CONDITIONS OF SUPERSONIC FLOW AROUND MULTIWEDGE BODIES

V. V. Kravets and A. I Shvets

UDC 533.6.011.5

An experimental study was made of some schemes for flow around multiwedge bodies at supersonic flow velocities. On the basis of data on the distribution of the pressure, on visualization of the flow, and on optical measurements, an analysis was made of the structure of the flow. Zones of breakaway of the flow were observed at the lateral surfaces of the lobes. In the nose part of a multiwedge body there is a three-dimensional configuration of attached plane shock waves, going over into a combined detached nonaxisymmetric wave directed toward the base of the body.

After the first articles [1-3] with the solution of the problem of the decrease in the resistance and the increase in the lifting force, there appeared a number of publications [4-17], devoted to the investigation of flow around three-dimensional conical and nonconical bodies with attached shock waves, developing this tendency. These investigations showed that flow around an element of a pyramidal body with plane surfaces, with a special choice of the geometry and of the Mach number, will take place with a plane shock wave located at the leading edges. The possibility of the realization of a flow with reflected shock waves, normal to the faces of the pyramidal body due to the choice of the form of the leading edge, was pointed out in [5].

In accordance with exact solutions obtained for flow schemes with regular [4] and Mach [6] interactions of the shock waves, pyramidal bodies of star-shaped cross section were constructed. Experimental confirmation of the proposed interactions of the shock waves and an analysis of possible flow schemes are given in [11-13] for models of the elements of a star-shaped body and of V-shaped airfoils, from which pyramidal bodies can be built up.

The flow schemes considered in [1-6] were calculated for a weak plane shock wave. The flow in a two-faced angle with a plane shock wave, corresponding to a strong shock wave at a wedge in a plane perpendicular to the leading edges, has been obtained theoretically [9] and experimentally [10]. The realization of flow in an angle with four plane shock waves intersecting along a single straight line has also been demonstrated; here shock waves reflected from this line in a direction perpendicular to it correspond to a strong shock wave reflected from a wall.

In [1-13] a study was made of flow around bodies of star-shaped cross section, having the property of homothety. For practical use of a pyramidal body as the nose part of a flying apparatus, its form must be changed in such a way that it can be connected to a fuselage in the form of a body of revolution, retaining the effect of the splitting of the shock wave into a system of interacting shock waves. In this case, bodies are obtained, the form of whose transverse cross sections are not similar, while the base is close to circular. The windward surface of a multiwedge body with swept-back leading edges of the lobes χ is made up of elements of the planes

$$xx_0 - yy_0 \pm zz_0 = 0$$

$$x_0 = \cos\frac{2m\pi}{n} - \operatorname{tg}\delta\operatorname{tg}\chi\cos\frac{(2m\mp 1)\pi}{n},\quad y_0 = \sin\frac{2m\pi}{n} - \operatorname{tg}\delta\operatorname{tg}\chi\sin\frac{(2m\mp 1)\pi}{n},\quad z_0 = \operatorname{tg}\delta\sin\frac{\pi}{n}$$

Here δ is the angle formed by the line of intersection of the planes of adjacent lobes and the axis of the body; n is the number of lobes. The upper and lower signs in front of the terms of an equation relate,

Moscow. Dnepropetrovsk. Translated from Zhurnal Prikladnoi Mekhaniki i Technicheskoi Fiziki, No. 3, pp. 59-66, May-June, 1974. Original article submitted October 12, 1973.

