AERODYNAMIC OF REENTRY SPACECRAFT CLIPPER

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At present time RSC Energia is carrying out research work on designing the reentry manned spacecraft of new generation to crew deliver, in-flight support and return. The spacecraft ought to take the place of Soyuz. Manned spacecraft Clipper having the reentry vehicle (RV) of lifting body type is a possible alternate solution (Fig. 1). In comparison with Soyuz suggested RV provides higher maneuverability and less overloading during descent phase.

Experimental and numerical investigations of reentry vehicle aerodynamic characteristics at descent phase have been carried out. The main peculiar properties of flowing about spacecraft have been revealed. Possibility of using Russia software for investigations of aerodynamics of lifting body type vehicles at a design phase is shown. Comparison of experimental and numerical results is presented.

Aerodynamic Configuration

Clipper aerodynamic characteristics at de-scent phase is analyzed in the paper. In order to provide controllability and aerodynamic equilibration for required angles of attack the aerodynamic control means - trim flap and air brake located in the bottom area are used in addition to jet control system (see Fig.1).

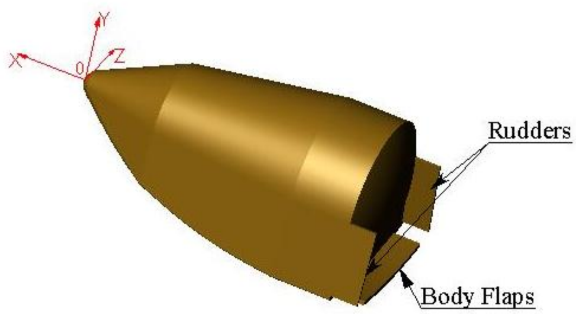

Fig. 1

The sections of a trim flap and air brake can deflect at equal angles δ_{flap} and δ_{ab} synchronously and at different angles differentially that permits to control vehicle flight along planes of pitching, rolling, and yawing.

During development works on choosing the spacecraft shape the following configurations of base aerodynamic assembling have been researched:

- change of square of sections of trim flap and air brake (~2 times);
- change of form of RV leeward generating line – broken and curvilinear;
- change of lengthening of vehicle by means of its affine transformation (K_l~1.3);
- change of radius of spherical bottom (~ 1.3 times);
- change of angle of bottom inclination;
- mounting blowing gas device into a bottom area from RV side surface in order to decrease longitudinal bottom force;
- modification of air brake flap form and etc.

Research Procedures for Aerodynamic Characteristic

During last years numerical methods for researching aerodynamic characteristics of aircrafts of different types have found a wide application in necessary range of Mach numbers, angles of attack and flight altitude. Testing of FlowVision [1], AeroShape-3D [2] programs and other software elaborated in Russia has confirmed their availability in design investigations of aerodynamic form of analyzed vehicle and preliminary determination of its aerodynamic characteristics. It was shown that using numerical methods could be successful only in cooperation with experimental and numerical researches.

Some results of conducted testing are presented in Figs. 2-3 and in the Table 1. Results of numerical investigations are compared with experimental data obtained during testing of the model scale ~ 1:43 at TSAGI T-114 and TSNIIMASH У-3, У-4, У-6 wind tunnels. On the base of the tests the optimal sizes of effective areas and grids for different flow regimes for calculations at production personal computer are selected.

