\end{aligned}
\qquad (2)
$$

here ΔS_i – area of i-th triangular element, , S_b – base section area, , S_0 – reference area for calculating C_{xo}, C_{yo}, $\bar{\tau}$ – tangent vector to body surface that lies in a plane of velocity vector $\bar{v}$ and local normal $\bar{n}$.

<u>The problem statement is the following:</u> to determine a body shape having maximal lift-to-drag ratio at given volume V, planform, oncoming flow Mach number, coefficients C_f, C_{pb}, nose part bluntness.

3. Solution technique

The problem is solved with the help of numerical method of local variations[9,10], which includes the following stages:

1. Initial configuration is specified with given volume, planform, nosetip bluntness, coefficients C_{x0}, C_{z0} and so on.
2. Lift-to-drag ratio K is calculated for the initial configuration using the formulas (2).
3. A certain small value $\delta << |y_{i,l}|$ is chosen, here $y_{i,l}$ - coordinate of arbitrary point (i, l) on body surface.
4. The coordinate $y_{i,l} = y(x_i, z_l)$ on body surface is varied: $y_{i,l} = y_{i,l} \pm \delta$ and coordinate of some another point is varied too $y_{j,k} = y_{j,k} \pm \delta_{j,k}$ in order to keep body volume V = const. Such variation of body surface we denote $\Delta_{i,l} = (\delta, \delta_{j,k})_{i,l}$. A variation is selected among $\Delta_{i,l}$ such that corresponds to maximal increase of K value. Then $y_{i,l}$ and $y_{j,k}$ are changed by a $y_{i,l} = y_{i,l} \pm \delta$, $y_{j,k} = y_{j,k} \pm \delta_{j,k}$ and the procedure is repeated for the next point ($i+1, l$) or ($i, l+1$).
5. If there is no variation $\Delta_{i,l}$ which makes K value greater, then $y_{i,l}$ is not varied and the procedure is repeated for the next point ($i+1, l$) or ($i, l+1$).
6. If there is no variation $\Delta_{i,l}$ which makes K value greater for any point (i, l), the parameter δ is reduced, for example by half ($\delta = \delta/2$) and items 4÷5 are repeated.
7. If δ reduction does not make K value greater, the optimisation process is terminated.

Numerical solution convergence was analysed while constructing an optimal configuration for a body with given volume and various angles of attack α. Practically similar shapes were obtained in all cases, and K_{max} values coincided.

4. Optimisation of descent vehicle configuration

Considering the problem about optimisation of DV configuration it is necessary to assign required bluntness radius or nose part shape that provide admissible heat fluxes toward DV body surface at descent trajectory. In this connection an initial configuration for optimisation procedure was "Clipper" model[1], and its volume, planform and radius of nosetip bluntness were not varied during computations. The initial shape is shown in Fig.1 illustrating also body surface partition into triangular elements.

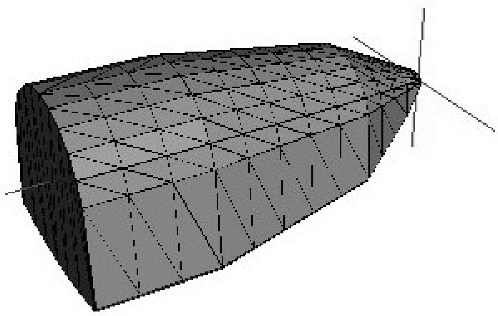

Figure 1: Initial configuration

Application of equations of ideal gas motion for determining the aerodynamic coefficients in the course of variational problem solution involves more sophisticated solution procedure and high run time. It follows from above analysis of the tangent wedge method that it is possible to provide high accuracy of C_x, C_y, m_z, K determination with appropriate choice of the coefficients k_1, k_2. For optimisation of "Clipper" configurations there were chosen values k_1 =1,5, k_2=0.1. In order to analyse the influence of k_1, k_2 on the problem solution, the configuration was optimised with k_1=k_2=2. Noticeable distinctions between two optimal configurations were not found, and values of lift-to-drag ratio differ by two percents at the most.

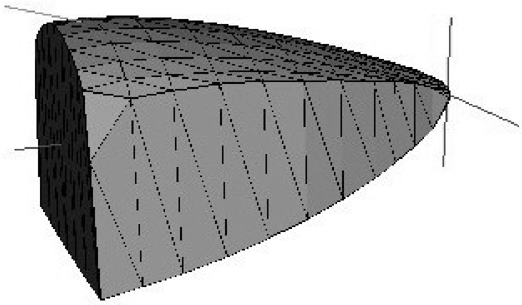

Figure 2: Optimal configuration

DV optimal configuration is shown in Fig.2, it is characterised by flat side surfaces. The lower surface has small curvature in longitudinal and transverse directions. The upper surface has variable slope to X-axis, slope angle reduces approaching to the base section. The body cross section looks like " upturned bucket". Such shape peculiarities of the optimal configuration are inherent to bodies with large volumetric parameter $\tau = V^{2/3}/S$. At increased value of τ parameter the side surface become parallel to Y-axis. Maximal lift-to-drag ratio is attained at the angle of attack such that velocity vector is parallel to the upper generatrix of the nose part.

