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No. 764

THE AERODYNAMIC ASPECT OF WING-FUSELAGE FILLETS

By H. Muttray

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THE AERODYNAMIC ASPECT OF WING-FUSELAGE FILLETS*

By H. Muttray

SUMMARY

Model tests prove the feasibility of enhancing the aerodynamic qualities of wing-fuselage fillets by appropriate design of fuselage and wing roots. Abrupt changes from maximum fuselage height to wing chord must be avoided and every longitudinal section of fuselage and wing roots must be so faired and arranged as to preserve the original lift distribution of the continuous wing. Adapting the fuselage to the curvilinear circulation of the wing affords further improvement. The polars of such arrangements are almost the same as those of the "wing alone," thus voiding the superiority of the high-wing type airplane known with the conventional design. Besides, protuberances such as windshields, etc., disturb the aerodynamic quality of a mid wing or low wing less than of a high wing, so that the latter actually becomes inferior by comparison.

For reasons of an appropriate aerodynamic and static combination of wing and fuselage, the further development of high-performance gliders should be carried on with mid-wing type monoplanes.

INTRODUCTION

The accepted method of raising the performance of gliders in past years has been to increase the wing span. But lately this practice has fallen into disuse after it was found that a large span entailed certain disadvantages which seemingly made this avenue of attack rather unadvised.

The attention of the designers was turned to other means for promoting higher flight performances.

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*"Die aerodynamische Zusammenfügung von Tragflügel und Rumpf. Luftfahrtforschung, vol. 11, no. 5, October 25, 1934, pp. 131-139.

There is, for example, the method of fairing the wing into the fuselage and of housing the pilot within a cabin-like enclosure. Both of these methods are intimately related insofar as the complete enclosure of the pilot must precede any aerodynamically favorable wing-fuselage combination. In point of fact, it was this very method of pilot-seat enclosure resorted to within the last few years, which really caused the renewed drive for wing fillets.

Hereinafter is the description of an essentially experimental investigation of wing fillets and various deductions.

2. PREVIOUS REPORTS

This experimental report is, as already indicated, based upon previous investigations made by the writer. The first of these goes back to 1928 and was published in Luftfahrtforschung (N.A.C.A. T.M. No. 517) (reference 1).

a) The Flow at the Wing Root of a Low-Wing Monoplane as Affected by Filleting

It is common knowledge that at higher lift values, that is, at greater pressure rises, the flow at the roots of a low-wing monoplane is very apt to break away as a result of the secondary flow, occurring in the angles or corners formed by the sides of the fuselage and the upper surface of the wing.

It is also known that the polar of a low-wing monoplane has a higher additive body drag than that of a high-wing monoplane. The disagreeable feature is the breakdown of the flow because the vortices shed at the wing tips may easily produce the so-called "tail buffeting." The breakdown of the flow and the growth of the additive drag are so much more pronounced as this angle between wing and fuselage is sharper. Now these objectional features can be avoided by designing the wing root along well-defined lines, namely, by rounding out the angles between wing and fuselage in such a manner that the fillet radii increase rearward. The rounding-out or filleting process insures a gradual change from fuselage to wing and thereby removes the cause for the secondary flow. Figure 1 illustrates the discussed shape of wing root for a 45° angle between fuselage and wing. The shapes 1, 2, and 3 differ in fillet radii. Shape 4, designated as "false fillet," does not give the desired effect.

The failure of this false fillet is undoubtedly attributable to the fact that it causes an increase in pressure rise over the suction side of the wing within range of the wing root, since the section of the wing root discloses a poor airfoil with excessively great thickness. Consequently, it is not only necessary to suppress any possible secondary flow by gradual change from fuselage to wing but also to provide at the same time for adequate streamlining. This is assured on the wing roots with fillets of rearwardly increasing radii.

Meanwhile this method of filleting has also found application in practical airplane design (reference 2). There is, for example, the Northrop "Gamma" express mailplane (fig. 2)* which, with its size of fillet radii, based upon recent wind-tunnel data (reference 3), presents a further advance.

b) Wings with Cut-Outs

The second study, briefly referred to here, relates to measurements on wings with cut-outs made in 1929 (reference 4). This investigation is intimately connected with the problem of "wing with fuselage," because when considering "wing with fuselage" or "wing with cut-outs" simply as "wing with variable chord," the problem is, obviously, the same. Now in the report on wings with cut-outs (reference 4), it had been shown that on the basis of this concept it was possible to obtain "wing-bridge" designs, which prevent the otherwise occurring vitiation of the wing polars due to the cut-outs. By "wing bridge" is meant the narrowed portion of the wing connecting the unchanged wing halves.

The sections of the wing bridge had to be designed as satisfactory airfoils and so arranged as to preserve as closely as possible the lift distribution of the wing without cut-out section. This is the case for a certain c_a value, such as angle of incidence of the wing when the value $c_a t$ (t = wing chord) at any point of the wing bridge is the same as that of the original wing at the same point. Strictly speaking, this is obtainable only for one angle of attack of the wing; but if this is chosen high enough the change in the total polar will be entirely negligible. For high-speed airplanes flying at low c_a values, this optimum angle of attack may be chosen correspondingly lower.

