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Air Dissociation Effects on Aerodynamic Characteristics of an Aerospace Plane

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Introduction

IN the second half of the 1970s, when a decision was made to realize an automatic landing of "Buran" in the first flight, it became necessary to return to the problem of the reliability and accuracy of the determination of nominal values of aerodynamic characteristics and the possible range of their deviation from nominal values under atmospheric descent conditions. Among other problems, it was necessary to assess the air dissociations effect on aerodynamic aircraft characteristics. In 1977, this author's paper obtained some estimates of possible deviations of the characteristics at hypersonic flight speeds from wind-tunnel results; in particular, the pitching moment (M_Z). A rough schematic of the lower aircraft surface shape and a method similar to the shock-expansion method were used to obtain these estimates.

The estimates have shown that the pitching moment deviation for the aircraft in an equilibrium dissociated airflow from its value for a gas with a constant specific-heat ratio $\gamma = 1.4$ that corresponds approximately to the wind-tunnel flow may be great, $\Delta M_Z \approx 0.01$. Therefore, an extensive investigation program was started in TsAGI that included computer calculations of simplified configuration characteristics and wind-tunnel tests using gases with different values of γ.

A special program package was developed to calculate the flow about an aircraft with a real nonsimplified configuration. The first estimate of the results was undertaken using the flight test data obtained by the Scientific-Production Association "Molniya" and the Flight-Test Institute in cooperation with TsAGI for a large-scale model of "Buran" (scale 1:8).[1] Furthermore, the paper presents the obtained results; physical causes of the detected effect are discussed; and flight test results for a large-scale (1:8) flying model and the first flight tests of "Buran" are compared.

Calculation and Laboratory Test Results

After the author obtained rough estimates of possible deviations of aerodynamic characteristics from their values in hypersonic wind tunnels, the first study stage included the calculation of a flow about a schematized aircraft configuration. A parallel program of wind-tunnel tests with gases having $\gamma \neq 1.4$ was started. (These data were used to confirm the effect existence and to evaluate the calculation techniques presented below.) Because the estimates have shown that the main contribution to the deviation of aircraft characteristics from their wind-tunnel values is caused by the effects on its lower surface flow, and the influence of nonequilibrium effects and the friction force variation due to dissociation is small, the full nonlinear Euler equations are used for an equilibrium dissociated flow.

Computational investigations of a schematic configuration were carried out by means of a marching method using the well-known numerical Godunov-Kraiko method generalized by A. G. Zarubin to the case of an equilibrium dissociated gasflow. The calculation results presented in the paper for a schematic configuration were obtained mainly in the period of 1978–1980 in the investigations of A. G. Zarubin, carried out together with the author of this paper. To obtain results quickly that allow an investigation of physical causes of an aerodynamic characteristic variation in case of air dissociation, and that are characterized by satisfactory correction calculation accuracy, the aircraft configuration was schematized in such a way that subsonic flow zones would be avoided. It is necessary to apply a fast marching calculation method. Furthermore, in order to obtain a databank, more accurate and tedious methods (see below) were used.

In a comparison of flowfields obtained for dissociating air and a thermodynamically perfect gas with $\gamma = 1.4$, it is seen first that the shock-layer thickness usually decreases significantly. Figure 1 presents the calculated values of γ for dissociating air along the lower body symmetry plane. It is seen that at $M = 23$ ($H = 70$ km, $V = 6.8$ km/s) and at angles of attack $\alpha \gtrsim 20$ deg, the value of $(\gamma - 1)/(\gamma + 1)$, which is known to be reverse to the gas compression in a strong shock wave, decreases considerably as compared to its value at $\gamma = 1.4$ and (which is useful for qualitative investigations) it is almost constant on the attachment line at the aircraft bottom at all values of $\bar{X}$ from 0.1 to 1 ($\bar{X} = X/L$, where L is the aircraft length). Useful information for further analysis is contained in Figs. 2–4. Here, the ordinate axes present aerodynamic drag, lift, and moment coefficients C_D, C_L, and M_Z of the aircraft portion that lies between its nose and a section that corresponds to the value of $\bar{X}$ on the abscissa axis (of course, the value of $\bar{X} = 1$ corresponds to the whole aircraft).