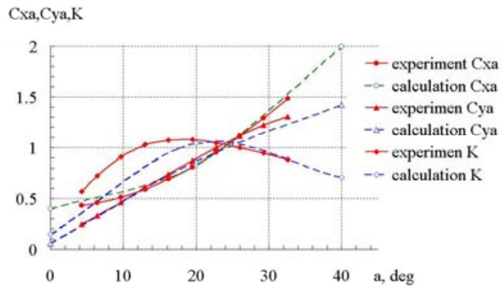

Fig. 2

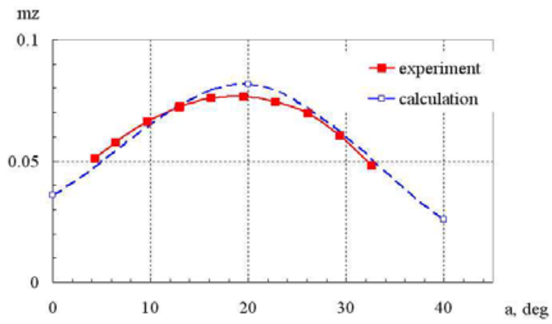

Fig. 3

Analysis shows that combination of experimental and calculated investigations permits to reduce volume and costs of planned experimental investigations without risk of lose reliability of obtained results. The less volume of tests can be reached owing to decreasing of variance of tested models and volume of methodical works.

RV Aerodynamic Characteristics

Aerodynamic characteristics of RV at super- and hypersonic velocities ($M_\infty > 4…15$) are obtained by calculations [2], [3], at sub- and supersonic velocities ($M_\infty \le 0.6…6.0$) – on the base of test results of 1:43 scale model and calculations using software [1], [2].

Coefficients of longitudinal (C_x), normal (C_y) forces and rolling (m_x), yawing (m_y) and pitching (m_z) moments are determined in body

Table 1.

Comparison of calculated and experimental values of reentry vehicle aerodynamic coefficients at M = 0.92

Charac-teristics	δ_{fl}	Calculation		Test	
		$\alpha = 0$	$\alpha = 10°$	$\alpha = 0$	$\alpha = 10°$
Cx	0	0.450	0.510	0.430	0.470
	10°	0.520	0.620	0.500	0.520
Cy	0	-0.025	0.625	0.020	0.066
	10°	0.130	0.890	0.160	0.830
m_z	0	0.004	0.020	-0.004	0.003
	10°	-0.055	-0.051	-0.068	-0.068

system of coordinates Oxyz; drag coefficient (C_{xa}), lifting force (C_{ya}) and fineness (K) – in wind body system of coordinates $O_a x_a y_a$ z_a with beginning in the mass center.

Conducted investigations of RV base configuration show the following:

- at hypersonic flight part at given centering the spacecraft is statically stable in all range of Mach numbers from 4.0 to 15.0 and keeps its auto balance at angles of attack $\alpha_b = 45^o \ldots 47^o$ at non-deviated operating control (see Fig. 3); fineness at balancing angle of attack is $K_b \approx 0.6$; maximum fineness at this part of flight reaches ~ 1,1 and realized at angle of attack ~ 20^o;
- with decreasing flight velocity the RV keeps static stability on pitching up to Mach number ~ 1.0; under this condition balancing angle decreases from $\alpha_b \approx 45^o$ at M = 4.0 to $\alpha_b \approx 27^o$ at M = 1.0 with simultaneous increasing of fineness up to ~ 1.2 at balancing angle of attack; at Mach number $\leq$ 0.9 (regime of landing parachute startup) the vehicle becomes statically unstable;
- enlargement of balancing flap in comparison with base configuration from ~ 0.6 m up ~ 1.0 m permits the vehicle to be static stable up to Mach number ~ 0.6 and provides fineness and balancing angles of attack the same as presented in Fig. 4.;
- in roll channel RV is statically stable or neutral at given positioning really through all flight range of Mach numbers from 15 to 0.9 and unstable in yawing channel; opening of air brake decreases degree of static instability in yawing;
- aerodynamic control elements (trim flap and air brake) are sufficiently effective through all range of Mach numbers; deflection of trim flap in a positive angle can provide vehicle balancing at angles of attack corresponding to maximum fineness (Fig. 5).