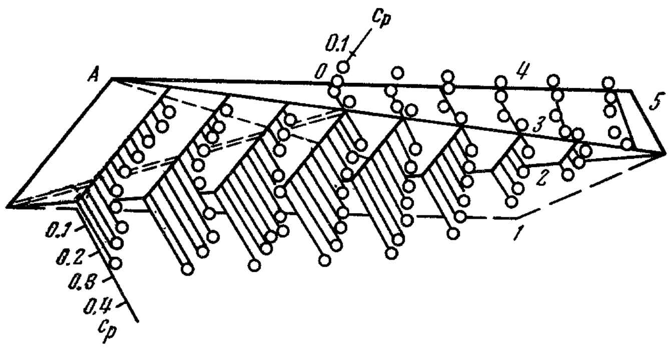

Fig. 1

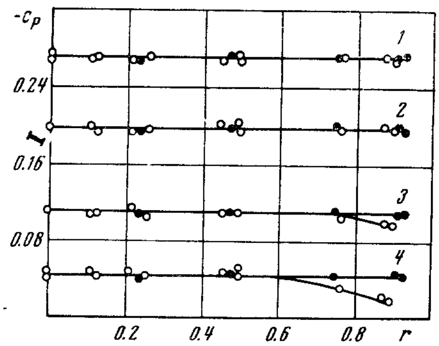

Fig. 2

respectively, to the right- and left-hand surfaces of a lobe (along the direction of the flow) with respect to the plane of its symmetry. The surface of a lobe in the length L tan δ tan χ − L (L is the length of the model), in addition to the windward part, is formed by the lateral wall

$$x \sin (4m \mp 1) \frac{\pi}{2n} + y \cos (4m \mp 1) \frac{\pi}{2n} - L \operatorname{tg} \delta \cos \frac{\pi}{2n} = 0,$$
$$m = 0, 1, 2, \ldots, (n-1)$$

In accordance with the construction of a multiwedge body, its axis and the planes of the lateral walls of the lobes are parallel.

To solve the problem of flow around conical nonaxisymmetric bodies, successful use has been made of a number of methods, for example, exact solutions [3, 4], hypersonic approximations [19], and numerical solutions [7]. For multiwedge bodies, as a result of the complex structure of the flow with a transition from a system of interacting shock waves to a single detached wave, and with the presence of a breakaway zone, up to the present time there are no theoretical solutions.

Tests were made of models of multiwedge bodies with the parameters n = 3, 4, 6, 8; χ = 0, 20, 40, 60, and 77°30'; δ = 12°30' (20 models). The leading edges of the lobes were made sharp to achieve flow with an attached shock wave. The length of the models L = 180 mm. Drainage openings with a diameter of 0.7 mm were arranged in cross sections perpendicular to the axis of the multiwedge body. To monitor the position of the models with respect to the angle of bank, several symmetrical openings were made in the surfaces of adjacent lobes. The experiments were made in an aerodynamic tube at Mach numbers of 2.5, 4, 6, and 7.8 and Reynolds numbers of $4.2 \cdot 10^{-6}$–$2 \cdot 10^{6}$, respectively (the Re number is referred to the length of the model). The value of the pressure at the drainage points was recorded with a GRM-2 instrument. The mean-square error in measurement of the coefficient of the pressure C_p, taking account of the inaccuracy in determination of the Mach number, did not exceed 3%.

During the course of the experimental investigations, the main stress was laid on study of the flow in the rear part. The drainage of the models in the length 0–L tan δ tan χ was more widely spaced in view of the fact that the flow around the leading part is analogous to that around pyramidal bodies [11-13]. The results of the investigations were brought down to three-dimensional representations of the distribution of the coefficient of the pressure over the windward and lateral surfaces of the body. Qualitatively, the results of tests for a number of models are similar to the data for a multiwedge body (Fig. 1, n = 6, χ = 0, M = 4, shows half of a lobe: 1 is the axis of the body; 2 is the line of intersection of the planes of the windward sides; 3 is the line of intersection of the planes of the windward and lateral sides; 4 is the line of intersection of the planes of the lateral side; 5 is a side of the polygon at the base of the body). In the region bounded by the leading edge of a lobe, the line of intersection of the surfaces of the windward sides, and Mach lines (dotted lines), constructed from the flow parameters behind the first and the reflected shock waves, the representation of the distribution of the coefficient of the pressure consists of two zones of constant pressures with a stepwise transition from one to the other, along the wake of the reflected shock wave (double dotted line).

