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FULL-SCALE INVESTIGATION OF THE MAXIMUM LIFT AND FLOW CHARACTERISTICS OF AN AIRPLANE HAVING APPROXIMATELY TRIANGULAR PLAN FORM

By

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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FULL-SCALE INVESTIGATION OF THE MAXIMUM LIFT AND FLOW CHARACTERISTICS OF AN AIRPLANE HAVING APPROXIMATELY TRIANGULAR PLAN FORM

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SUMMARY

An investigation of the DM-1 glider, which has approximately triangular plan form, airfoil sections similar to the NACA 0015-64, an aspect ratio of 1.8, and a 60° swept-back leading edge, has been conducted in the Langley full-scale tunnel, together with auxiliary studies of $\frac{1}{15}$-scale model triangular wings, carried on in the $\frac{1}{15}$-scale model of the full-scale tunnel. The DM-1 glider was designed as part of a German research program directed toward the development of a supersonic airplane. The glider had a maximum lift coefficient of 0.60, whereas the $\frac{1}{15}$-scale model tests gave a maximum lift coefficient of approximately 1.0. The addition of sharp leading edges to the DM-1 glider increased its maximum lift coefficient to 1.01. Removing the vertical fin from the glider, sealing the large control-balance gaps, and installing a semispan sharp leading edge increased the maximum lift coefficient to 1.24. It is concluded from these tests that the airfoil sections having sharp leading edges or small leading-edge radii, which are believed to be desirable for supersonic flight, will also have acceptable and perhaps superior low-speed characteristics when used in highly swept-back wings.

The flow over triangular wings of low aspect ratio at low scale is characterized by vortices above the upper surface of the wing, inboard of the tips. These vortices aid in obtaining high maximum lift coefficients, and they can be produced at large scale by using airfoil sections having sharp leading edges.

It appears that with triangular wings of aspect ratio of about 2 maximum lift coefficients of the order of 1.2 can be obtained. The corresponding angles of attack, however, are likely to be considerably larger than those for existing conventional airplanes. Furthermore, since the lift-drag ratio approaches 1, the angles of descent without

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power are likely to be prohibitive and airplanes using this type of wing probably will not land safely without power.

INTRODUCTION

Research directed toward the attainment of supersonic flight has led to interest in the high-speed characteristics of wings of high sweep and of low aspect ratio. At present, however, there is only limited full-scale data on the maximum lift and stalling characteristics of such wings. An investigation of the DM-1 glider, which was designed in Germany as a part of a research program directed toward the development of a supersonic airplane, was made in the Langley full-scale tunnel to obtain information on the characteristics of an airplane configuration having an approximately triangular plan form. The first tests of the DM-1 glider in the Langley full-scale tunnel disclosed that the maximum lift coefficient of the glider was considerably lower than had been indicated by previous small-scale tests of similar configurations at DVL in Germany and in several tunnels in the United States (see reference 1). The program was therefore interrupted and an investigation to determine the cause of the low maximum lift was undertaken. The present paper includes a detailed account of the steps leading to the use of a sharp leading edge to improve the maximum lift coefficient, a discussion of the aerodynamic phenomena involved, and curves showing the aerodynamic characteristics of several modifications of the DM-1 glider.

SYMBOLS

α	angle of attack, degrees
C_L	lift coefficient
C_m	pitching-moment coefficient
C_D	drag coefficient
A	aspect ratio

EQUIPMENT AND TESTS

DM-1 Glider and Modifications

The DM-1 glider was designed as one step in a German research program directed toward the development of a supersonic airplane. The eventual airplane was to have been powered with a jet engine. The DM-1 glider had no power and was intended primarily for the investigation of the flying characteristics at high angles of attack.

The DM-1 glider had an approximately triangular plan form, airfoil sections similar to NACA 0015-64, an aspect ratio of 1.8 and a 60° swept-back leading edge. It was constructed almost entirely of wood; the skin was $\frac{1}{16}$-inch three-ply birch plywood and the spars and ribs were of conventional box-beam construction. The principal dimensions of the glider are given in figure 1(a) and table I. General views of the glider mounted on the full-scale-tunnel balance supports for tests are shown in figure 2. The glider as received was equipped with a rudder for directional control and elevons for lateral and longitudinal control. Details of these surfaces are also shown in figure 1(a) and table I. The balance on the control surfaces was similar to other elliptical overhung control balances. The balance gap was relatively large, however, and the shape of the wing just ahead of the balance gap was elliptical. A typical section through the control surface and the rear part of the wing is shown in figure 1(b).

The basic configuration for the investigation was the original DM-1 glider, which had the control-balance slots open and the large vertical fin on. The first modification made to improve the maximum lift characteristics was the addition to the wing of the semispan sharp leading edge shown in figure 1(b). Next, the vertical fin was removed which left the glider as shown in figures 2(b) and 2(c). The three configurations tested with the vertical fin removed were:

(1) Glider wing with control-balance slots open

(2) Glider wing with control-balance slots sealed to prevent air flow through them and faired over on the upper surface

(3) Same as configuration (2) with the sharp leading edge added

Small-Scale Models

As a further aid in the study of the characteristics of the flow over the DM-1 glider, two triangular-wing models, one having airfoil sections 15-percent thick and the other having very thin and sharp-edge sections, were constructed for tests in the $\frac{1}{15}$-scale model of the Langley full-scale tunnel (reference 2). These models were not exact scale models of the DM-1 glider, but had the same aspect ratio, the same ratio of model size to tunnel size, and slightly greater sweepback.

Tests

The aerodynamic characteristics of each glider configuration were determined throughout the angle-of-attack range at zero angle of yaw. The tunnel airspeed for the full-scale tests was limited to approximately 45 miles per hour, because of the light structure inside the glider that was available for connection with the model supporting struts. This airspeed corresponds to a Reynolds number of 4.5×10^6 based on the mean geometric chord of 10.97 feet. For each of the glider and model configurations investigated, the direction of the flow and the progression of the stall, as indicated by wool yarn tufts attached to the wing, were determined. Observations of the flow were also made by use of zinc chloride smoke. The direction and nature of flow over the model wings were observed with a single wool streamer attached to the end of a hand-held probe.

MAXIMUM-LIFT INVESTIGATION AND FLOW STUDIES

The variations of the pitching-moment coefficient, the drag coefficient, and the angle of attack with lift coefficient for the basic configuration are shown by the curves labeled "Original DM-1 glider" in figure 3. The maximum lift coefficient was approximately 0.6 and the accompanying stall, as indicated by the tuft surveys (fig. 4(a)), progressed inward from the tips in much the same manner as the stall of conventional wings of high taper ratio. The maximum lift coefficient was about 0.3 less than was indicated by low-scale wind-tunnel tests of various triangular wings and triangular flat plates having about the same aspect ratio. (See references 1, 3, and 4.) Moreover, the wing stalled at an angle of attack of 18°, whereas the low-scale tests indicated that the stall angle would be about 40°. Some fundamental difference between the flow over the full-scale wing and the flow over the model wing appeared to exist.

The investigation of the flow over the $\frac{1}{15}$-scale models in the model tunnel showed, in agreement with references 1, 3, and 4, that the wings stalled at angles of attack near 40°, and there was no particular evidence of tip stalling at angles of attack below maximum lift. Furthermore, there was no significant difference in the flow for the sharp-edge thin section and for the 15-percent thick wing. The flow for these model wings was characterized by two vortices, which originated at the apex of the triangle and increased in size as they passed downstream, with their cores located above the upper surface of the wing and inboard of the tips.

