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AERODYNAMIC CHARACTERISTICS OF WAVE WINGS

A. I. Shvets

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Optimal lifting forms are given much attention. We continue a study of traditional wings and of various new arrangements based on the conception of the wave wing — a Λ-wing with a planar shock wave on the leading edges. In analyses done on the basis of exact solutions, pyramidal nose ends with minimal resistance [1, 2] and a Λ-wing of minimal aerodynamic efficiency [3] were constructed. Calculations based on Newtonian theory [4] and experiments [5, 6] have established that the resistance of a star-shaped object at supersonic velocities is almost two times less than that for an equivalent cone, while the aerodynamic efficiency of Λ-wings exceeds the efficiency of an equivalent trangular wing by 10-15% [5, 7]. In our last study, we analyzed subsonic flow around of Λ-wings [8], the aerodynamic characteristics of a Λ-wing with a conical break on its surface [9] and with a break on the leading edge [10]. We will now give experimental results and a comparison of the aerodynamic efficiency of several types of wave wings: Λ-wings, triangular wings with a conical break, pryamidal objects with wings, and lined Λ-wings.

1. Λ-Wings. Models in the form of a combination of a thin central cone (with a half-angle of 7°) with two rigidly attached triangular wings have been tested (the angle of sweep in the plane of the wing is $\chi = 60°$). The obtained results indicate that a decrease in the included angle of the Λ-wing changes the buoyancy coefficient insignificantly, while the coefficient of head resistance is reduced. For a decrease in the angle Λ from 180 to 150°, the aerodynamic efficiency increases by 15-20% in comparison with the efficiency of a planar triangular wing. An increase in the efficiency of a Λ-shaped wing with a decrease in the included angle occurs not because of the increase in the buoyancy of the wing but due to the decrease in its resistance, i.e., an effect arises that greatly reduces the resistance of a body with a star-shaped cross section [6].

2. Conical Break of Triangular Wings. The effect of varying the cross section of a Λ-wing is schematically indicated in Fig. 1, where *a* is the original Λ-wing in the design mode with a planar shock wave; b and c denote the possible structures of the discontinuities for displacement of the internal fin from the leading edges and for formation of a convex angle in the plane of compression — there is a tendency for displacement of the shock wave inside the wing. For displacement of the internal fin to the leading edges — the formation of the concave angle — one approximates a fuselage positioned between the main planes of the wing with a system of shock waves displaced outwardly (Fig. 1d, e).

For a measurement of aerodynamic characteristics of wings with a break, four models have been tested simulating combinations of a thin central cone ($\theta = 7°$) and two rigidly attached

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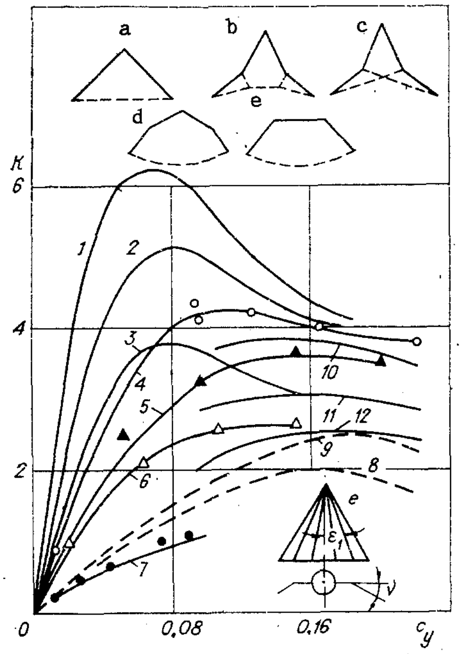

Fig. 1

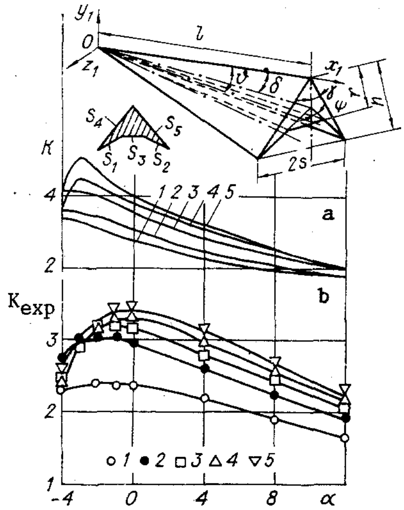

Fig. 2

triangular wings with a central chord c = 0.094 m (Fig. 1). The leading edges of the wings from the leeward side have a wedge-shaped slant at 15° for obtaining discontinuities connected to sharp edges. Each wing has a conical break, and the angle between the line of the break and axis of the model ε_1 was 15°. In the plane that is normal to the leading edge of the wing, the break angles of the wings are ν = 0, 20, 30, and 79° (models 1-4, respectively). The planar triangular wing with ν = 0 has an angle of sweep χ = 61°, while all of the other wings are formed from the first change in the angle ν. A study was made for the following incident flow parameters: M = 5.96, $Re_c = 2.3\cdot 10^6$, α = −1−+15°. The rms error is