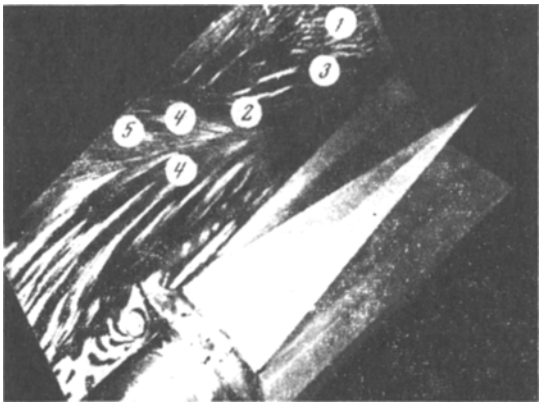

Fig. 3

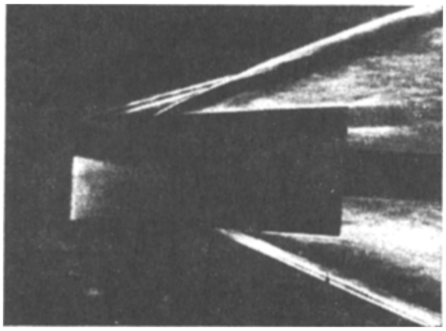

Fig. 4

The results of tests of multiwedge bodies in the length 0-L tan δ tan χ are in agreement with the data from investigations of star-shaped bodies with a bend of the lateral surface, pyramidal bodies, and a right two-sided angle [11, 13, 16]. A flow scheme with regular interaction between the waves is realized in a definite range of Mach numbers. The distribution of the pressure at the windward side of lobes depends mainly on the position of the system of the first intersecting shock waves; in the region ahead of the shock wave falling on the face of the lobes there is an increase in the pressure, determined by the interaction between the shock wave and the boundary layer [10]. The shock wave falling on the windward side (a face of the two-sided angle) induces ahead of itself a region of local breakaway of the boundary layer.

Behind the reflected shock waves, the flow is directed parallel to the line of intersection of the windward sides of adjacent sides. According to the representation of the pressure distribution, there is flow-over from the windward to the lateral side of a lobe. Here there is breakaway of the flow with the formation of pairwise cortical plaits, rotating in opposing directions and having a point of tangency in the plane of symmetry of the lobe. The viscous interaction of the main flow preceding the system of shock waves, with breakaway flow, promotes an increase in the pressure near the edge of the lateral side of the lobe. In this zone, the viscous forces are found to be sufficient to shift the breakaway line to the lateral surface, which is confirmed by the distribution of the visualizing covering on the model.

The coefficient of the pressure on the lateral side changes from a positive value, determined by the flow-over from the windward to the lateral side, to negative in the breakaway zone and, near the plane of symmetry of the lobe again takes on a positive value (Fig. 1). The latter fact is connected with the effect of the velocity head of the flow, turned toward the lateral side; here, in distinction from breakaway flows, forming with flow around an offset or a bottom cut, in this case, the pressure near the plane of symmetry of the lobe exceeds the static pressure in the oncoming flow. As a result of the flow from the breakaway zone toward the line of separation of the breakaway flow, the stream filaments come not from the boundary layer, as in a two-dimensional flow, but from an ideal flow having a large stagnation pressure [18]; in a deflected vortical plait, the velocity rises, and its component along a normal to the lateral side corresponds to $M > 1$. In a supersonic jet directed toward the central part of the lateral side, there is formed a shock wave, which can be noted on photographs of the flow. Behind the reflected shock wave, the pressure near the line of intersection of the windward and lateral sides of the lobe falls monotonically downstream.

A decrease in the Mach number from 4 to 3 leads to a qualitative change in the picture of the flow; the breakaway zones at the lateral surfaces are propagated to the whole rear part, which corresponds to a negative value of C_p at both the lateral and windward sides.