Tuft surveys and smoke-flow studies made of the full-scale DM-1 glider showed that no vortex flow such as that for the $\frac{1}{15}$-scale model existed above the upper surface of the wing. The only vortices present were the usual ones originating at the wing tips. Diagrams for the flow patterns over the full-scale DM-1 glider and the $\frac{1}{15}$-scale models are shown in figure 5. The reason for the fundamental difference between the flow patterns is believed to be as follows: According to the theory of reference 5, the flow about a triangular wing can be represented as the sum of a cross component, which at each transverse section is approximately the theoretical two-dimensional flow about the section (see fig. 5(b)), and the longitudinal component. In general, such a two-dimensional transverse flow cannot exist, because of the boundary-layer separation around the highly curved edges; however, when the longitudinal velocity component is combined with the transverse component, the boundary layer follows an easy curve around the leading edge as indicated in figure 5(a) and is not necessarily forced to separate. For either the actual glider or the small models, it is expected that, even at low angles of attack, the boundary layer in this flow around the leading edge could not withstand the adverse pressure gradient just behind the leading edge. For the full-scale glider, any separation of the laminar layer would, however, merely induce transition to a turbulent layer, which eventually would separate near the trailing edge. On the $\frac{1}{15}$-scale model, however, such transition does not occur, because of the low Reynolds numbers. (See reference 6.) Hence, the flow separates completely near the leading edge, and the cross component takes on the appearance of figure 5(d). When the longitudinal component of the velocity is superimposed, the trailing vortices are formed above the upper surface of the model wing, as indicated in figure 5(c). Similar vortices have been observed at the side of a rectangular flat plate by Winter (reference 7). The actual stall possibly occurs at the angle of attack for which a stream line of the flow off the leading edge fails to curve over enough to meet the upper surface of the wing again before it trails downstream.

It appeared that if the vortex action could be produced on the full-scale glider, large gains in the maximum lift coefficient would result. Inasmuch as the phenomenon was attributed to a separation at the leading edge of the wing, it was decided to force this separation by providing the full-scale wing with a sharp leading edge. Preliminary investigations indicated that a 3-inch strip of sheet metal projecting outward from the wing leading edge and extending half way along it (fig. 1(b)) would produce the desired results. Smoke-flow observations and tuft surveys indicated that the large vortices originating at the apex of the triangle which were observed at low scale were then present over the full-scale glider. The aerodynamic characteristics for this configuration are shown in figure 3. The maximum lift was increased to a value of 1.01 at an angle of attack of 31°. The drag coefficient was not increased any appreciable amount at low lift coefficients. The stable slope of the pitching-moment curve was reduced by the sharp leading edge, and the tuft surveys (fig. 4(b)) indicated a tendency toward tip stalling.

The results obtained with this configuration, together with the exploratory work done at low scale had accomplished the original objective of determining the reason for and correcting the low maximum lift. However, inasmuch as both the unusually large control balance gaps and the large original vertical fin may also have been affecting the maximum-lift characteristics of the airplane adversely, a further investigation was made to determine their effects and also to determine the influence of sharp leading edges on the maximum lift of the wing alone. The results of this investigation are shown in figure 6. The maximum lift coefficient, based on the wing area of the basic configuration increased to 0.92 when the vertical fin was removed. The lift curve still begins to break at a lift coefficient of about 0.6 and an angle of attack of about 18°, as was the case with the fin on. Closing the elevon control-balance slots increased the maximum lift coefficient to 1.05. With the addition of the sharp leading edges, the highest maximum lift coefficient (1.24) was obtained. Tuft photographs for the three fin-off configurations are shown in figures 4(c) to 4(e). As was the case with the vertical fin on, the increases in drag coefficient at the low angles of attack due to the sharp leading edges do not appear significant. The sharp leading edges attached to the wing for these tests were not faired into the wing, and it is probable that a wing having sharp-leading-edge airfoil sections would have less drag.

The maximum lift coefficient obtained for the optimum configuration is in good agreement with the model results, and with the low-scale results of references 1, 3, and 4. It is of interest, also, to note that according to the theory of reference 5 $\frac{dC_L}{d\alpha} = \frac{\pi}{2}A$ or 2.83 for the present case; whereas the experimental value is only about 2.26. As pointed out in reference 5, the simplified theory overestimates $\frac{dC_L}{d\alpha}$ for aspect ratios above 1.0; the value given for elliptical wings by the more exact theory of Krienes is 2.39 for an aspect ratio of 1.8 (fig. 5 of reference 5). The slope of the lift curve (fig. 6) increases from 1.8 at low angles of attack to approximately 2.26 and then decreases to 1.2 for angles of attack above 28°. The value of 2.26 was used in the preceding comparison, since it covers the straight-line part of the lift curve.

In order to determine the usefulness of the maximum lift obtained, the values of the lift-drag ratio must be considered since this relationship determines the power-off rate of descent. At a lift coefficient of 1.0, the lift-drag ratio is 2.5, which corresponds to an angle of descent of about 22° and a rate of descent of 0.37 times the flight speed. At a lift coefficient of 1.2, the lift-drag ratio is 1.5 and the corresponding angle and rate of descent are 34° and 0.56 times the flight speed, respectively. It is concluded that if any reasonable rate of descent is to be maintained for airplanes with wings similar to that of the DM-1 glider, it will be necessary either to use power for landing or to restrict the design to relatively low wing loadings.

CONCLUDING REMARKS

The original DM-1 glider, which had approximately triangular plan form, airfoil sections somewhat similar to the NACA 0015-64, an aspect ratio of 1.8 and a 60° swept-back leading edge, had a maximum lift coefficient of 0.60, whereas $\frac{1}{15}$-scale tests of a similar configuration gave a maximum lift coefficient of approximately 1. The addition of sharp leading edges to the original DM-1 glider increased the maximum lift coefficient to 1.01. Removing the vertical fin from the glider, sealing the large control-balance gaps, and installing a semispan sharp leading edge, increased the maximum lift coefficient to 1.24. It is concluded from these tests that the airfoil sections having sharp-leading edges or small leading-edge radii which are believed to be desirable for supersonic flight, will also have acceptable and perhaps superior low-speed characteristics when used in highly swept-back wings.

The flow over triangular wings of low aspect ratio at low scale is similar to that which H. Winter (see NACA TM No. 798) observed over rectangular flat plates of low aspect ratio and is characterized by vortices above the upper surface of the wing inboard of the tips. The action of these vortices is favorable in maintaining orderly flow over the upper surface of the wing to very high angles of attack and thereby aids in obtaining relatively high maximum lift coefficients. At large Reynolds numbers this vortex flow can be produced by using airfoil sections having sharp leading edges, or very small leading-edge radii.

With triangular wings of aspect ratio of about 2, maximum lift coefficients of the order of 1.2 can be obtained. The corresponding angles of attack, however, will be considerably greater than those for conventional airplanes. Furthermore, since the lift-drag ratio is approaching 1, the angles of descent without power are likely to be prohibitive and airplanes using this type of wing probably will not land safely without power.

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7. Winter, H.: Flow Phenomena on Plates and Airfoils of Short Span. NACA TM No. 798, 1936.