Peculiarities of Spacecraft Aerodynamics

Numerical and experimental investigations reveal some peculiarities of flow around RV and aerodynamic characteristics as follows:

- considerable effect of RV bottom part on force and moment characteristics;
- sizeable deflection of air brake sections effect on RV pitching moment;

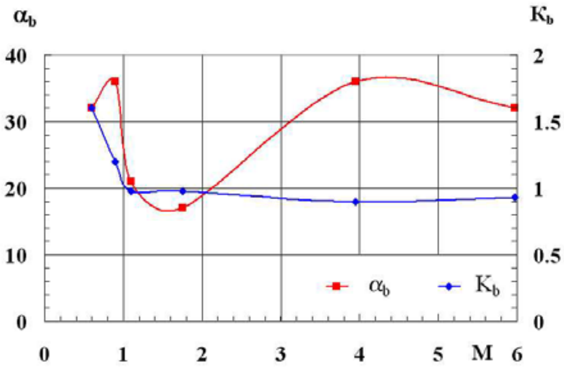

Fig. 4

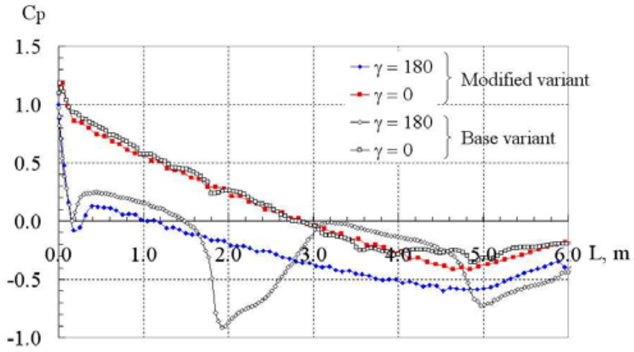

Fig. 6

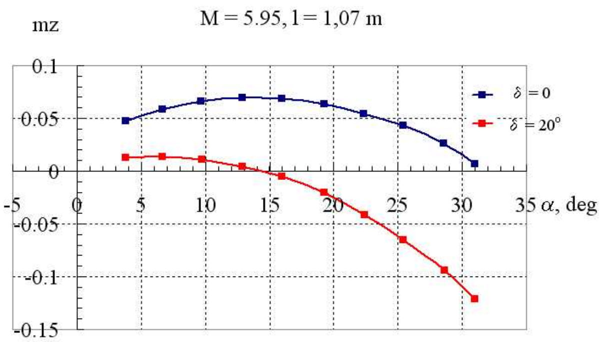

Fig. 5

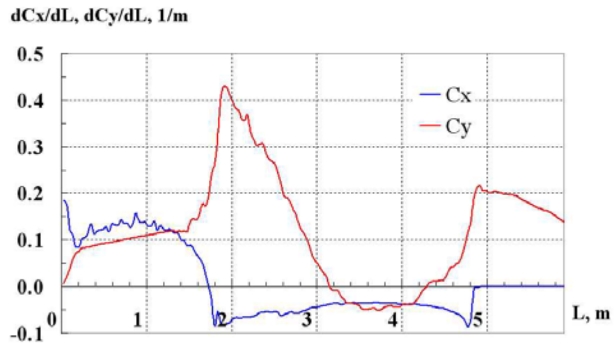

Fig. 7

– effect of bottom holder on model aerodynamic characteristics at subsonic and transonic velocities at testing in wind tunnels.

Influence of Bottom Area on Spacecraft Aerodynamic Characteristics

Some individual elements of assembling effect on RV aerodynamic characteristics have been analyzed using numerical calculations results.

Pressure distribution (see Figs. 6 – 7) along windward and leeward RV generating line in the symmetry plane as well as longitudinal and normal force distribution diagrams along the body at Mach number 0.92 show individual elements contribution to aerodynamic characteristics.

It is significant to note that pressure monotonously decreases from nose part to bottom along lower surface of vehicle - it is typical for spherical surfaces, and pressure near the jogs of upper generating line varies stepwise that is typical for cylindrical bodies.

Table 2.

Components of RV longitudinal force coefficient

M	α	C_x	C_{xb}	C_{xb}
0.92	0	0.45	0.04	0.41
	10°	0.51	0.042	0.468
4.0	0	0.4	0.325	0.075
	20°	0.48	0.405	0.075
	40°	0.62	0.54	0.08

Depression (C_p<0) realized near jogs of cone lee generating line at transonic velocities causes appearance of considerable normal forces in these zones. Depression in the bottom part mainly determines total RV longitudinal force particularly at transonic flight velocities (Table 2).

