ANALYTICAL APPROACH TO THE PROBLEM OF SLENDER BODY SEPARATION FROM A CAVITY OR SOLID SURFACE TO A FREESTREAM

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Unsteady aerodynamic and dynamic problems of slender round body separation from a cavity or solid surface to a freestream are studied analytically. Using the asymptotic theory and plausible physical assumptions aerodynamic problems are simplified and in the first order approximation are reduced to elementary unit tasks, which have analytical solutions. On the base of these results, the fast and effective method is developed to calculate the separating body trajectories in subsonic, transonic and supersonic flows including critical regimes of ricochet from shear layer or return to carrier body.

In the case of separation from a cavity, the body motion is divided to three phases: A – the body is inside the cavity, B – the body crosses the shear layer separating the cavity flow from external stream; C – the body moves inside the external stream. In the case of external separation the third phase is only. The following assumptions are used to simplify the problem:

$$\delta,\ \frac{l_0}{l'} << 1,\ \frac{\delta l_0}{\delta' l'} << 1,\ \frac{V_0^*}{\delta u_\infty} \le O(1),\ \ \alpha = \frac{\alpha^*}{\delta} = O(1),\ \ \delta^2\,\mathrm{Re} >> 1,\ \ \mathrm{Re} = \frac{\rho_\infty u_\infty l_0}{\mu_\infty},$$

$$\frac{\delta_s^*}{\delta l_0} << 1,\quad H_0 = \frac{H_0^*}{\delta l_0} >> 1,\quad d_0 = \frac{D_0^*}{\delta l_0} >> 1,\quad L_0 = \frac{L_0^*}{l_0} \ge O(1).$$

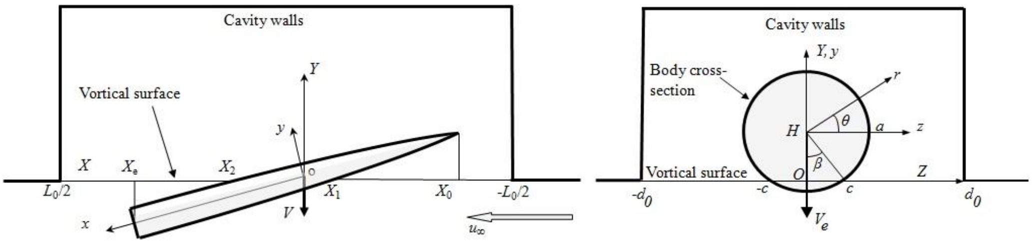

Fig. 1. Flow scheme for the phase B, coordinate systems and notations.

Here l_0 and l' are body and carrier length; δl_0 and $\delta' l'$ are their thickness; H_0^*, D_0^* and L_0^* are cavity height, wideness and length; δ_s^* is shear layer thickness; V_0^* is vertical body velocity scale, α^* is angle of attack; the index "∞" corresponds to freestream conditions. Due to these assumptions, in the first order approximation, the carrier surface is considered as a plate , the slender body theory can be applied, the viscous effects are took to the boundary layer, the shear layer is approximated by free vortical surface, and the cavity side wall influence is negligible.

In the inviscid region, the flow is described by slender body theory. The flow is divided to two asymptotic regions – the inner region with dimension of the order of δl_0, and the outer region, the dimension of which is defined by the body length and unsteady effects. In the inner asymptotic region the aerodynamic problems are reduced to the 2D Laplace equation in cross-section planes; to obtain analytical results vortical surface perturbations are disregarded. Solutions are obtained by the multipole expansion method for phases A and C, and using the conformal mapping for the phase B. The flow scheme and notations for the phase B are shown in Fig. 1. These results allow us to derive analytical expressions for the lift force, pitching moment and pressure drag for all phases of motion.

In the outer region, the axisymmetric flow around equivalent body of revolution is described by Laplace, Karman-Guderley or wave equations for subsonic, transonic or supersonic flows. Analysis of higher order approximations is conducted; the shape of equivalent body and the dependence of wave drag from problem parameters are obtained in analytical form for phases B and C. The classification of different unsteady regimes in the far flow-field is done.

On the base of small perturbation theory, effects of induced by the carrier distributed flow inhomogeneity and the body interaction with incident weak shock wave on the body motion are analyzed. Approximated analytical expressions for contributions of these effects to forces and moments are derived. Empirical correlations are used to calculate the base and friction drags

The obtained results allow us to develop a fast and effective numerical method to calculate body trajectory parameters. Analytical solutions of simplified equations of motion are obtained, and similarity parameters are found. Dynamics of ogive-cylinder body separation from rigid surface and from cavity to subsonic, transonic and supersonic freestreams are investigated. Effects of body mass and dimension, freestream and initial conditions, the distributed flow inhomogeneity and shock wave on the body motion are studied.

Examples of calculations are presented in Figs. 2 and 3. The center of mass (CM) trajectories for bodies of different diameters in Fig. 2 demonstrate a possibility of body ricochet at separation from the cavity to transonic stream. In Fig 3, the bifurcation of the angle of attack time history at separation from cavity to subsonic flow is shown.

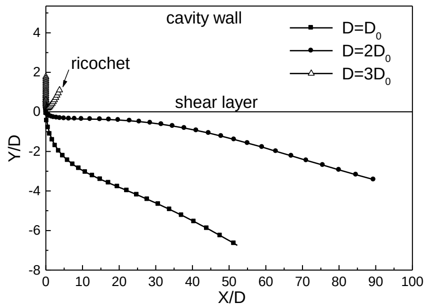

Fig. 2. CM Trajectories, $M_\infty = 0.999$.

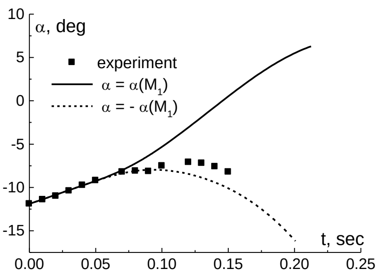

Fig. 3. Angle of attack evolution $M_\infty \approx 0.2$

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