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TABLE I

DIMENSIONS OF THE DM-1 GLIDER

Wing:	
Span, feet	19.6
Wing area, square feet	215.0
Aspect ratio	1.8
Airfoil section	Approximately NACA 0015-64
Thickness, percent chord	15
Point of greatest thickness, percent chord	40
Root chord, feet	20.75
Mean geometric chord, feet	10.97
Wing twist, degrees	0
Dihedral, degrees	0
Sweepback (L.E.), degrees	60
Sweepforward (T.E.), degrees	15
Vertical location of center of gravity, percent root chord from chord line	0
Horizontal location of center of gravity, percent root chord	50
Horizontal control surfaces:	
Total elevon area, square feet	23.3
Elevon chord, feet	1.95
Elevon hinge location, percent chord	27
Elevator angle range, degrees	28 to -24
Aileron angle range, degrees	21 to -21
Total trim flap area, square feet	6.97
Trim flap chord, feet	1.38
Vertical tail:	
Height, feet	8.58
Area, (to chord line of wing) square feet	89.6
Aspect ratio	.82
Airfoil section	Approximately NACA 0015-64
Thickness, percent chord	.175
Point of greatest thickness	.40
Root chord, feet	19.7
Angle of sweepback (L.E.), degrees	65
Angle of sweepforward (T.E.), degrees	0
Rudder area, square feet	8.01
Rudder chord, feet	1.32
Hinge location, percent	.27
Rudder angle, degrees	±23

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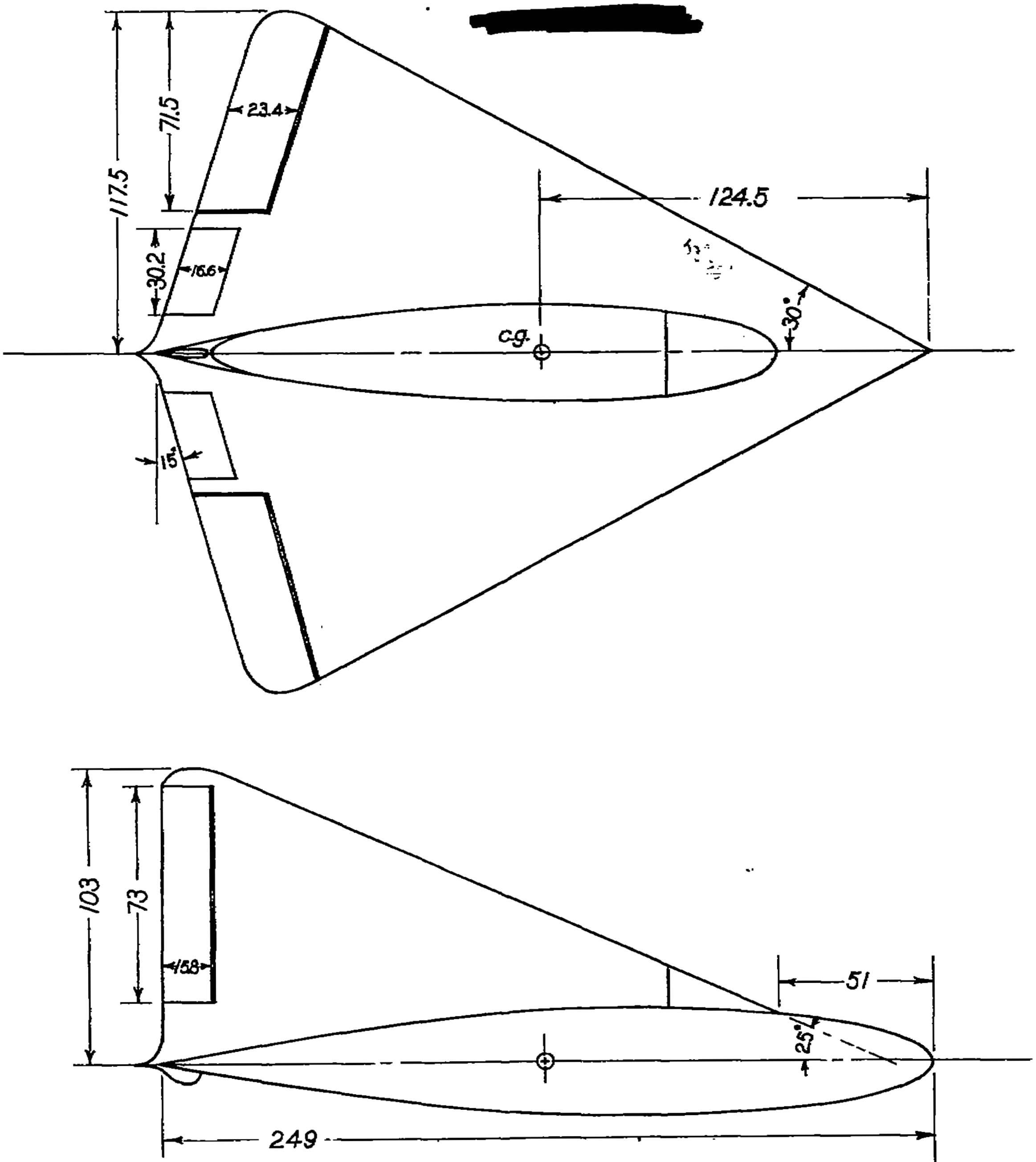

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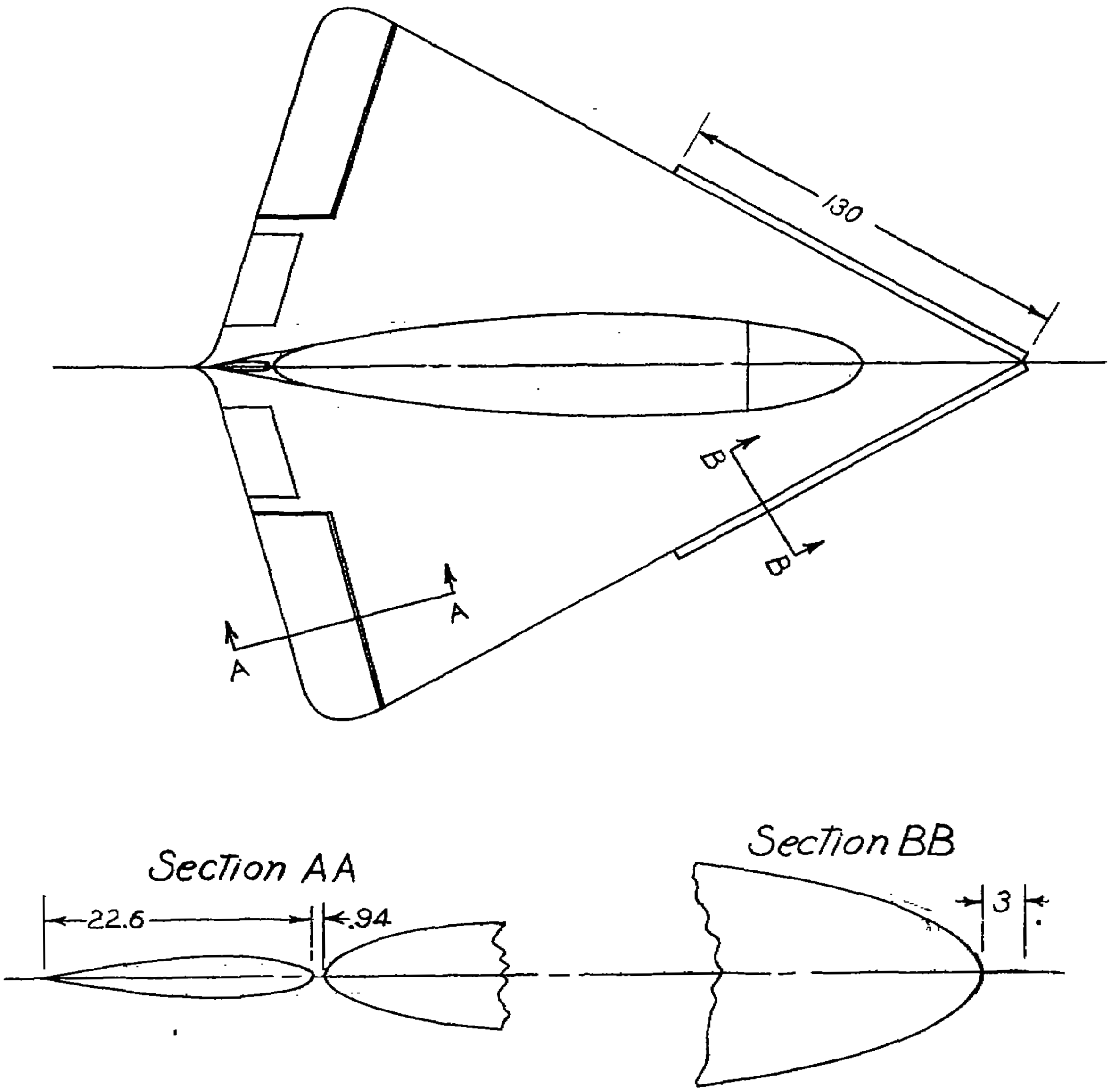
(A) Principal dimensions of original glider.