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*Luftfahrt-Rundschau der Z.F.M., No. 8, 1933.

The choice of wing-bridge profile and the calculation of the particular angle of incidence for a certain angle of attack of the unchanged wing is very simple when proceeding from elliptical lift distribution because then the induced angle of attack over the span is invariable. The angle of setting of the profile of the original wing and any wing-bridge profile at the same point is then simply equal to the difference of the effective angles of attack pertaining to the c_a values for the profiles.

It is more difficult to define the lift distribution and the corresponding induced drag for the remaining angles of attack of the wing at which the lift distribution of the original wing is disturbed. However, there have been published some very valuable reports, especially of recent date, which permit a theoretical analysis of the total polars of wings with variable chord and variable profile without excessive paper work. For example, there is the fundamental treatise of I. Lotz, of 1931 (reference 5), which has already been applied in various cases (reference 6).

3. APPLICATION OF PREVIOUS RESULTS TO THE DESIGN OF FUSELAGE AND WING ROOTS

The more recent and largely experimental study , recounted hereinafter, contains a synthesis of the arguments upon which the older and just-mentioned reports had been based. According to the first report there should be a steady, smooth change-over from fuselage to wing. According to the second, the cross section at any point of the fuselage or the transition from fuselage to wing should be of such form and setting as to preserve the distribution of c_a t values of the "wing without fuselage."

The first requisite is readily met with a cut through wing and fuselage perpendicular to the direction of flow, such as shown in figure 3 for a mid-wing type monoplane. The only provision on the basis of the results of the first report is that the angle formed between fuselage and wing and the fillet radius be sufficiently great and increase rearward. The second requirement is, as already mentioned, readily tractable when considering the wing as effective line. But in the case of "wing with fuselage" this concept is only an approximation, even if very satisfactory, in contrast to the "wing with cut-out," because the wing-part "fuselage" can hardly be considered part of an effective line, owing to its great chord.

In order to avoid this difficulty, the design of fuselage shapes which were to assure a better fairing-in between fuselage and wing than that afforded from the theory of the effective line, we developed a simple semi-empirical method of approximation, which shall be discussed in a subsequent section.

4. DESCRIPTION OF MODELS DESIGNED
ACCORDING TO SECTION 3

An original fuselage-wing model designed according to the discussed simple method of calculation is shown in figure 4. The original wing has elliptical contour and $\lambda = 7.1$ aspect ratio. It is a Joukowski airfoil with parameters $\frac{d}{l} = 0.1$ and $\frac{f}{l} = 0.125$ (d = thickness, f = camber, $l = \frac{t}{2}$). Fuselage and wing root are also Joukowski airfoils. The thickness parameter was kept constant at 0.1, while camber and incidence of fuselage and wing-root airfoils were modified. The front view of fuselage and wing root reveals the absence of all corners, even on the fuselage. The profile chord follows from the constant thickness parameter.

With the provision that for equal c_a t value - we chose $c_a = 1.2$ - for "wing alone" and "wing with fuselage", the centers of pressure of all profiles lie on a straight line and assure a limitation of the model as seen from above, which about corresponds to the usual conditions of a "fuselage with wing", the camber parameters f/l and the angles of attack a_e were computed as function of the running span coordinate with the aid of the well-known test data on Joukowski airfoils (reference 7).

Figure 5 shows model No. 1. It is seen that the volume of the fuselage, except in the thick wing roots - which may, in fact, be partly figured in with the fuselage - is chiefly placed in the nose of the fuselage. This is due to the Joukowski type fairing of the fuselage. The side edges of the rear end are also noteworthy. In figure 6 these lateral fuselage edges have been removed. It will be noted that the ratio of cross-sectional area of fuselage to wing area equals 1:40. The wing section

It will be noted that the ratio of cross-sectional area of fuselage to wing area equals 1:40. The wing section covered by the fuselage section was not included in the cross-sectional area of the fuselage.

5. DESCRIPTION OF COMPARATIVE MODELS OF CONVENTIONAL DESIGN

Before discussing the results of the polar measurement a description of several comparative models is attempted. The first one is shown in figure 7. Its fuselage has the same volume as that of the previous one but was designed approximately according to the usual method albeit not employed in the design of gliders of the conventional type. The wing is the same as before. The fuselage is of square section and symmetrical in side view.

Figures 8 and 9 represent the fuselage with wing roots. In figure 9 the fuselage edges of the suction side of the wing have been hollowed out.

Figures 10 and 11 illustrate model No. 2: a parasol monoplane; that is, a wing-fuselage combination, considered as "standard type" for gliders until comparatively recently. The model was studied with and without fuselage "neck." The fuselage of elliptical section and contour has the same volume as the previous ones.

6. WIND-TUNNEL TESTS OF MODELS

DESCRIBED IN SECTIONS 4 AND 5

Figure 12 shows the polar of "wing alone" and the first models with fuselage faired smoothly in the wing (model No. 1). The noteworthy feature is that the polar of the wing-fuselage model No. 1 differs very little from that of "wing alone." The discrepancy is smallest within $c_a = 1.0$ to 1.2, that is, in the range of the desired equal lift distribution. A check revealed that the difference in drag of polar (1) and (2) for $c_a = 0.9$ to 1.3 exactly corresponded to the expected higher profile drag due to the increased surface; that is, it was apparently reduced to a minimum. Ostensibly there is a substantial, although gradual, increase in additive fuselage drag above $c_a = 1.3$.