First, it can be seen that the discrepancy in the results is attributed mainly to a flow about the aircraft afterbody. A

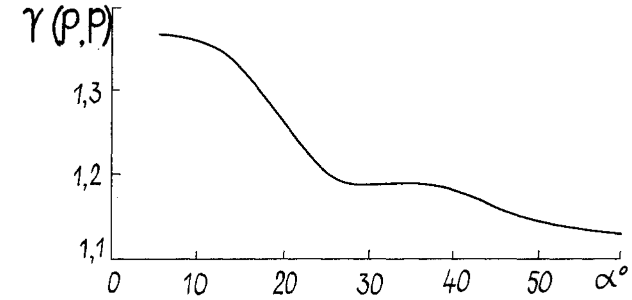

Fig. 1 Value of γ near the lower aircraft surface.

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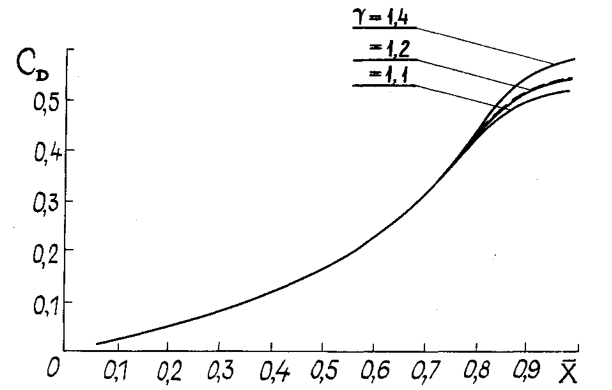

Fig. 2 Aerodynamic drag coefficient (– – –, equilibrium dissociated air).

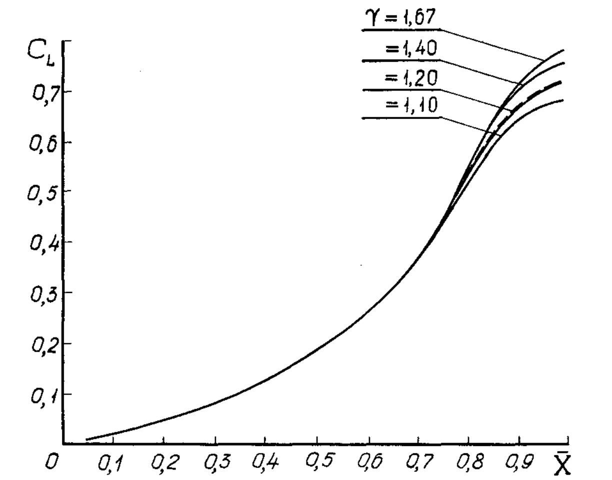

Fig. 3 Aerodynamic lift coefficient (– – –, equilibrium dissociated air).

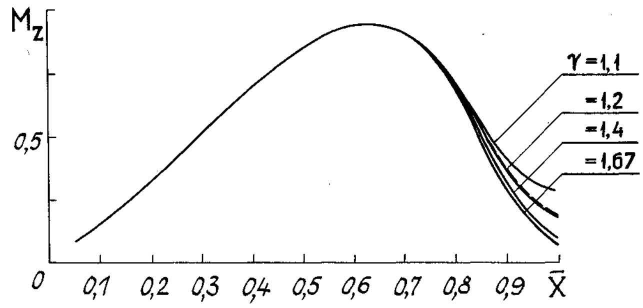

Fig. 4 Pitching moment coefficient (– – –, equilibrium dissociated air).