Figure 1.- Dimensions of the DM-1 glider. (All dimensions are in inches.)



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(b) Dimensions of the sharp leading edges
and of the elevon control slots.

Figure 1.- Concluded.

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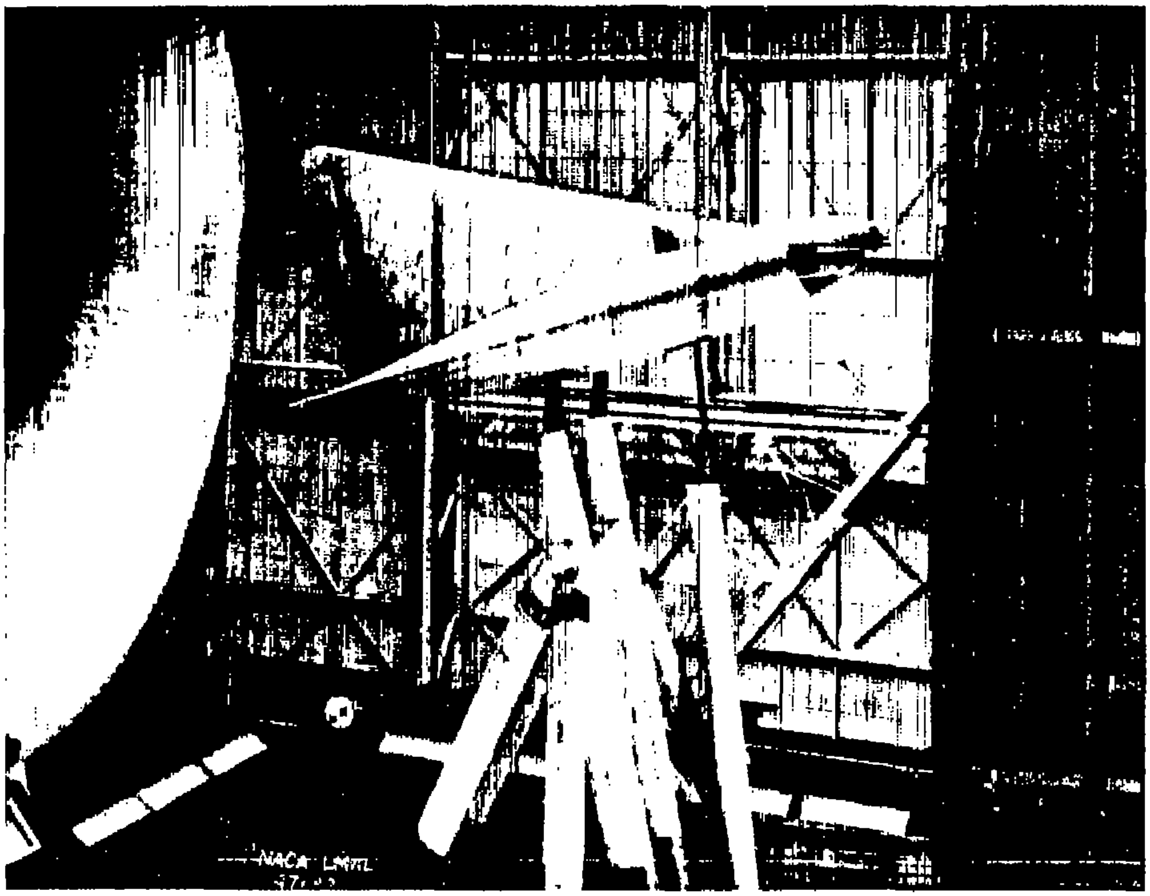

(a) Original configuration; three-quarter side view.

Figure 2.- The DM-1 glider mounted on the Langley full-scale-tunnel balance supports.

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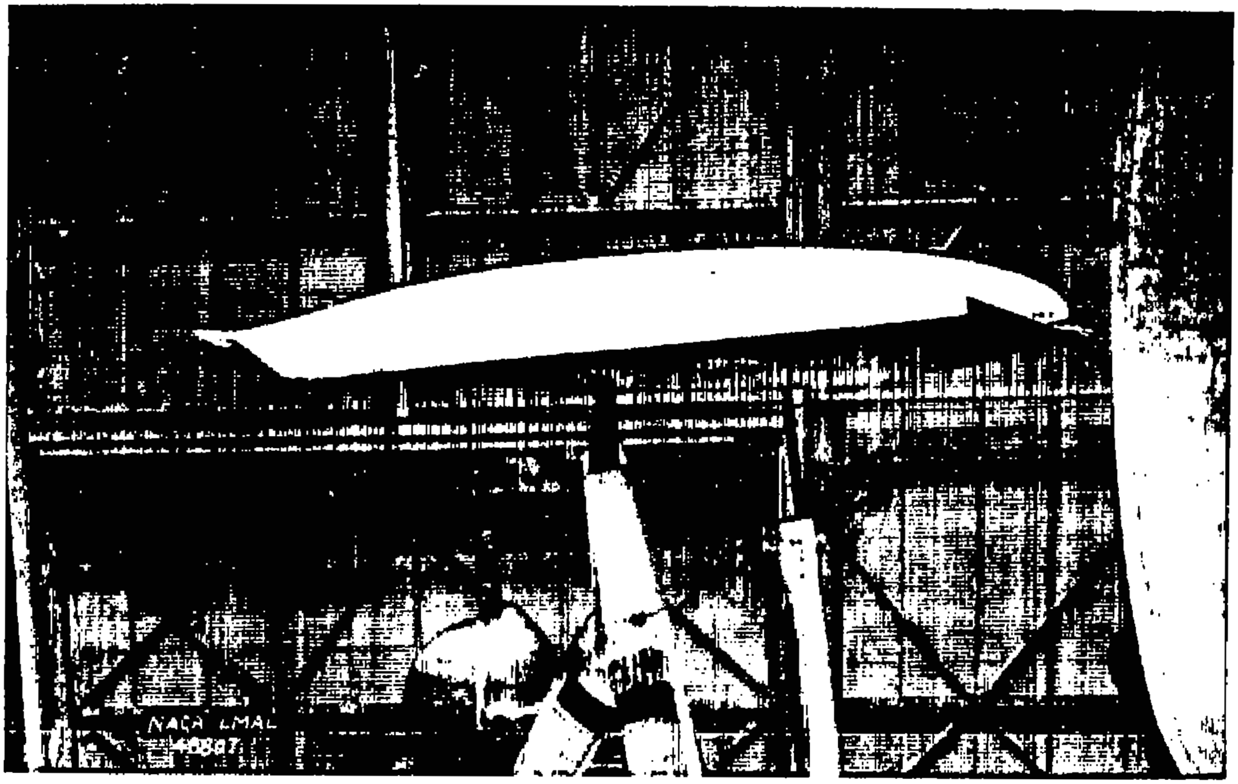
[redacted]



(b) Vertical fin removed; side view.