The pressure at the bottom cut remains approximately identical, with a certain lowering for points at the periphery, lying in the plane of χ (Fig. 2, $\chi = 0$, $n = 6$, $\delta = 12°30'$, $r = r_1/R$: r_1 is the distance from the axis to a drainage point in the bottom cross section; R is the distance from the axis to the edge in this cross

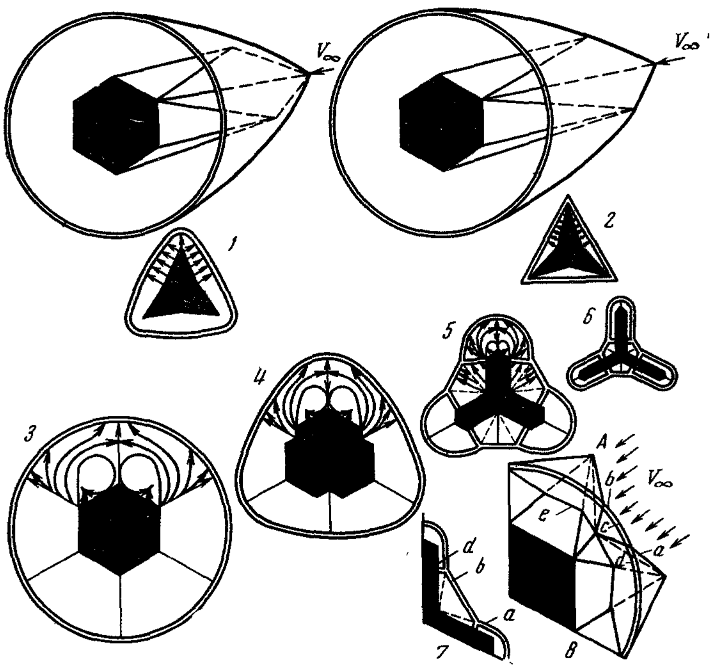

Fig. 5

section; the open points relate to the plane χ, and the solid points to the plane δ; the M numbers 1.5, 2, 3, and 4 correspond to curves 1-4). Analogous results were obtained in all the models investigated. An increase in the arrow-shaped character of the leading edge means a restructuring of the multiwedge body to a regular pyramid $\delta = \pi/2 - \chi$, for which the values of the bottom pressure in the planes of the angles δ and χ coincide.

During the experiments on the study of the structure of the flow around multiwedge bodies, visualization lines were generated at the windward and lateral sides of the model and in the plane of symmetry of a lobe. The identity of the flows on both sides of the plane of symmetry of a lobe, with zero angles of attack and slip, permitted using a thin plate with a sharp leading edge, installed parallel to the oncoming flow (Fig. 3, $\chi = 0$, $n = 6$, $M = 4$). In the section near the leading edge of the plate the flow lines are parallel straight lines. Here there is homogeneous flow 1 with the parameters of the oncoming flow. Downstream from the wake of the reflected shock wave at the plate 2, the direction of the flow lines approaches the axis of symmetry.

Behind the lines of intersection of the windward and lateral sides, there is breakaway of the flow, passing through the shock wave attached to the leading edge, and flow-over of the gas into region 3; analogously, into region 4 there enters a flow breaking away behind the reflected shock wave. The flow in region 4 is divided into two parts by the flow line 5; in one of them the gas, together with the viscous stream, is carried downstream; in the other part, the flow is turned toward the body [16, 18]. In sections 3 and 4 there is flow-over of the visualizing covering to the lateral side of the lobe. In the rear part, with an increase in the distance from the surface of the body, there is a decrease in the effect of ejection of the breakaway flow, and the limiting flow lines become less curved.