Comparing the c_m curves, it is seen that the c_m curve of model No. 1 deviates with respect to that of "wing alone", and in particular that the c_m values of the wing-fuselage model are lower, which really should not occur, at least, within the range of $c_a = 1.2$. The cause must lie in the circulation around the fuselage, according to the observations made with streamers. It was noted that at the nose of the fuselage, at least at higher c_a values, the flow was upward as a result of the covered flow due to the presence of the wing, while at the rear end the flow was downward. And it was this observation that led to the design of the fuselage according to the second method of approximation described elsewhere. The graph also shows in dashes the polar of the same wing-fuselage model No. 1 without side edges of the fuselage portion aft of the wing, which, as is seen, has no particularly vitiating effect on the polar. This was to be expected since the rear end contributes little or nothing to the lift, so that the cutting away of the rear edges of the fuselage profiles effects no changes. But one direct result of the investigation is that in the design of the fuselage the nose and that part of it which receives the wing, are of greatest importance.

Figure 13 shows the polar diagram of "wing alone" of the first comparative model (mid-wing type with square fuselage) and of its modified "comparative model." The changes consisted, as previously stated, in hollowing out the fuselage edges on the suction side of the wing. The surprising fact following a study of the polar of the original comparative model is the relatively high additive fuselage drag and an almost direct right-handed bend of the polar at $c_a = 1.5$. The cause here lies in the low-wing effect. The modified type also shows this behavior, although to a lesser degree.

Figure 14 contains the polars of the second comparative model, together with the polar of the "wing alone." Here no substantial effect on the "wing alone" polar was anticipated because the low-lying fuselage hardly disturbs the flow. Accordingly, the polar of the "wing with fuselage" has the same shape as that of the "wing alone." There remained only a certain additive body drag which, within the mean range of the polar, has a minimum value. The $c_{a_{max}}$ value of the "wing alone" is almost exactly reached, especially when the fuselage "neck" is omitted.

Figure 15 is a compilation of additive body drag, ranging from 0.00125 for model No. 1 (mid-wing type with smooth fuselage fairing), to 0.0030 for the first comparative model (mid-wing type, square fuselage), and 0.00150 to 0.00200 for the second comparative model (parasol wing, elliptical fuselage). The mean values are:

Model No. 1,	0.00175
1st comparative model,	0.00400
2d comparative model,	0.00250

A comparison of model No. 1 with the parasol type is very interesting. It is found that the additive body drag of model No. 1 is only about 0.7 times that of the parasol wing. Of course, it should be remembered that, as seen in figure 15, on approaching $c_{a_{max}}$ the conditions are reversed; i.e., model No. 1 has a higher additive body drag and $c_{a_{max}}$ becomes smaller.

7. ADAPTING THE FUSELAGE TO THE AIR FLOW ROUND THE WING

Anent the discussion of the polar of model No. 1, it was pointed out that the moment coefficients of model No. 1, relative to "wing alone" were attributable to the curvilinear flow around the fuselage. This readily suggested fitting the fuselage to the curvilinear wing flow so as to assure the same moment curves and at the same time reduce the additive body drag. Our procedure in the design of such a wing-fuselage model was as follows:

First we plotted the streamline pattern for that c_a value at which the fuselage was to fit best to the flow by means of conformal transformation; that is, for two-dimensional flow. Then we calculated for the wing of infinite span the interference velocities in the plane of symmetry of the wing for points in front of the wing. These followed from a vortex system consisting of the two boundary vortices and their infinite extensions to the right and left of the wing. The flow pattern in front of the wing was corrected by means of the calculated values, and a corresponding correction for the flow aft of the wing was also effected; only for the latter the downwash due to the boundary vortices was not computed as it was accurately known from previous downwash investigations aft of elliptical wings.

The result was the flow pattern shown in figure 16. The manner of bending the profiles to the curvilinear flow is illustrated in figure 17.*

Figures 18 and 19 show the first thus-designed model, designated as No. 2. Figure 20 shows the differences between model fuselage No. 1 and No. 2. The polar of model No. 2 was measured repeatedly.

Figure 21 contains the diagram of the last measurement, together with that of "wing alone." The chief results of curving the fuselage were a very widely extended zone at $c_{a_{max}}$ and a somewhat higher $c_{a_{max}}$ than for the "wing alone." The lower point of separation of the polar has moved upward similar to that for markedly cambered airfoils. The moment curve shows that the moment coefficients of "wing alone" and model No. 2 coincide in the vicinity of $c_a = 1.2$.

The polar diagram further depicts the body drag coefficients of the first and second measurement of model No. 2. In the first measurement, where the fuselage was still new and therefore perfectly smooth, a small portion of the polar had approximately zero drag. Between the first and second measurements various modifications had been effected on the fuselage which may have raised its drag. On the average, we may count with a minimum drag of $c_{w_R} = 0.001$; that is, very little less than model No. 1.