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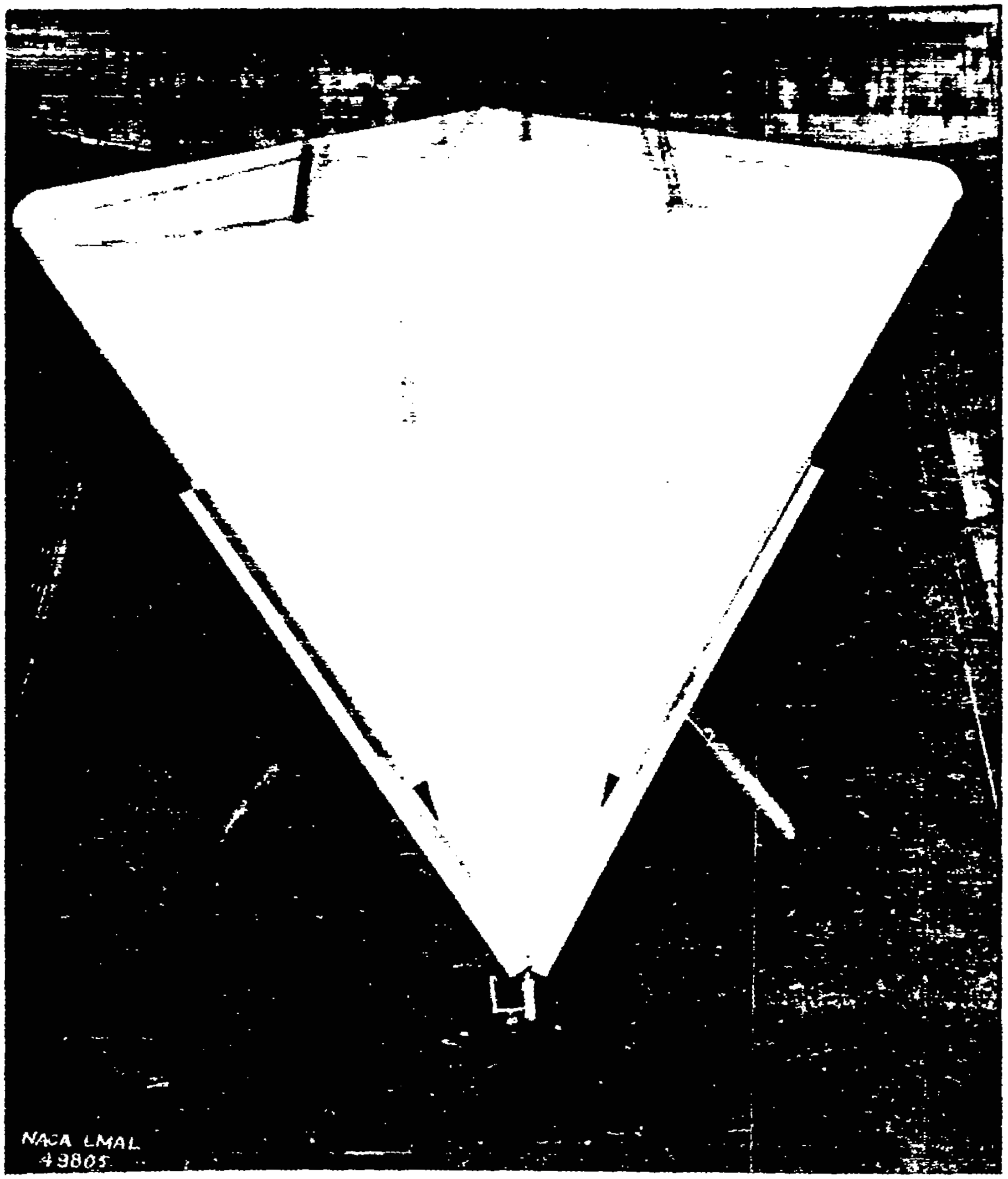
Figure 2.- Continued.



(c) Vertical fin removed and semispan sharp leading edge attached; top view.

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Figure 2.- Concluded.

[redacted]