Aerodynamic coefficients of the optimal model at M=10 are plotted against angle of attack in Fig.3. Their values obtained through numerical integration of Navier-Stocks and Euler equations, Euler equations and using the formulas (1), (2) are close and demonstrate good accuracy of the tangent wedge refined method. The dependencies $K(\alpha)$ for the initial body, shown in Fig.4, were obtained by the tangent wedge method (formulas (1), (2), k_1=1.5, k_2=0.1), and by numerical integration of the equation of ideal gas motion. Calculation results are close and in good agreement with data from paper[1]. Optimisation of the body configuration allows to rise maximal lift-to-drag ratio from K_{max}=1.18 to K_{max}=1.40 (Fig.4). Lift-to-drag ratio of the optimal body for Mach numbers over M=6 is practically the same as for M=6.

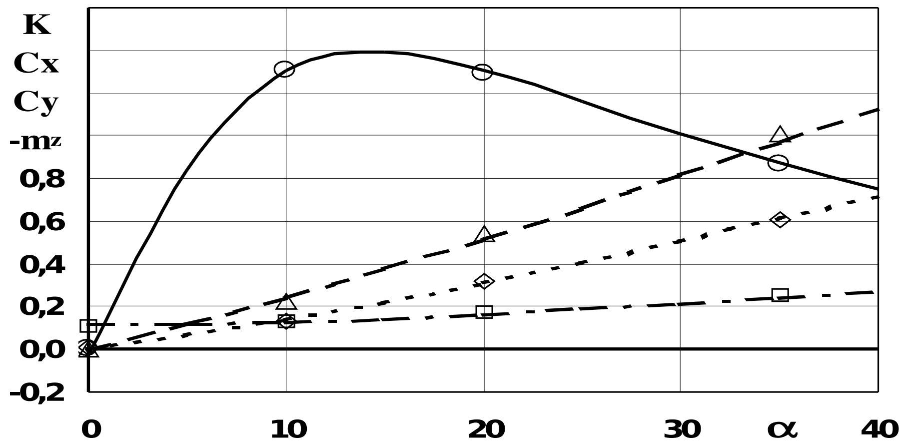

Figure 3: Aerodynamics characteristics of the optimal configuration at M=10 V=0.0718, C_f=0.
k_1=1.5, k_2=0.1 (lines),
points –Euler, Navier-Stocks equations: O – K; - C_x; Δ - C_y , ◊ – m_z

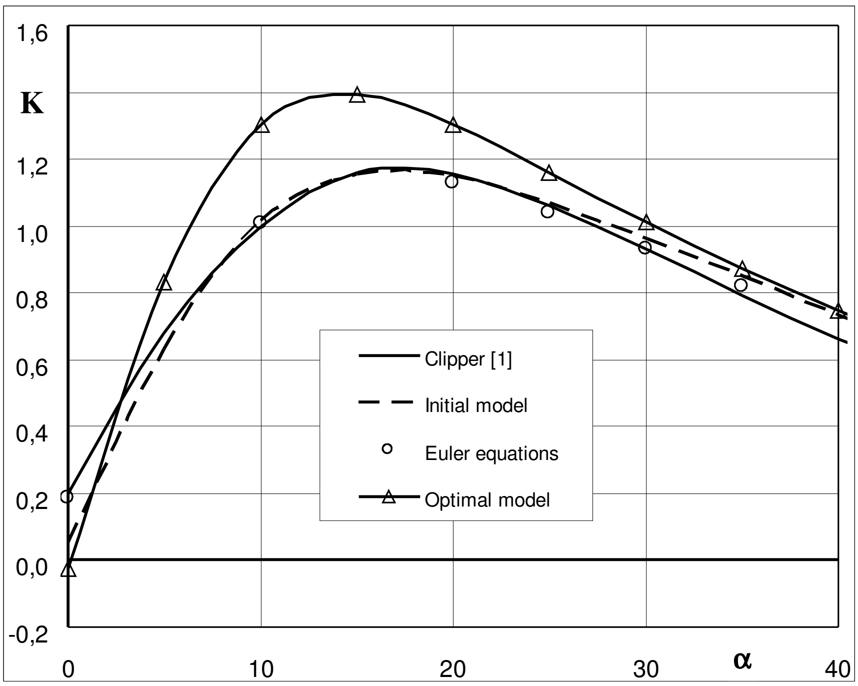

Figure 4: Lift-to-drag ratio of the initial and optimal models at M=10, C_f=0.
(k1 = 1.5, k2 = 0.1)

Numerical simulation results define a low pressure level at optimal body side surface (Fig.5), and this causes instability in roll and yaw direction at small yaw angles β. In order to provide DV stability and control, flaps are mounted in its base region (Fig.6). Aerodynamic characteristics of descent vehicles with flaps deflected at the angle

δ are calculated by the formulas (1), (2) with above values of the parameters k_1, k_2 using the same algorithm, which is used for the configuration optimising procedure.