8. COMPARISON BETWEEN HIGH WING, MID WING, AND LOW WING WITH FUSELAGE DESIGNED ACCORDING TO SECTIONS 3 AND 4

The question arose as to whether the obtained satisfactory approach of the wing-fuselage polar to that of the "wing alone" was limited to the mid-wing arrangement or whether it could be obtained equally well with the same satisfactory results to high- or low-wing arrangements.

Accordingly, a high-wing arrangement and a low-wing arrangement were investigated. In these the body lines were taken from the mid-wing arrangement but the form was

*The designs and calculations were made by Fritz Freytag, according to the data of the writer.

distorted up or down, respectively, until the suction side, or pressure side, became straight in the front view. In addition to the warping vertically there was a change in the camber of the longitudinal sections; the low-wing body sections were more heavily cambered to correspond with the more sharply bent flow over the suction side of the wing. The high-wing body sections were not cambered so much.

Figures 22-25 illustrate the high- and low-wing models, and figure 26, the polar diagrams of these models without windshield.

The low wing is distinctly superior from the point of view of additional body drag. On the other hand, this fact should not be stressed too much because the lower point of break-away of the low-wing polar lies equally higher. But the so-called low-wing effect is in any case definitely nonexistent, which at least proves that the polar of the low wing need not necessarily be inferior to that of the high wing.

9. EFFECT OF WINDSHIELD ON HIGH WING, MID WING, AND LOW WING (fig. 27)

The disturbance of the flow due to the windshield mounted at the same place is less on the low wing than on the high wing. And inasmuch as we must count on such disturbances on the fuselage in the form of fresh-air vents for the pilot, edges, and slots of the cockpit cowling, etc., it is readily seen that the low wing is superior to the high wing. This may be explained by the fact that such disturbances on the low wing are farther away from the wing and consequently not as effective.

This fact proves that the high or parasol wing, as generally employed in glider design, is certainly not eligible to be called the "standard type." On the contrary, it may be assumed that in the future we shall see mid-wing and low-wing type gliders which are just as legitimate.

10. EFFECT OF A STEP ON THE UPPER SIDE OF THE FUSELAGE ON A MID WING

The visibility in a mid wing and low wing of the shown designs is perfectly satisfactory, especially when the pilot sits in front of the wing. But in order to ascertain whether visibility could still further be improved without vitiating the polar, we studied the effect of a break or step on the top of the fuselage of the mid wing (figs. 28 and 29). It was found to be altogether negligible.

11. DESIGN OF A GLIDER WITH AERODYNAMICALLY AND STATICALLY BENEFICIAL WING-BODY FILLETS

In conclusion, we submit a preliminary glider design with the described type of fillets (fig. 30); that is, of a trapezoidal mid wing with greatly increased chord near the fuselage. The roughly computed sinking speed of this aircraft is, to be sure, not much lower than with the parasol type of identical span and weight because the polars of both correspond approximately to that of the "wing alone." But it should be remembered that because of its great wing-root spar heights and the absence of the "neck" the mid-wing type can be built easier and consequently stronger.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

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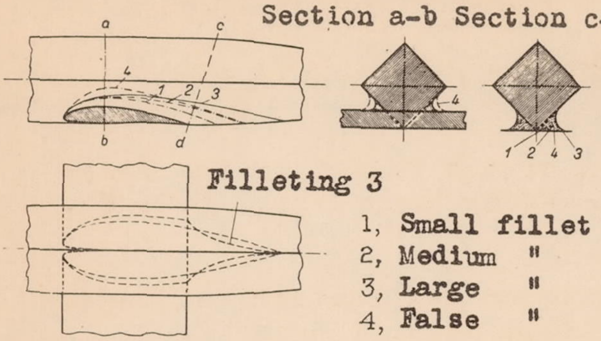


Figure 1.-Wing root with sharp angle between fuselage sides and plane of wing.

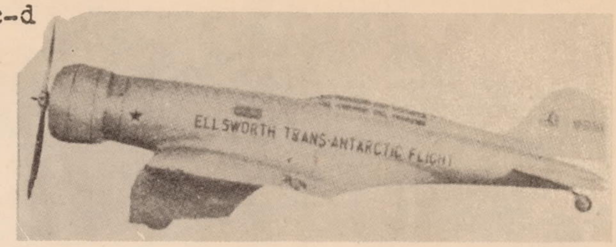


Figure 2.-Northrop-Gamma air express with wing-root design according to fig. 1 .

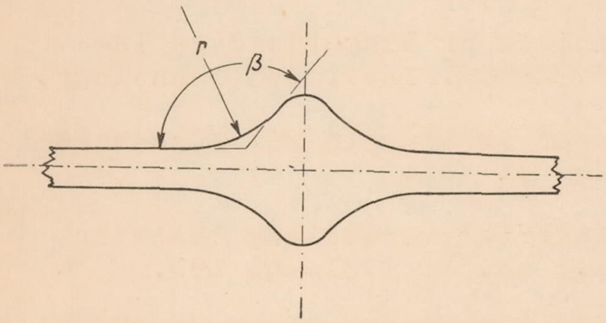


Figure 3.-Front view of aerodynamically beneficial filleting.