To reduce bottom part effect on RV moment characteristics it was made spherical.

Influence of Air Brake Opening on Pitching

Depression (C_p<0) realized near jogs of cone lee generating line at transonic velocities causes appearance of considerable normal forces in these zones. Depression in the bottom part mainly determines total RV longitudinal force particularly at transonic flight velocities (Table 2).

To reduce bottom part effect on RV moment characteristics it was made spherical.

One of most difficult problem is control elements cross effect on RV aerodynamic characteristics. In Clipper case considerable air brake opening influence on pitching moment was found on the base of experimental researches results. Increasing of opening angle δ_{ab} leads to intensification of this dependence that causes decreasing of static stability margin or static instability increasing of vehicle within the investigated range Mach numbers (0.6…1.75). The experimental data of RV aerodynamic characteristics at M_∞ = 1.1 and δ_{ab}=0.45° is shown in Table 3.

Table 3.

Air Brake influens on aerodimamics at M∞ = 1.1

δ_{ab}	C_x	C_y	C_{pb}	m_z
0	0.79	0.37	-0.43	0.072
45°	0.98	0.32	-0.56	0.079

As would be expected from common physical understanding air brake opening should lead to pitching moment decrease, in other words, to negative component Δm_z appearance due to aerodynamic forces acting on brake flaps and applied to RV below its center of mass. But they have observed opposite effect.

In order to explain the causes of such aerodynamic characteristics behavior the numerical calculations of flow around RV with air brake flap deviated or not have been conducted. The research allows finding the following:

- longitudinal force component acting on air brake cause pitch moment component $\Delta m_z \approx$ -0.008;
- opening of air brake leads to change the flow pattern in vehicle bottom region that is connected with abrupt increasing of depression. This is confirmed by measurements of bottom pressure in model tests. At the same time buildup of vehicle longitudinal bottom force at ~20% leads to appearance of positive moment component $\Delta m_z \approx 0.01$, because the point of its application is higher than center of mass ($y_T < 0$);
- air brake opening produces pressure increasing at vehicle body side and upper surfaces in front of brake flap that leads to normal force decreasing and positive moment appearance component $\Delta m_z \approx$ 0.02;
- partly normal force decreasing at body is compensated for normal force increasing, acting on trim flap due to increasing of depression in bottom area and on upper flap surface. Increasing of depression at lee side of trim flap leads to appearance of negative pitch component ($\Delta m_z \approx$ -0.012) that partly compensates negative effect of increasing of longitudinal force and moment of normal force at a body.

Influence of Bottom Holder on Aerodynamic Characteristics at Model Tests

Because of considerable flow influence in bottom area on aerodynamic characteristics ($Cx_b \approx 0.8C_x$) special investigations on analyzing influence of bottom holder used at model tests in wind tunnel on obtained results have been carried out.

Holder diameter in accordance with the requirements of technical conditions on tests at wind tunnel was chosen equal to d/D ≈ 0.3 (here d – diameter of holder, D – diameter of cylindrical part of model body).

Calculations [4] of flow around the model with bottom holder and without it using software [1] at transonic flow regimes (M ~ 0.92) show the following:

- presence of bottom holder changes flow pattern in bottom area and distribution of pressure through bottom surface (Fig. 8);
- holder leads to decreasing of total longitudinal force coefficient by ~ 10 - 15%;
- depression at a trim flap surface looking at bottom area and correspondingly normal force and hinge moment of flap are decreased;
- holder weakly effects on pressure distribution along side RV surface.