more detailed pressure distribution analysis has shown that the result is associated, to a considerable extent, with expansion waves on the wing and in the region of a rarefied deflected flow on the fuselage afterbody. It can be understood, if one recalls that the pressure in expansion waves drops (e.g., in the Newton-Buseman shock layer) when the flow turns through one and the same angle the more, the value of $\gamma - 1$ is less. At a trajectory point under consideration at the aircraft bottom, the value of γ is close to 1.2 (Fig. 1) and, therefore, the aerodynamic characteristics for dissociated air are also close to the results obtained at $\gamma = 1.2$. It is clear that an excessive rarefaction at the aircraft bottom downstream of the mass center $\bar{X} = 0.65$, with respect to which the longitudinal moment coefficient M_Z is calculated, results in the fact that $\Delta M_Z > 0$. It is also clear that the relative variations of the aerodynamic force coefficients $\Delta C_D/C_D$ and $\Delta C_L/C_L$ are less considerable because C_D and C_L are not small. At angles of attack that are close to the aircraft selfbalancing regime $\Delta M_Z \approx 0$, the variation of ΔM_Z is rather appreciable. The body flap deflection required to compensate this effect may result in a noticeable increase of the heat flux toward it.

It is clear that, as the angle of attack α increases, which results in a static gas temperature rise near the lower aircraft surface and in a decrease of $\gamma - 1$ in this regime, the dissociation effect on the pitching moment variations increases. These respective results are presented in Fig. 5. (The dependence of the correction on the flight altitude and the Mach number is attributed to the same variation of $\gamma - 1$.) In general, in orer to obtain approximate estimates of the effect (but not for a databank generation requiring a greater accuracy) for configurations of the type of "Buran" or "Columbia," it is quite admissible to apply the correlation using an effective value of γ that can be introduced in the following form:

$$h(\rho, p) = \frac{\gamma(\rho, p)}{\gamma(\rho, p) - 1} \cdot \frac{\rho}{p}$$

where p, ρ, h are the air pressure, density, and enthalpy.

In the same years (1978–1980), two TsAGI experimentor groups investigated the effect in wind tunnels using both air or nitrogen and other gases with the values of $\gamma \neq 1.4$. A. S. Korolyov, together with his colleagues, carried out some investigations in an updated impulse wind tunnel using nitrogen, carbon dioxide (CO_2), and argon. A model having the shape of one of the "Buran" modifications was used in the test. Fig. 6 shows typical results of this investigation. It can be seen that the predicted effect is confirmed well by the test results.

The results of another experimentor group (P. I. Gorenbukh et al., 1980), who performed their tests in a special

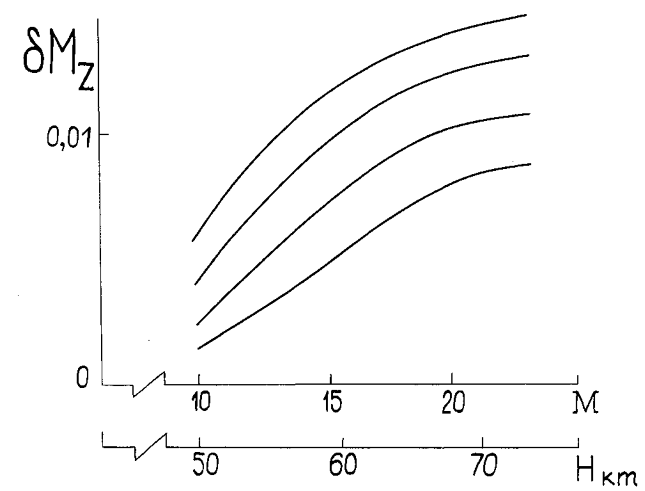

Fig. 5 Pitching moment correction to air dissociation influence.