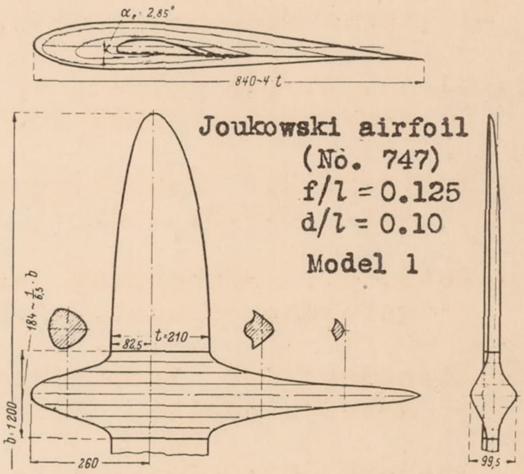


Figure 4.-Wing and fuselage with fuselage faired smoothly into the wing. (Model no.1)

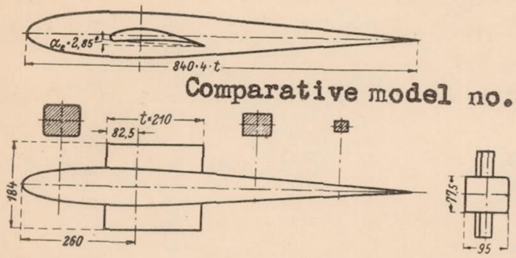


Figure 7.-Comparative model:wing with square fuselage (mid-wing type).

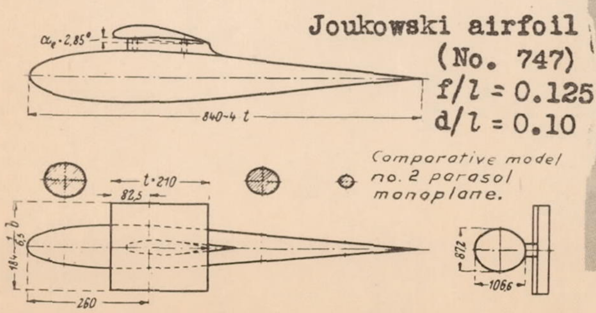


Figure 10.-Comparative model no.2 ; parasol type.

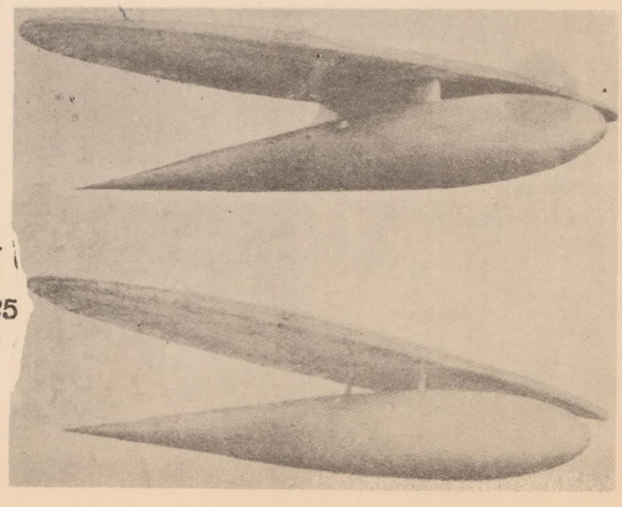


Figure 11.-Three-quarter front view of parasol model with and without "neck".

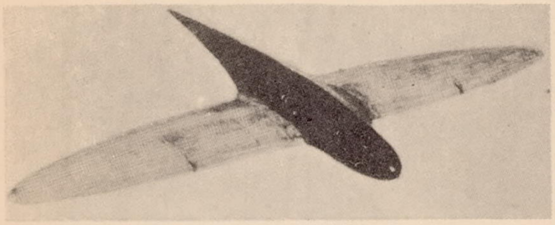


Figure 5.-Three-quarter front view of model no.1 .

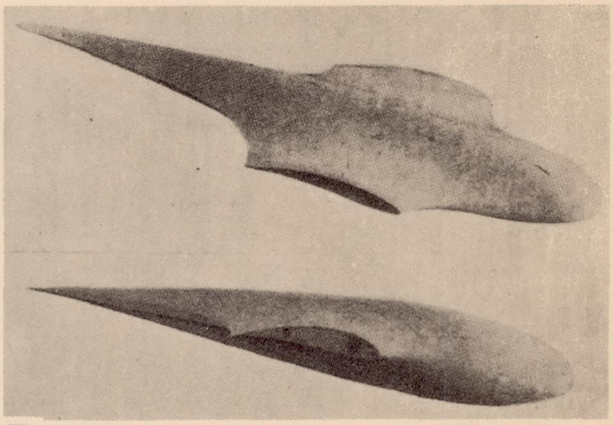


Figure 6.-Three-quarter front view of fuselage with wing roots of model no.1(side edges of fuselage removed).

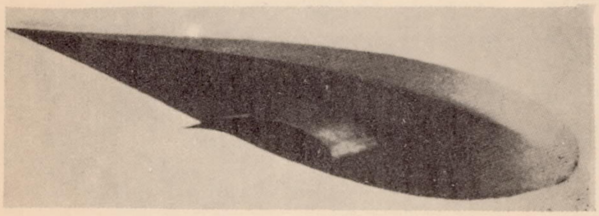


Figure 8.-Wing roots and fuselage of comparative model no. 1.