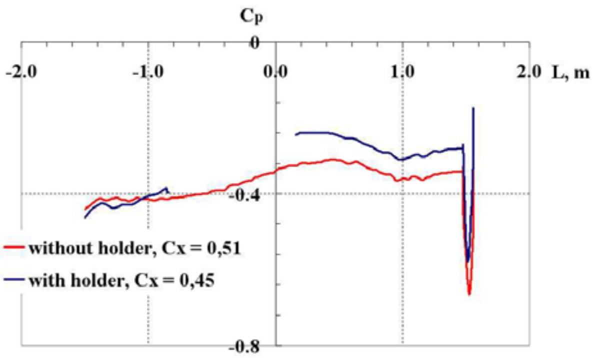

Fig. 8

So in spite of bottom holder dimensions meet the requirements of methodical recommendations (d/D < 0.3) its negative effect on determined RV aerodynamic characteristics is considerable particularly at transonic velocities. Downsizing holder relative diameter till 0.2 lowers effect a little but doesn't eliminate it. Therefore vehicle designers are facing with a difficult problem of scaling experimental researches results in wind tunnels of all basic aerodynamic characteristics (C_x, C_y, m_z, C_z, m_y) and control elements efficiency to full-scale condition.

Influence of Shape of Spacecraft Individual Elements

In this section the results of numerical investigation of some measures presented above on development of RV aerodynamic assembly base variant are analyzed. In particular the influence of a vehicle upper part shape (modified vehicle) and gas blowing effect into bottom area are analyzed.

Comparison of aerodynamic characteristics for base and modified variants is given in Table 4 at Mach numbers 0.92 and 4.0.

Modification of shape of upper part has a favorable impact on aerodynamic characteristics: C_x is decreasing, C_y and K are increasing, m_z is going down. Appreciable minimums and maximums of C_p in distribution diagrams of pressure (see Fig. 6) disappear that leads to more favorable construction loading.

In order to reduce bottom resistance particularly for sub- and transonic flight velocities it is proposed to blow gas taken away from side surface of vehicle into its bottom area. For that intake devices in the form of flaps opened at fixed angle are installed at side surface of vehicle in its tail part (Fig. 9). Gasdynamic channels through which gas from side surface flows into bottom area are placed under the flaps. Numerical calculations show that in that case appreciable bottom pressure growth in comparison with base variant happens as well as vehicle longitudinal force decreases nearly by 9%. But decrease of total vehicle longitudinal force is no more than 5% due to additional resistance of flaps – intakes. Our efforts directed to intensification of positive effect of gas blowing into bottom area by means of increasing gas flow 2 times owing to upsizing flap dimension and gas dynamical channel don't lead to a positive result. Variant of intake device mounted flush on a side surface (without flaps -

Table 4

Influence of spacecraft upper surface modification on aerodynamic characteristics

M	α	Assembling modification	C_x	C_y	$-m_z$	C_{xa}	C_{ya}	K
0.92	0	base	0.433	-0.025	0.0089	0.433	-0.025	-0.058
		modified	0.400	0.003	0.0044	0.400	0.003	0.008
	10°	base	0.471	0,651	0.0098	0.577	0.559	0.97
		modified	0.432	0.689	0.0099	0.545	0.604	1.107
4.0	0	base	0.403	0.067	0.0067	0.403	0.067	0.166
		modified	0.404	0.075	0.0091	0.404	0.075	0.186
	20°	base	0.49	1.15	0.088	0.85	0.91	1.072
		modified	0.505	1.19	0.099	0.88	0.95	1.075

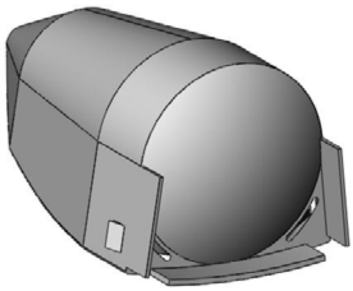

Fig.10

intake devices) shows that effect is not great in comparison with basic variant.

Conclusion

Preliminary experimental and numerical investigations of flow around reentry spacecraft Clipper are conducted. Some peculiarities of vehicle aerodynamics are examined. It was shown that numerical results obtained using FlowVision and AeroShape-3D software are in a good agreement with experimental data and allow explaining particular properties of RV aerodynamic characteristics and optimizing spacecraft shape.

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[4] A.A. Dyadkin, T.V. Simakova, S.M. Drozdov. Effect of holder elements on aerodynamic characteristics of models at testing in wind tunnels. International symposium «Fundamental problems of high velocity flows», Russia, 2004