An optical method was used to study the system of shock waves with flow around multiwedge bodies. The flow around the nose part of a multiwedge body with a length L tan δ tan χ is analogous to flow around the elements of a star-shaped body [13]. Chernyi [19] demonstrated the possibility of achieving flows with attached shock waves along the leading edges, with an attached shock wave at the tip of the body, detached from the leading edges, and with a shock wave detached from the tip of the body and the leading edges of the lobes. The latter case corresponds to flow around a multiwedge body with large aperture angles of the windward sides of the lobes. The flow schemes established for the elements of star-shaped bodies are realized also for models with an arrow-shaped character of the leading edges of the lobes $\chi > 0$, with corresponding values of the geometric parameters and the Mach numbers. For example, for a model with $n = 6$ and an arrow-shaped character $\chi = 60°$ with $M = 2$, the results obtained confirm the possibility of a scheme with a conical shock wave, attached to the tip of the body. A shock wave detached in the vicinity of the tip of a multiwedge body, and attached along some length of the leading edges of the lobes, is obtained with $\chi = 0$, $M = 1.5$.

A flow with a nearly plane shock wave, lying at the leading edges of the lobes is achieved with $\chi = 40$, $M = 2$, and $\chi = 60°$, $M = 3$. The intersection in space of two shock waves, attached to the leading edges of the lobes, is achieved, for example, for models with $\chi = 0$, 40°, $n = 6$, $M = 3$ and $\chi = 0$, $n = 3, 4, 8$, $M = 4$ (Fig. 4, $\chi = 0$, $n = 3$, $M = 4$). In a length approximately equal to 0–L $\tan\delta \tan\chi$, the lines of the shock waves are straight lines, which bears witness to the conical character of the flow between the lobes. The same result was obtained also in investigations made on drained models. In cross sections located in the rear part of the model, there is a gradual restructuring of the intersecting shock waves, and their degeneration in a transverse cross section into a detached shock wave. In the plane of the base of a multiwedge body, the form of the shock wave is obtained with rotation of the model around its longitudinal axis, and recording of the shock waves in each fixed case.

Schemes of the flow around a multiwedge body with a shock wave attached to the tip of the body and along the leading edges of the lobes are shown on Fig. 5 (1 and 2, respectively). The figure gives also transverse cross sections of multiwedge bodies in a range of lengths 0–L $\tan\delta \tan\chi$ with the configuration of the shock wave shown by the double line. The lines with arrows indicate the direction of the trajectories of particles in projection on the plane of the transverse cross section. The four following cross sections (3–6) illustrate the restructuring of a flow with a Mach intersection of the shock waves and the formation of a detached shock wave in the rear part of the body. In one of the cross sections, a system of shock waves 7 is realized, analogous to flow around a two-sided angle [14-16]. In addition to the configurations of the shock waves, the figure also shows the three-dimensional scheme of the flow around a multiwedge body ($n = 3$) with interacting shock waves 8.

Under the conditions of supersonic flow with a shock wave attached to the tip of a multiwedge body 1, the flow has the property of conical flows in the length 0–L $\tan\delta \tan\chi$. Further downstream there is flow-over of the flow lines from the windward side to the lateral side, and the establishment of a vortical character of the flow, identical to 3 and 4. With a definite geometry of the nose part of a multiwedge body 2, the value of the deviation of the flow lines in a plane shock wave is described by the two-dimensional theory of an oblique shock wave. In this case, the flow also has the property of conical flows, and the projections of the flow lines in a transverse cross section are parallel. In the rear part of the body, at a distance from the tip greater than L $\tan\delta \tan\chi$, there is breakaway flow at the lateral side.

The representation of flow around multiwedge bodies, taking account of the scheme of the interaction of the shock waves *a* and d (8) along the line c, with the Mach configuration b, can be supplemented by a consideration of the motion of an elementary volume of the gas through the above-mentioned sections. The first rotation of the flow takes place at the shock wave *a*, attached to the leading edge of a lobe. In a region bounded by the plane of the lobe and by the attached, *a*, and reflected, d, shock waves, the flow deviates by an angle determined by the value of the velocity ahead of the shock wave *a*, and by its position. Under these circumstances, the angle of deviation of the flow lines is reckoned in a plane perpendicular to the shock wave, *a*, and drawn through the direction of the velocity of the unperturbed flow. Behind an attached shock wave, the flow line is deflected toward the line of intersection of the windward and lateral sides of the lobe. Further, beyond this line there is breakaway of the flow. The remaining flow, passing through the surface of the reflected shock wave, has a new direction, which is determined analogously to the preceding, but from the position of the reflected wave and the vector of the velocity behind the attached shock wave. In the bottom region of a multiwedge body, there is a flow consisting of pairs of vortices, whose number is equal to the number of lobes.