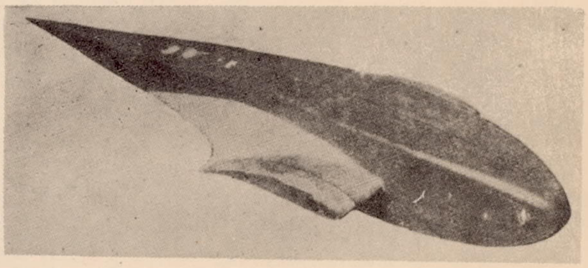


Figure 9.-Wing roots and fuselage of comparative model no. 1 with filleting.

Figure 19.-Side view of model no.2 .

Figure 23.-Fuselage and wing root of low-wing model with wind shield.

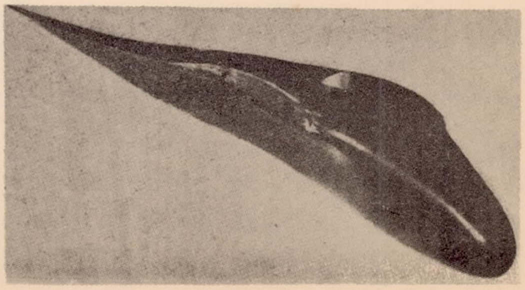


Figure 25.-Fuselage and wing root of high-wing model with windshield.

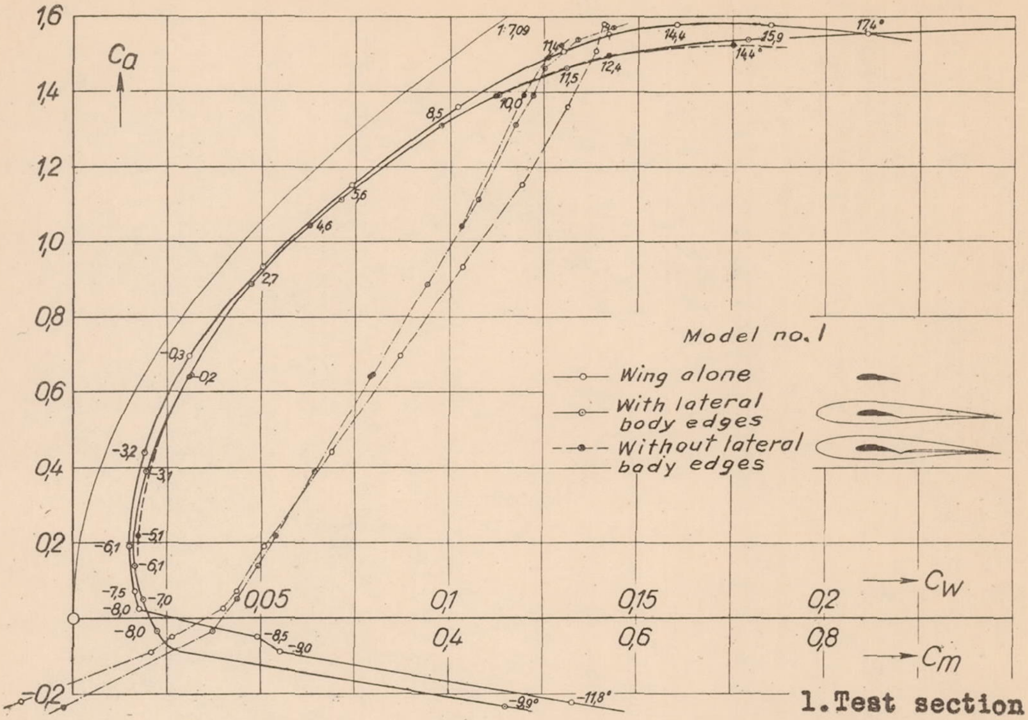


Figure 12.-Polar diagram of "wing alone" and of model no.1 .