$$|\sigma_{c_n}| = 3-5\%, \quad |\sigma_{c_\tau}| = 4-6\%, \quad |\sigma_{c_p}| = 0.7-0.8\%,$$

where c_n, c_τ, and c_p are coefficients for the normal and tangential forces and the pressure center.

When calculating the aerodynamic coefficients, the characteristic area is taken to be the area for the wing with ν = 0. Depending on the form of the model of the wing with the break, the aerodynamic resistance coefficient has a minimum value for the range of attack angles of α = 3-8°. The dependence $c_y = f(\alpha)$ in this range of attack angles is close to linear. When $\alpha \geq 10°$, an increase in ν leads to a reduction in c_y. The maximum aerodynamic efficiency for a planar triangular wing is achieved when $\alpha \simeq$ 8-9°, where an increase in ν shifts the value of K_{max} toward larger attack angles.

Results are given in Fig. 1 for experimental data on Λ-wings with an included angle Λ (1-3 corresponds to Λ = 150, 160, 170°), for the models of triangular wings with a conical break (4-7 corresponds to ν = 0, 20, 30, 79°), and for arrangement schemes with a negative (8 is for Λ = 120°) and positive α (9 is for Λ = 120°) V-shapes [11].

For the same buoyancy coefficient, the value of $K = f(c_y)$ for triangular wings with a conical break decreases with an increase in ν, while for Λ-wings, the aerodynamic efficiency increases with a decrease in Λ. A study of the effect of the positioning of the Λ-wing in the cone [11] on the aerodynamic efficiency indicates that for arrangements with a negative Λ-shape, $K = f(c_y)$ is greater than it is for a positive V-shape and exceeds the efficiency of a wingless cone. It is known that for systems with upper positioning of the wings, K_{max} is achievable for smaller angles of attack than is possible for systems with lower positioning of wings due to constructive interference. For a wing with a conical break, larger angles facilitate the organization of an intense shock wave at the leading edge, and the resistance of the system is increased while its aerodynamic efficiency is reduced.

3. Pyramidal Body with Wings. We will consider supersonic flow around a pyramidal lifting body with five faces (Fig. 2). The leeward surface of the wing is formed by two intersecting faces, while the windward surface is made with three: a central face and two lateral

faces. The cross section of the wing is made in the form of a concave pentagon. The wing is symmetric relative to the plane $z_1 = 0$ and has a length equal to ℓ. The parameters characterizing the geometry of the wing are as follows: ψ is the included half-angle of the wing ($\psi = \Lambda/2$), δ is the angle between the axis Ox_1 and the intersection line of the lateral faces of the windward surface of the wing, s are the semispans of the wing, ϑ is the angle between the axis Ox_1 and the central face of the windward surface in the plane of symmetry. When $\vartheta = \delta$, the central face becomes a line, and the body takes the form of a Λ-wing. When $\vartheta = \vartheta_0$, where ϑ_0 is the angle between the planes of the leading edges and the axis Ox_1, the body takes the form of a three-faced pyramid with the plane of the windward surface. The angle of attack α is referenced from the axis Ox_1. The flow is considered in the related coordinate system $Ox_1y_1z_1$. To find the pressure distribution over the body surface for supersonic flow, one can use the Newton equation. As a characteristic area for calculating the coefficients, we will use the area of the wing in the plane $S_{surface} = s\ell$. The equations for the coefficients of the tangential and normal forces have the form