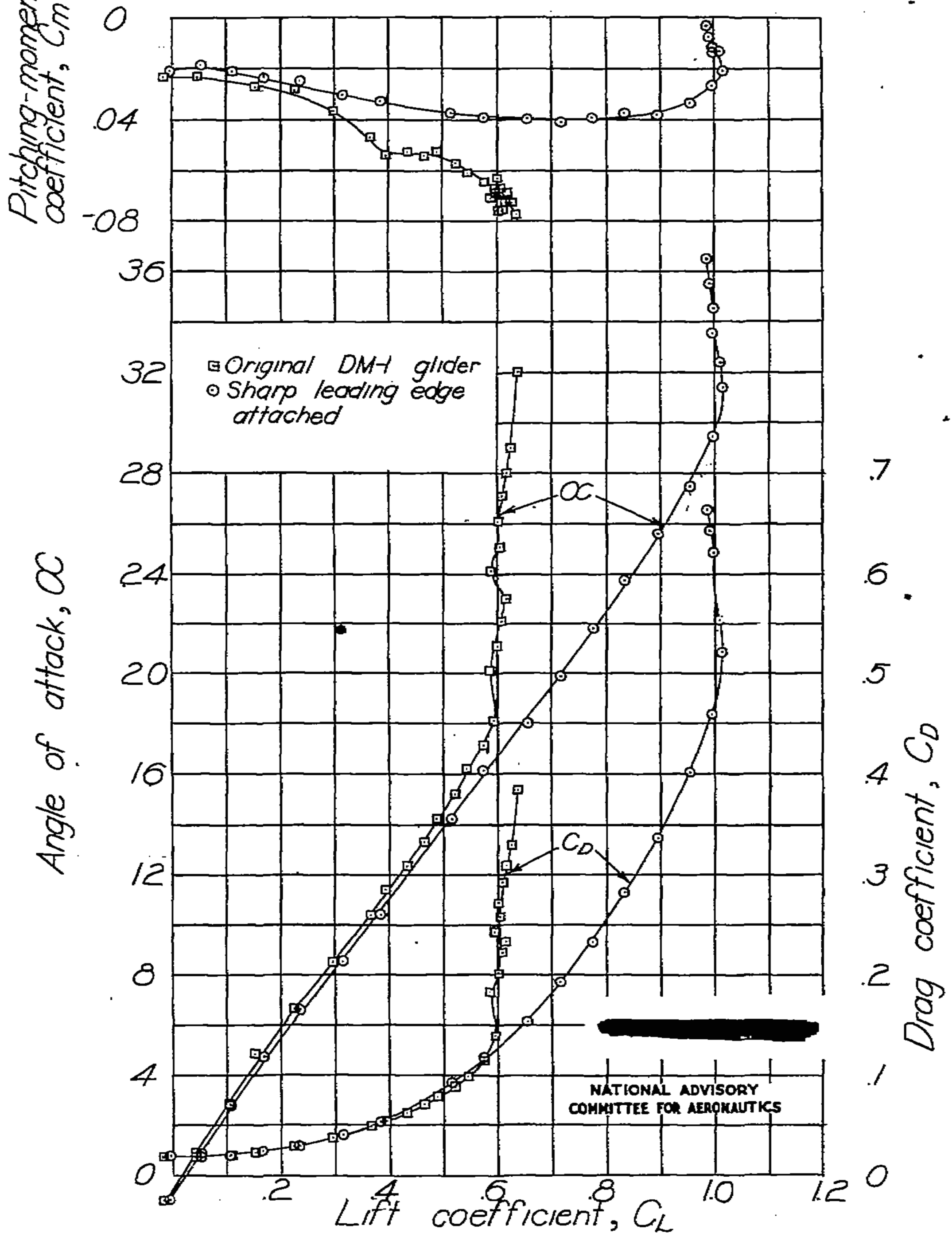

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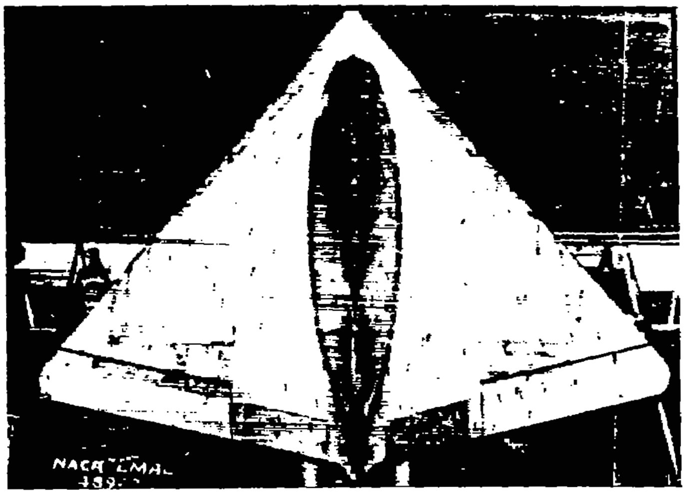
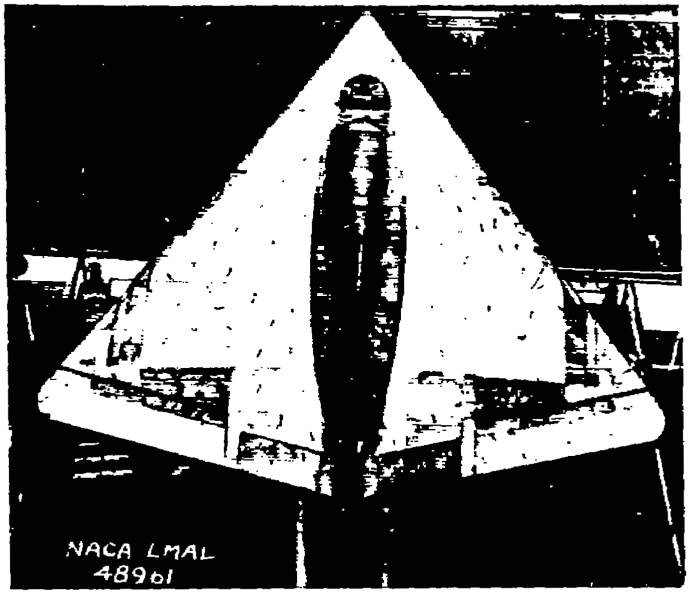
Figure 3.- Aerodynamic characteristic of the DM-1 glider with and without sharp leading edges.



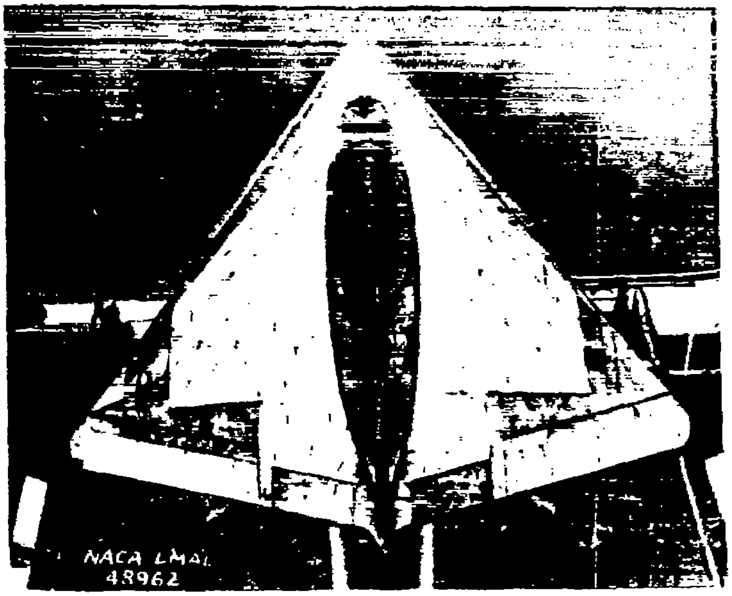
α = 16.1



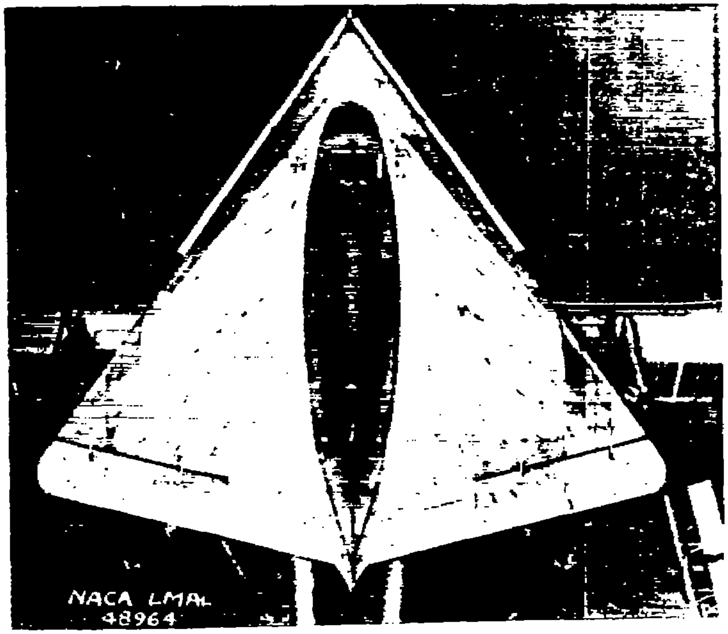
[redacted] α = 20.1

(a) Original DM-1 glider.

Figure 4.- Tuft surveys of the flow over the DM-1 glider.



α = 18.9



[redacted] α = 31.4

(b) The DM-1 glider with semispan sharp leading edge installed.

Figure 4.- Continued.