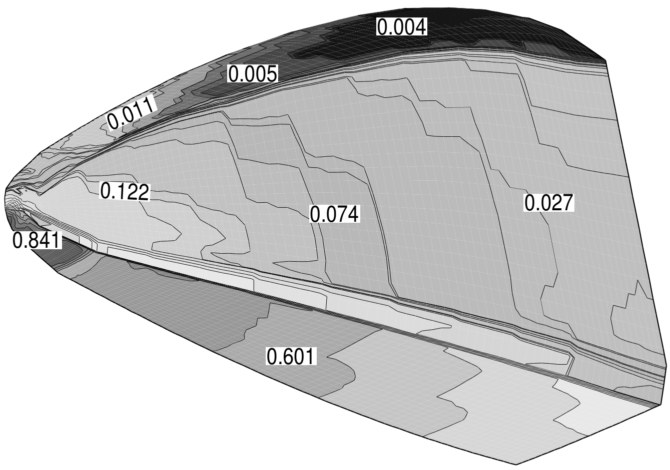

Figure 5: The pressure distribution ($P/2q_\infty$) around body surface at M=10, α=35°. Navier-Stocks equations

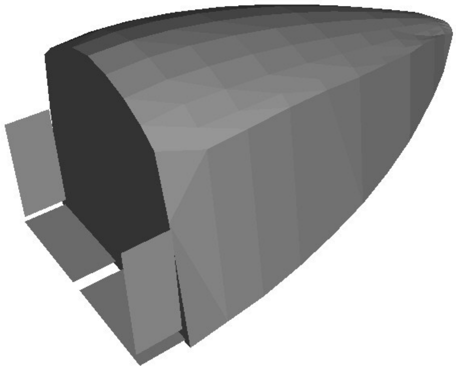

Figure 6: Descent vehicle with flaps

As an example, Fig.7 illustrates pitch moment $m_z(\alpha)$ with respect to the center of gravity (x_{cg}=0.65, y_{cg}=–0.08) at M=10 and different deflection angles δ. The flaps' dimensions correspond to DV"Clipper" flaps. With δ=0 the optimal decent vehicle has trim angle $\alpha\approx 35°$, and this angle reduces if flap deflection angle increases. Note that $K(\alpha)$ dependencies on Fig.7 are calculated for DV with flaps.

4. Conclusion

Application of the local tangent wedge refined method along with variation method of local variations enables to compose a simple and efficient algorithm for determining a descent space vehicle configuration taking into account restrictions due to its external dimensions, heat regimes and so on.

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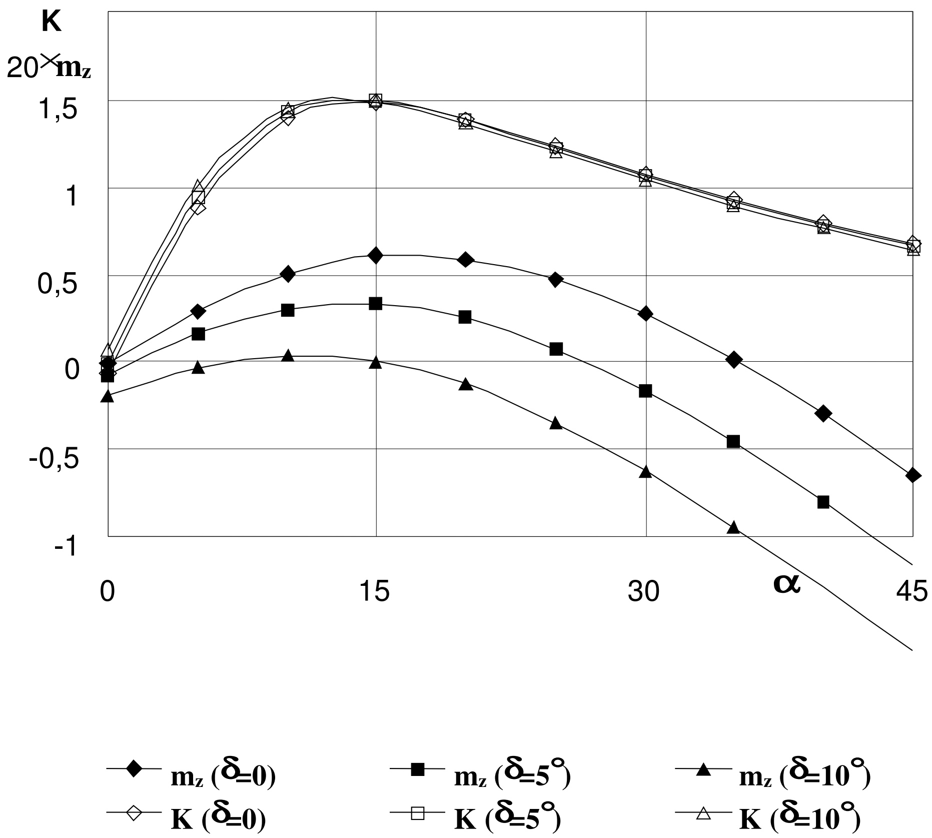

Figure 7: Lift-to-drag ratio and pitch moment of the optimal model, M=15.

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