$$c_\tau = \left[2\,\frac{\cos^2\alpha\sin^2\psi\,(\tan^2\delta + \tan^2\alpha) + \sin 2\alpha\tan\delta\sin^2\psi}{1+\tan^2\delta\sin^2\psi}\tan\delta + \right.$$
$$\left. + \frac{c_f}{\sin\psi\sqrt{1+\tan^2\delta\sin^2\psi}}\right]\left[1 - \frac{l}{s}\tan\psi(\tan\theta - \tan\delta)\right] +$$
$$+ 2\frac{l}{s}\sin^2(\alpha+\theta)\tan\psi\tan\theta(\tan\theta - \tan\delta) + c_f\frac{l}{s}\cos\theta\tan\psi(\tan\theta - \tan\delta) + \frac{c_f}{\sin\gamma},$$
$$c_n = 2\,\frac{\cos^2\alpha\sin^2\psi\,(\tan^2\delta + \tan^2\alpha) + \sin 2\alpha\tan\delta\sin^2\psi}{1+\tan^2\alpha\sin^2\psi} \times$$
$$\times\left[1 - \frac{l}{s}\tan\psi(\tan\theta - \tan\delta)\right] + 2\frac{l}{s}\tan\psi(\tan\theta - \tan\delta)\sin^2(\alpha+\theta) - \sin^2\alpha\sin^2\gamma.$$

In the equation for determining the coefficient for the normal force, the last term $\sin^2\alpha\sin^2\gamma$ is considered a normal force created by the faces S_4 and S_5. The coefficient of friction c_f is taken to be 0.001.

Calculations were made with these equations for the aerodynamic characteristics of bodies with the parameters $\ell/s = 3.06$, $\Lambda = 70°$, $\delta = 12°$ (Fig. 2a). The ratio r/h (r is the distance from the axis of the model to the central face of the windward surface in the base cross section, h is the distance from the axis of the model to the line uniting the leading edges to the base cross section) was taken as the following: 1; 0.75; 0.5; 0.25; 0, which corresponds to $\vartheta_1 = 19°$, $\vartheta_2 = 17°$, $\vartheta_3 = 16°$, $\vartheta_4 = 14°$, $\vartheta = \delta = 12°$ (models 1-5).

For measuring the total aerodynamic characteristics of Λ-wings with a conical break of windward surfaces, five models were prepared whose fundamental geometric parameters were the same as those in the Λ-wing configurations above. The model is made in the form of a Λ-wing with sharp leading edges, with the parameters $\ell = 150$ mm, $s = 49$ mm, $\Lambda = 70°$, $\delta = 12°$, and with four detachable bushings attached to the windward surface. The angle of attack was referenced from the line of intersection of the leeward planes (Fig. 2a). The area of the wing in the plane was taken to be the characteristic area for calculating the aerodynamic coefficients. Tests were conducted for M = 3 and $Re_\ell = 3\cdot 10^6$. The relative RMS error of the measurements was

$$\bar\sigma_{c_x} = \pm 5\%, \quad \bar\sigma_{c_y m_z} = \pm 3\%.$$

The test results indicate that c_y as a function of the angle of attack is almost linear, and the buoyancy coefficient monotonically increases with an increase in the ratio r/h for a constant angle of attack. The model with the form of a triangular pyramid (r/h = 1) possesses higher resistance that the Λ-wing.

The measurement results for the forces were used to calculate the aerodynamic efficiency (Fig. 2b; points 1-5 correspond to models 1-5). The more rapid increase in the resistance in comparison with the buoyancy force when making a transition from a Λ-wing to a three-faced pyramid leads to a decrease in the aerodynamic efficiency. The maximum aerodynamic efficiency for c_y = const is exhibited by the Λ-wing, but this changes negligibly up to r/h = 0.4. Consequently, for a small loss in efficiency, one may increase the useful volume of the Λ-wing with additional filling near the line of intersection of the leeward surfaces.

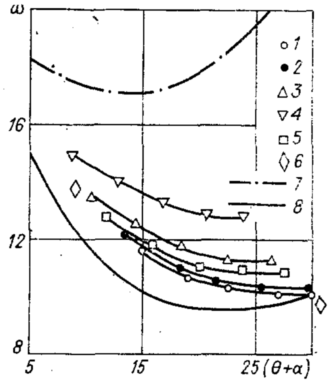

Fig. 3

The aerodynamic quantities determined experimentally for M = 3 (Fig. 2b) greatly differ from those calculated with Newtonian theory (Fig. 2a). In addition, the nature of the dependences c_x, c_y, K = f(α) is similar. This makes it possible to use Newtonian theory to establish qualitative relations between the aerodynamic characteristics and the geometric parameters of the test body for moderate supersonic velocities. In both cases, filling of the internal volume of the Λ-wing is associated with an increase in c_x and c_y and a reduction in the aerodynamic efficiency, which is maximum for $\alpha < 0$.