LITERATURE CITED

1. G. I. Maikapar, "The wave resistance of nonaxisymmetric bodies in a supersonic flow," Prikl. Matem. Mekhan., 23, No. 2 (1959).
2. T. R. F. Nonweiler, "Aerodynamic problems of manned space vehicles," J. Roy. Aeronaut. Soc., 63, No. 585 (1959).
3. V. V. Keldysh, "Exact solutions for supporting bodies with one and two plane shock waves," Inzh. Zh., 1, No. 3 (1961).
4. A. L. Gonor, "Exact solution of the problem of the flow of a supersonic stream of gas around some three-dimensional bodies," Prikl. Matem. Mekhan., 28, No. 5 (1964).
5. V. V. Kelydsh, "The intersection in space of two plane shock waves," Prikl. Matem. Mekhan., 30, No. 1 (1966).

6. A. L. Gonor, "Three-dimensional flows with Mach interaction of shock waves," Izv. Akad. Nauk SSSR, Mekhan. Zhidk. Gaza, No. 6 (1966).
7. V. I. Lapygin, "Calculation of supersonic flow around V-shaped airfoils by the method of determination," Izv. Akad. Nauk SSSR, Mekhan. Zhidk. Gaza, No. 3 (1971).
8. N. F. Vorob'ev and V. P. Fedosov, "Flow of a supersonic stream around a two-sided angle (conical case)," Izv. Akad. Nauk SSSR, Mekhan. Zhidk. Gaza, No. 5 (1972).
9. V. V. Keldysh, "Investigation of flow in the vicinity of V-shaped airfoils formed by flow surfaces behind plane shock waves," Izv. Akad. Nauk SSSR, Mekhan. Zhidk. Gaza, No. 4 (1967).
10. Yu. I. Zaitsev and V. V. Keldysh, "Special cases of flow near a supersonic edge and the lines of intersection of shock waves," Uch. Zap. TsAGI 1, No. 1 (1970).
11. A. L. Gonor and A. I. Shvets, "Investigation of the pressure distribution at some star-shaped bodies with $M \approx 4$," Zh. Prikl. Mekhan. Tekh. Fiz., No. 6 (1965).
12. A. L. Gonor and A. I. Shvets, "Investigation of the system of shock waves with flow around star-shaped bodies," Izv. Akad. Nauk SSSR, Mekhan. Zhidk. Gaza, No. 3 (1966).
13. A. L. Gonor and A. I. Shvets., "Flow of a supersonic stream around V-shaped airfoils with $M = 3.9$," Izv. Akad. Nauk SSSR, Mekhan. Zhidk. Gaza, No. 6 (1967).
14. A. F. Charwat and L. G. Redekeopp, "Supersonic interference flow along the corner of intersecting wedges," AIAA J., 5, No. 6 (1967).
15. R. H. Korkegi, "Limit case for supersonic inviscid flow in the corner of intersecting wedges," AIAA J., 7, No. 3 (1969).
16. V. S. Dem'yanenko and E. K. Derunov, "Flow of a supersonic stream around a right two-sided angle," Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 2 (1971).
17. V. N. Mikhailov and V. S. Tamilov, "Supersonic flow in an angle formed by intersecting plates," Izv. Akad. Nauk SSSR, Mekhan. Zhidk. Gaza, No. 2 (1972).
18. V. S. Avduevskii and K. I. Medvedev, "Investigation of the breakaway of a laminar boundary layer at a cone under an angle of attack," Izv. Akad. Nauk SSSR, Mekhan. Zhidk. Gaza, No. 3 (1966).
19. G. G. Chernyi, "Investigation of bodies with very small resistance with large supersonic velocities," Prikl. Matem.Mekhan., 28, No. 2 (1964).