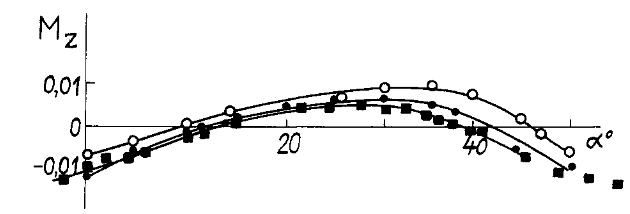

Fig. 6 Pitching moment coefficient as a function of angle of attack (●: $M = 19.6$, $Re_L = 2.8 \times 10^5$, $\gamma = 1.4$; ○: $M = 13$, $Re_L = 2 \times 10^5$, $\gamma = 1.2$; ■: $M = 9.8$, $Re_L = 3 \times 10^6$, $\gamma = 1.4$; moment reference point $\bar{X}_T = 0.65$; $\bar{Y}_T = 0.0275$).

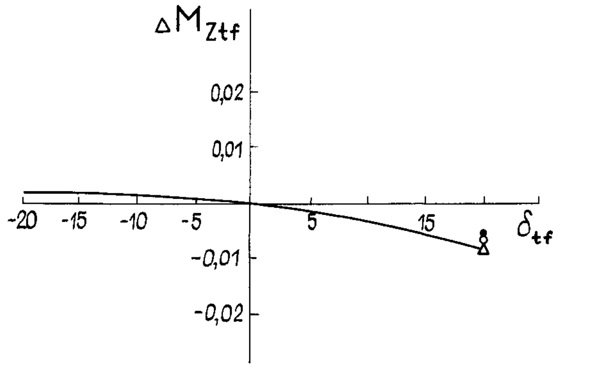

Fig. 7 **Body flap efficiency (○: $\gamma = 1.667$, $M = 17.8$, He; ●: $\gamma = 1.2$, $M = 7$, freon; Δ: $\gamma = 1.4$, $M = 7.93$, air; — calculation for equilibrium dissociated air).**

hypersonic wind tunnel GT-2M with freon -14 ($\gamma = 1.2$) and helium ($\gamma = 1.67$), also confirmed a considerable increase in the trim angle of attack when the value of $\gamma - 1$ decreases.

At the same time, another effect following from the calculations of G. Zarubin and the author of this paper; that is, a weak variation of the body flap efficiency during the variation of $\gamma - 1$ was also confirmed. Of course, this result reflects the peculiarities of the flow about the special shape of the "Buran" afterbody that has region of rarefied deflected flow. The gas upstream of the body flap passes first through an expansion wave and then through an oblique shock wave. This result is shown in Fig. 7. Without a region of a rarefied deflected flow for the aircraft with almost a flat bottom, the dissociation must result in an increase in the trim flap efficiency as compared to its value for a gas with $\gamma = 1.4$.

The corrections to aerodynamic characteristics for the "Buran" flight configuration, which were included in the databank, are contained in the papers of a group of TsAGI investigators; namely, A. P. Bazzhin, Yu. Ja. Mikhailov, and others.

The problem was solved using computational aerodynamics methods with a sufficiently accurate reproduction of the "Buran" shape, and using the full Euler equations for equilibrium dissociated air. The solution for bluntness was obtained by means of the time-dependent method. It gave initial data for marching techniques that were used for supersonic flow portions. The greatest difficulties were associated with the flow calculation in the region of the interaction of the bow shock wave with the shock wave upstream of the wing. In this region, the problem was solved again by using the time-dependent method. And again, the obtained initial data were used in the marching technique for the remaining aircraft portion.

Comparison of Preflight Data with Flight Test Results

The methods and results of ground investigations of the air dissociation effect on aerodynamic characteristics of the aerospace plane "Buran" were summarized in 1980. They were verified in flight tests of large-scale flying models. The author of this paper presented some results of these tests in Ref. 1.

Later, an approximate assessment of this effect was confirmed as a result of the Space Shuttle Orbiter flights.[2] An approximate assessment for the Columbia vehicle is published by American scientists in Ref. 3.