The pitching moment m_z as a function of α for all models is close to linear in the investigated range of attack angles. An increase in the ratio r/h has practically no effect on the static stability m_z^{α}. In addition, the balancing angle ($m_z = 0$) shifts to smaller α when going from a Λ-wing to a three-faced pyramid.

During the tests of Λ-wings with a conical break in the windward surfaces, photographs were obtained for M = 3 of the flow with the IAB-451. One can see the shock wave, which is connected to the nose of the model and appears as a projection of a wave that is curvilinear in the plane normal to the incident flow. The data on flow spectra can be used to determine the outflow of the shock wave from the windward surface in the plane of symmetry of the wing. The angle ω between the shock wave and the windward surface in the plane of symmetry of the wing as a function of the angle (θ + α) between the direction of the incident flow and the windward surface in the plane of symmetry is shown in Fig. 3. Besides the experimental data for the five models, points are given for the triangular wing with an half-angle of 20° at its vertex [12], and calculated curves are shown for a wedge and for a cone with cone angles of (θ + α) (1-5 — models 1-5, respectively; 6 — a triangular wing [12]; 7 — a wedge; 8 — a cone). The triangular wing [12] is situated in the flow in the same way as the windward face of the three-faced pyramid (model 1). For all models, the shock wave approximates the wing for an increase in α, and, for the investigated range of attack angles, the minimum of the curve ω = f(θ + α) is not attained.

4. A Lined Λ-Body. Experiments were done on flow around models whose windward side was formed by lines connecting the Λ-shaped leading edge with the plane of the trailing edge (Fig. 4), while the models had the form of rectangles in their lateral projections and the transverse cross sections were formed by reinforced Λ-bodies turning into a triangle at the base section. We considered aerodynamic characteristics of concave surfaces, which can be used in configurations for aircraft with different useful volumes and with air intakes. Three models were tested with angles between the leading edges of Λ = 120, 90, and 60° for M = 2, 3, 4, and $Re_\ell = (3.6\text{-}7.3)\cdot 10^6$ in the range α = −4 ... +12°. The leading edges were positioned along the normal to the external fin (the line of intersection of the leeward surfaces), from which the angle of attack is referenced. The line connecting the windward surfaces (the analog of the line connecting the windward surfaces of a normal Λ-wing, from which the angle of attack is referenced) is, along with the fin angle, equal to δ = 12, 15, and 20° for models 1-3, whose span is 0.112; 0.085; 0.0643 m, respectively. The models have a constant mid section area of S = 0.0018 m² and a length of ℓ = 0.15 m and are set on a base restrainer with a diameter of 0.01 m. The angle of attack is referenced from the line of intersection of the leeward surfaces, which are situated along the flow lines of unperturbed flow for α = 0. When calculating the aerodynamic coefficients, the plane $S_{surface}$ is taken to be the characteristic area.

In the investigated range of attack angles, the resistance and buoyancy force increase monotonically for all models with the exclusion of α > 6°, where for models 1 and 2 a maximum

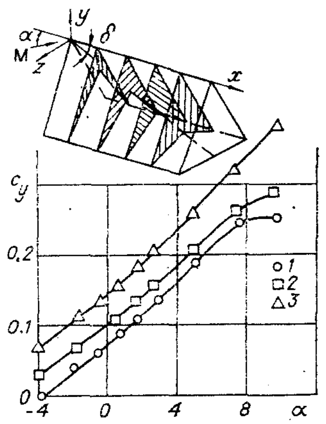

Fig. 4

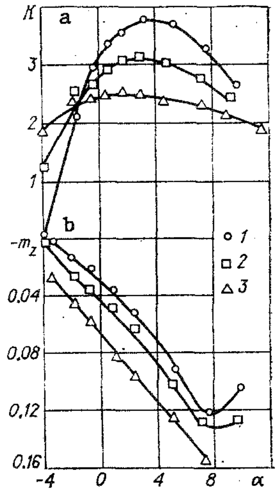

Fig. 5

for c_y is observed (see Fig. 4, M = 4). The minimum resistance is achieved for larger absolute values of the negative attack angles than those obtained in the experiments ($\alpha \approx -5$ ... $-8°$). One should note that for tests with thin Λ-wings [7], where the attack angle is referenced from the line of intersection of the windward planes, the minimum resistance and the value $c_y = 0$ is attained near $\alpha \approx 4°$ due to the thickness of the model. If the angle of attack is referenced from the line of intersection of the windward surfaces, the value of $c_{x\,min}$ will correspond to $\alpha \approx 7$-$12°$.