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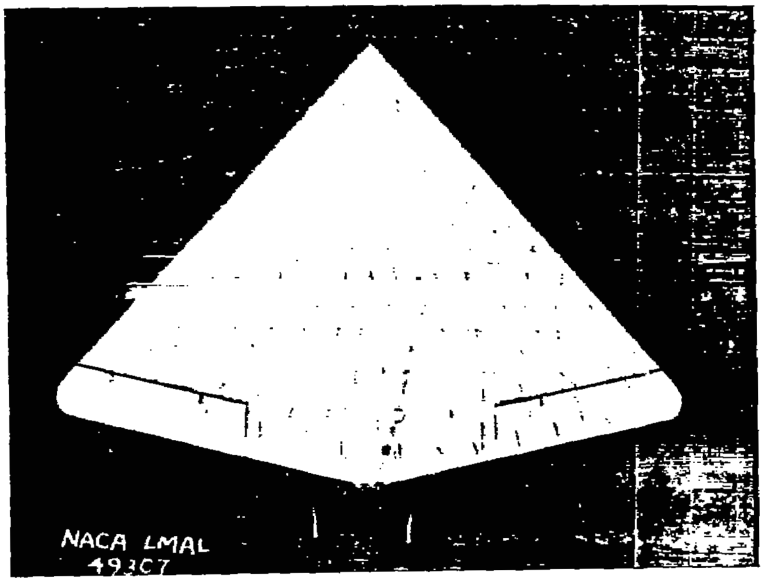
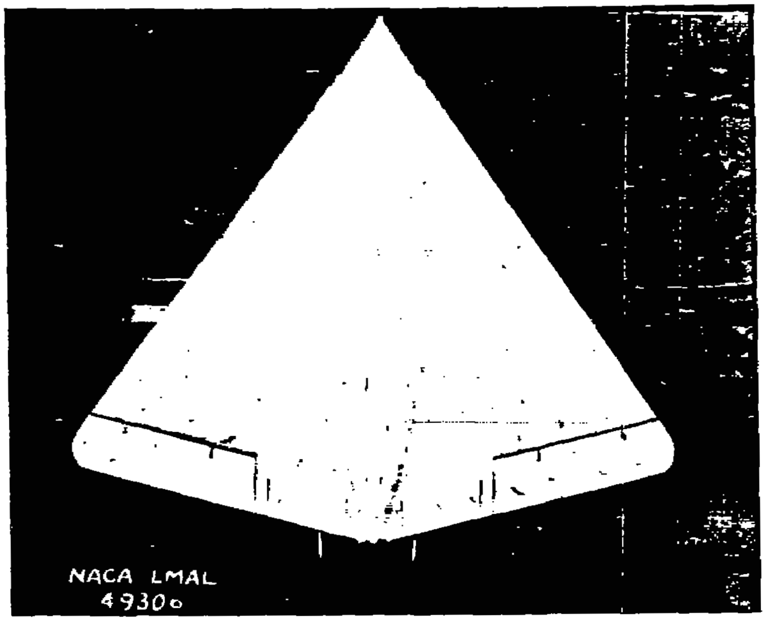


α = 14.5



α = 34.8

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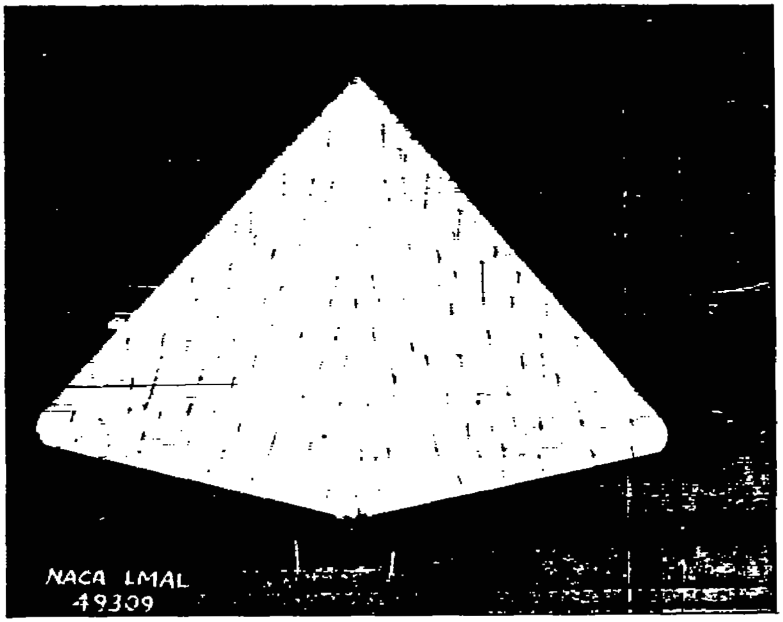
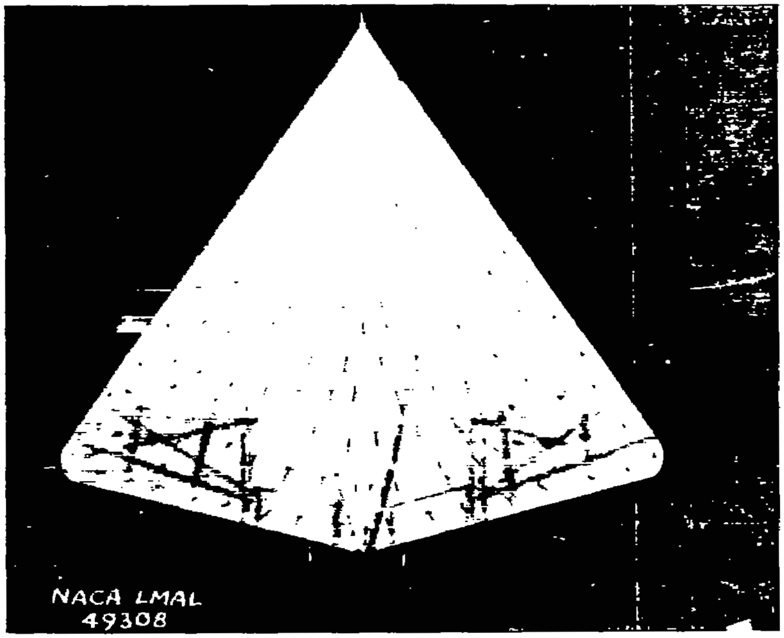
(c) Wing of the DM-1 glider with elevon control slots open.

Figure 4.- Continued.



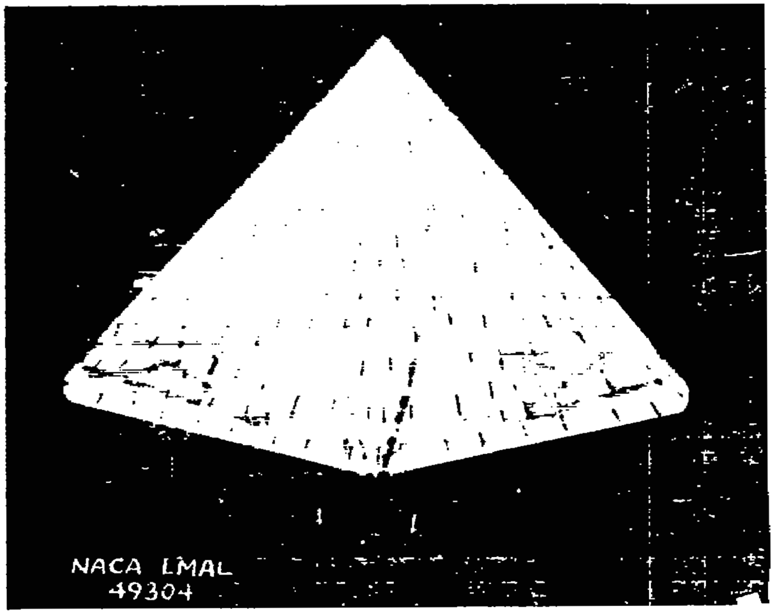
α = 14.5



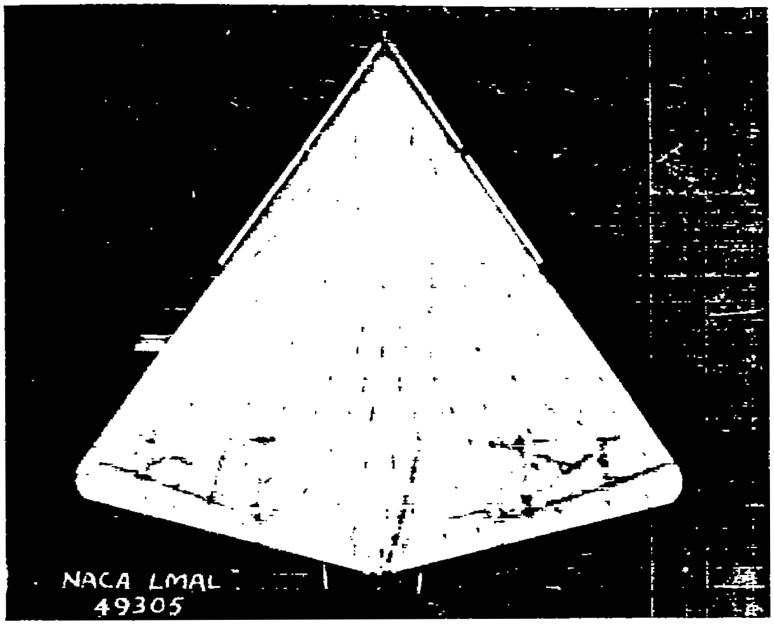
α = 34.5 [redacted]

(d) Wing of DM-1 glider with elevon control balance slots sealed.