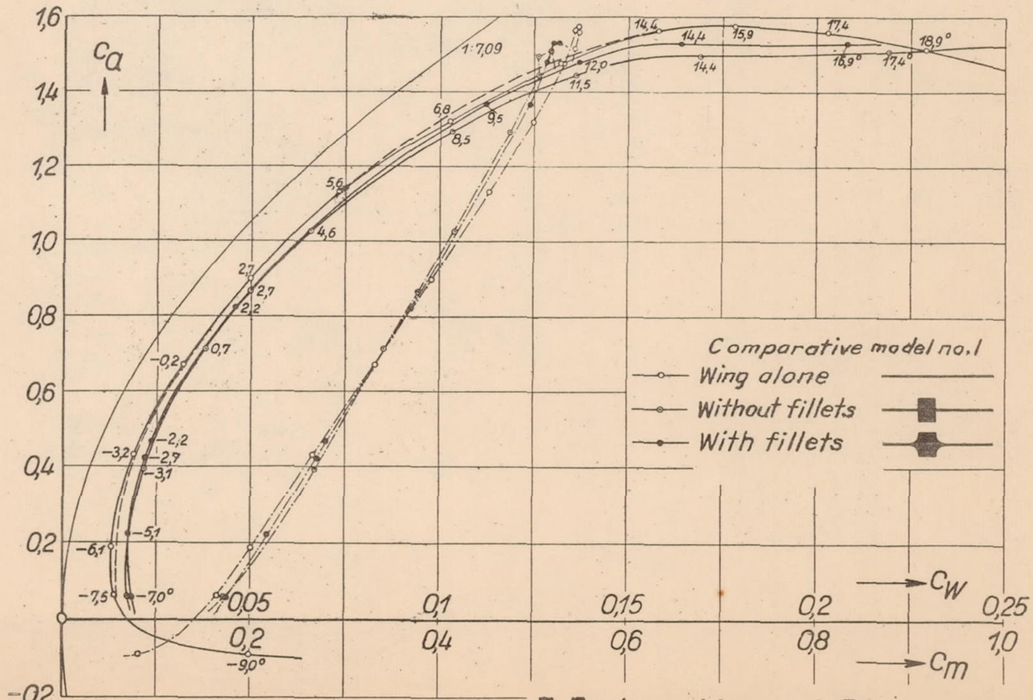


Figure 13.-Polar diagram of "wing alone" and of comparative model no.1 .

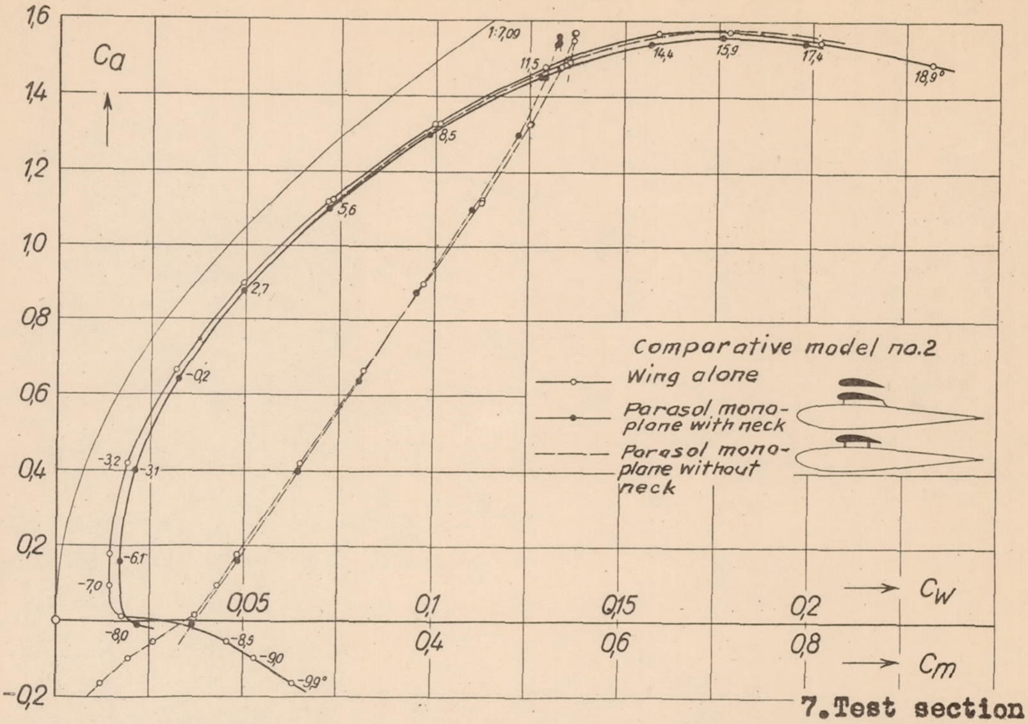


Figure 14.-Polar diagram of "wing alone" and of comparative model no.2 .

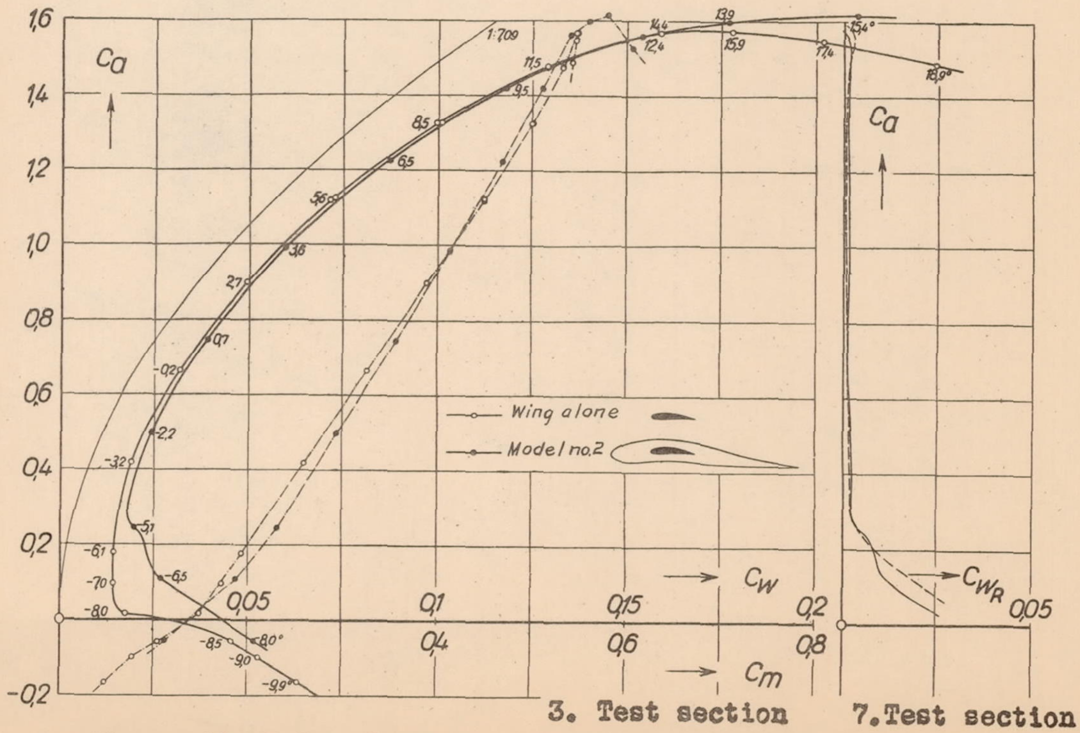
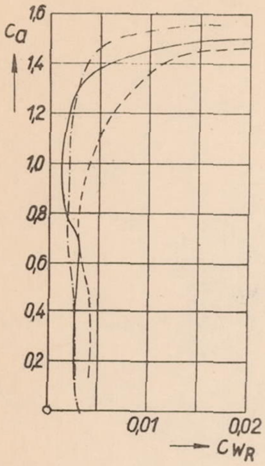