The final data confirmation obtained as a result of all flight tests and the "Buran" flight in November 1988 is illustrated in Fig. 8. In this plot, the results in large wind tunnels of TsAGI are presented for $M = 10$ and for an undeflected control surface configuration. The Reynolds numbers at which the tests were carried out are somewhat different (some of the results given were obtained during a long period when the test technique was improved, but the data scatter observed

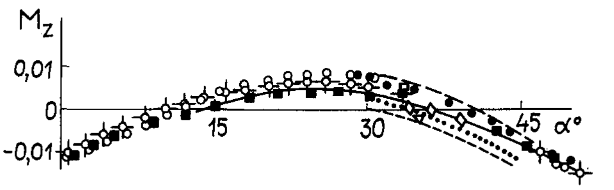

Fig. 8 Comparison of preflight data with flight test results (wind tunnel: -o-, ○, ●: $Re = 3 \div 4 \times 10^6$; ■: $Re = 0.8 \times 10^6$; flight model (1:8 scale): ∇: $Re = 10^6 \div 10^7$; Buran flight: □, -+-, ◇: $Re = 1.2 \times 10^8 \div 5.3 \times 10^6$; - - - - data book for Buran; — calculation, perfect gas).

is insignificant for our purposes). The full-scale flight test results are given after some processing. At flight angles of attack α and Reynolds number, moment values of M_Z were found from trimming conditions $M_Z = 0$ and for the case of introducing the corrections to the control surface efficiency (elevons—δ_l, body flap—δ_{tf}, and air brake—δ_{ab}), as well as to the air dissociation. It is clear that this should be done to compare the results with wind-tunnel data where $\gamma \approx 1.4$. The figure also presents computer calculation results for a perfect $\gamma = 1.4$, an ideal gas $Re = \infty$, as well as nominal values and scatter from the "Buran" preflight databank. It can be seen that the preflight test technique gives quite satisfactory results.

One remark should be made, however. It can be seen in the figure that at high angles of attack $\alpha \gtrsim 40$ deg), there appears a tendency of the wind-tunnel data to diverge from the calculated results for a perfect gas. According to the assessment of S. M. Zadonsky, the effect can be attributed to an increase of the base pressure that acts on the wind-tunnel model body flap that is associated with the support influence. Figure 8 gives estimates of these effects.

Conclusions

First, the reliability and accuracy of preflight predictions of the aerodynamic characteristics of the aerospace plane "Buran" for flight regimes that are not simulated adequately in wind tunnels led to a complex technique based on theoretical estimates, hypersonic wind-tunnel tests using both air and gases having other thermodynamic properties, on computational aerodynamics methods, and, finally, on flight tests of large-scale flying models.

Second, clear understanding of the physical nature of the observed effects makes it possible to draw conclusions concerning the applicability limits of the obtained results and the possibility of improving the aerodynamic characteristics of aerospace planes of the type considered. For example, it is clear a priori that the developed approach requires a substantial modification for the vehicles of this class with a long re-entry lateral range.

Third, in fact, this requires a considerably higher hypersonic lift/drag ratio, which is associated inevitably with flight at lower angles of attack. In this case, it seems necessary to provide a more correct accounting of the flow at the leeward vehicle side where viscosity forces and nonequilibrium thermodynamic processes can have a noticeable effect.

References

[1]Lozino-Lozinsky, G. Ye., and Neyland, V. Ya., "The Convergence of the 'Buran' Orbiter Flight Test and Preflight Study Results and the Choice of a Strategy to Develop a Second-Generation Orbiter," AIAA Paper 89-5019, July 1989.

[2]Young, J. C., Perez, L. F., Romere, P. O., and Kanipe, D. B., "Space Shuttle Entry Aerodynamic Comparisons of Flight 1 with Preflight Predictions," AIAA Paper 81-2476, Nov. 1981.

[3]Maus, J. R., Griffith, B. J., and Szema, K. Y., "Hypersonic Mach Number and Real Gas Effects on Space Shuttle Orbiter Aerodynamics," AIAA Paper 83-0343, Jan. 1983.