Figure 4.- Continued.



α = 14.5

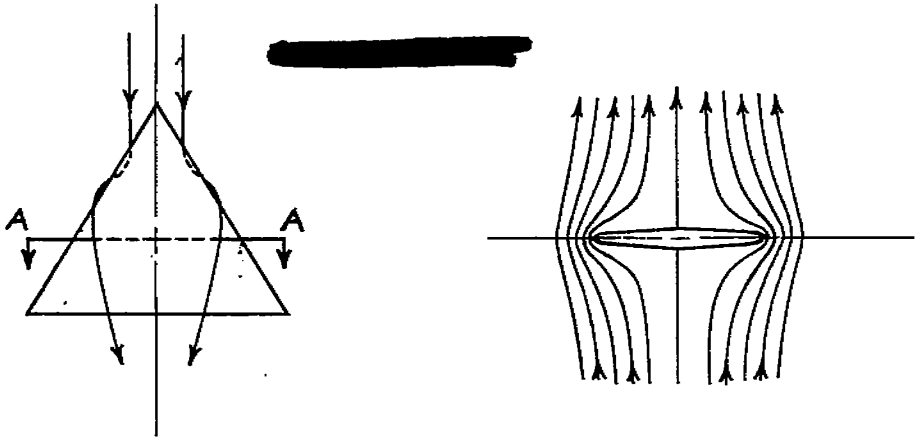


α = 34.3

(e) Wing of DM-1 glider with elevon control balance slots sealed and semispan sharp leading edge installed.

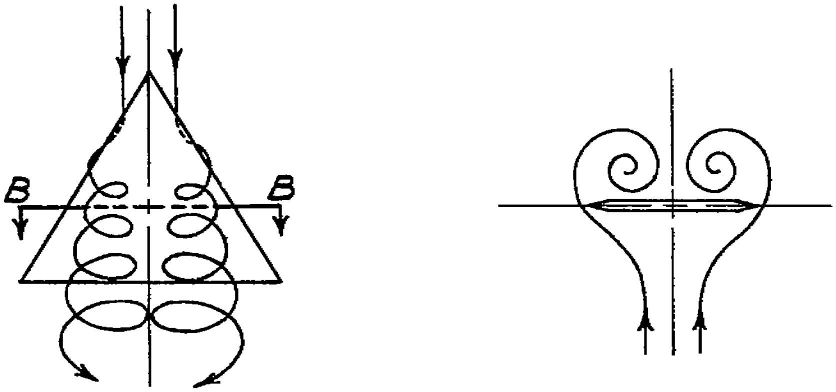
Figure 4.- Concluded. [redacted]

[redacted]



(a) Elements of flow over a triangular wing having a rounded leading edge at high Reynolds numbers.

(b) Elements of the vertical component of flow over section AA.



(c) Elements of flow over a triangular wing at low Reynolds numbers or over a triangular wing having a sharp leading edge.

(d) Elements of the vertical component of flow over section BB.

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Figure 5.- Diagrams of the flow over triangular wings.

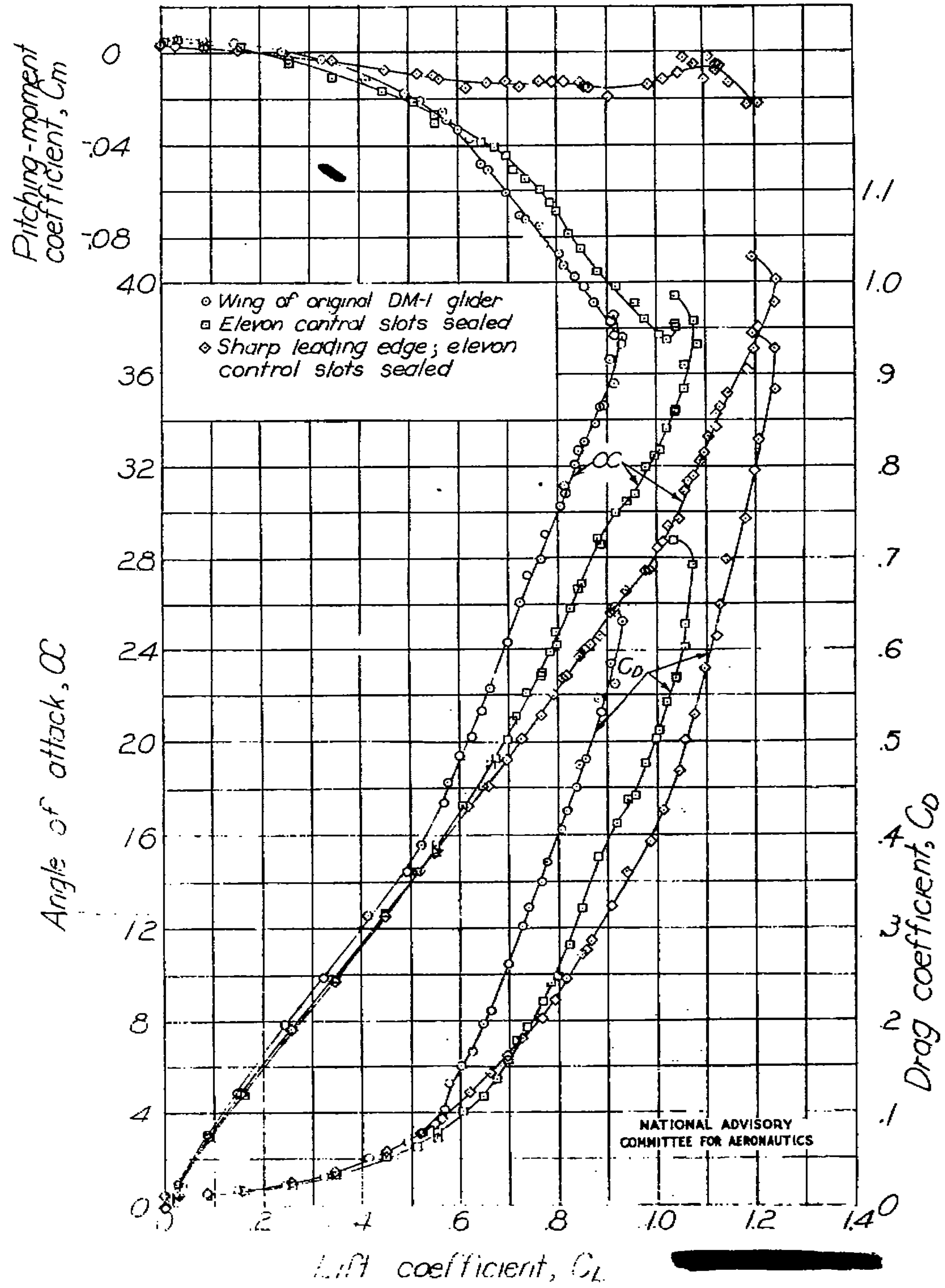

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Figure 6. - Aerodynamic characteristics of the DM-1 glider with the vertical fin removed.