A decrease in the angle Λ leads to an increase in c_x and c_y, but K_{max} is reduced. One should note that these data correspond to test results for Λ-wings [7], where the aerodynamic efficiency of lines Λ-bodies is attained for α = 2-5° (Fig. 5a, M = 4). A decrease in the included angle shifts the position of the maximum of K = f(α) to larger α for M = 2 but has little effect for M = 3, while for M = 4, K_{max} goes toward smaller α. It would be of interest to compare the aerodynamic efficiency for lifting bodies for a constant value of c_y. When c_y = const, the value of K increases with an increase in the included angle (see Fig. 1, M = 4; the models of the lines Λ-bodies 1-3, the definitions 10-12, respectively). It is evident from the experimental results that a change in M from 2 to 4 leads to an increase in the efficiency.

We will consider the pitching moment m_z as a function of the angle of attack (Fig. 5b, M = 4). For $\alpha = -4$ ... $+3°$, the models have negative derivatives $\partial m_z/\partial\alpha$ and, therefore, are stable relative to some position determined by the condition $m_z = 0$. When M = 2, for an increase in the quantity of the Λ, the restoring moment increases in absolute value, but the range of stable flow decreases, and if model 3 is stable up to α = 7°, then model 1 is stable only up to 3°. For M = 4, a change in the effect of M on this moment is observed; the absolute value of m_z increases for a decrease in the included angle Λ. In addition, when M goes from 2 to 4, the range of stable flow increases to α = 7°.

The pressure center coefficient c_p for all models decreases with a decrease in Λ, but for M = 2, c_p (α = 2°) decreases from 0.4 to 0.24, while for M = 4 it is reduced from 0.45 to 0.43. In the range of stable flow around the models, an increase in α initially increases c_p but later reduces it.

Schlieren photographs were taken of the flow. The shock wave, whose form is determined by a system of interacting discontinuities from the leading edges, was projected onto the camera above the model along with the form of the windward surface. Since the flow for a lined Λ-body is nonconical, then, in contrast to broadening the flow around Λ-wings where the track of the discontinuity in the flow region is limited by the characteristics of the trailing edge and accurately corresponds to flow inside the Λ-wings, the projections of the discontinuity above the wing are not straight lines.

For model 1 with M = 2, a slight distortion in the line above the model was observed that is the projection of regular interaction of the discontinuities from the leading edge. For M = 4, this line is almost straight inside the Λ-body. The projections of the discontinuity for models 2 and 3 are bands with clearly defined leading boundaries. An analysis of the system of discontinuities for Λ-wings [7] indicates that flow is possible in a band with a Mach wave system and with a curvilinear departing wave.

One can see from the photographs of the flow that for an increase in the cone half-angle (when going from model 1 to model 3), the discontinuity above the model increases the curvature, and for model 3 for M = 2, a shock wave is formed that is connected to the lateral parts of the leading edge but departs from the edge near the line of intersection of the internal surfaces. In most cases, the dependence $\omega = f(\alpha)$ (the angle ω is formed by the line connecting the point of intersection of the projection of the discontinuity with the upper edge of the model) is close to linear, and in the investigated range of α, the value of ω is constant and increases only for models 2 (for M = 2) and 3 (for M = 4). One should note that in tests with Λ-wings [7] for large included angles ($\Lambda > 140°$), the increase in α up to 20° insignificantly pushes the wave connected with the edge toward the axis, while a further increase in α does not change the separation of the wave. In addition, for $\Lambda < 140°$, there is an increase in the separation of the wave for $\alpha > 20°$.

As a result of these experiments, the aerodynamic coefficients of several lifting configurations with a triangular form and with a concave windward surface have been determined. It was shown that for triangular wings with a conical break, the aerodynamic quality is reduced for a decrease in the included angle. For pyramidal bodies with wings, the transition from the Λ-wing to the three-faced pyramid leads to a reduction in the aerodynamic efficiency, but the useful volume of the Λ-wing may be increased with an insignificant loss in efficiency with additional filling near the line of intersection of the windward surfaces. For lined Λ-bodies, a decrease in the angle Λ is accompanied by a reduction in the aerodynamic efficiency, while if M goes from 2 to 4, the quality is increased.

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