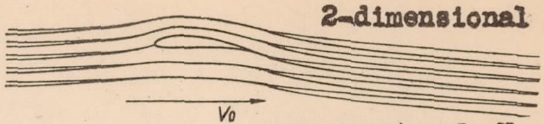
Figure 21.-Polar diagram of "wing alone"and model no. 2.



——— Model I
— — —1, Comparative model 1 (Square body)
-·-·-·-2, Comparative model 2 (Parasol monoplane)

Figure 15.- Body drag coefficients of model no.1 and comparative models nos.1 and 2 .

2-dimensional flow



3-dimensional flow

Figure 16.-Flow around wing in two and three dimensional flow.

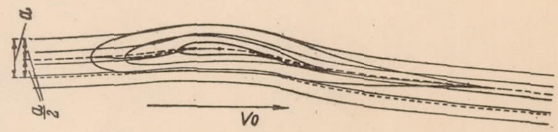
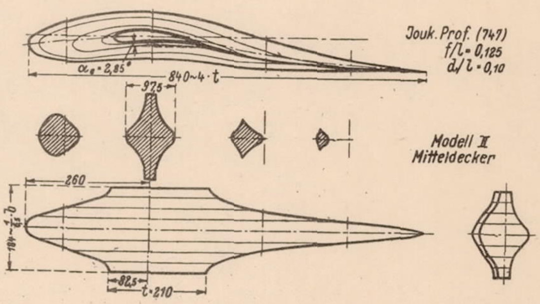


Figure 17.-Adaptation of fuselage to flow around wing.



Joukowski airfoil (No. 747)
$f/l = 0.125$
$d/l = 0.10$

Model no. 2 mid-wing monoplane.

Figure 18.-Wing and fuselage of model no. 2.

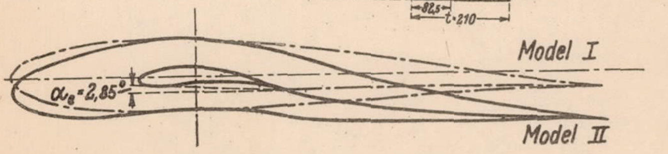
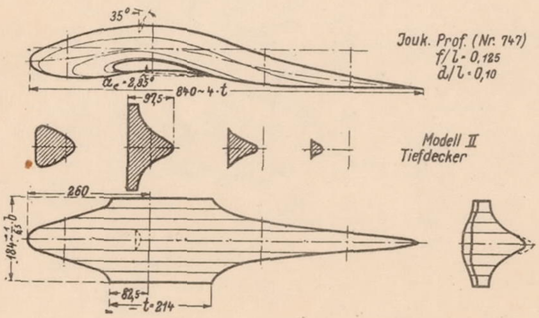


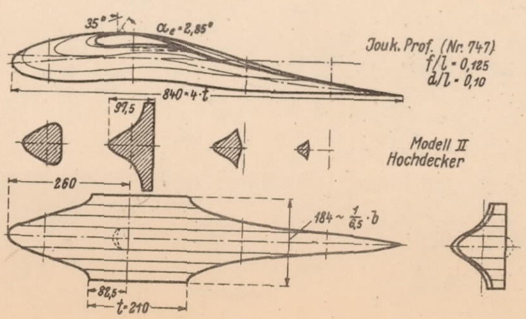
Figure 20.-Comparison of bodies of models no.1 and 2 .



Joukowski airfoil (No.747)
$f/l = 0.125$
$d/l = 0.10$

Model no.2 low-wing monoplane.

Figure 22.-Low-wing type.



Joukowski airfoil (No.747)
$f/l = 0.125$
$d/l = 0.10$

Model no.2 high-wing monoplane.

Figure 24.-High-wing.

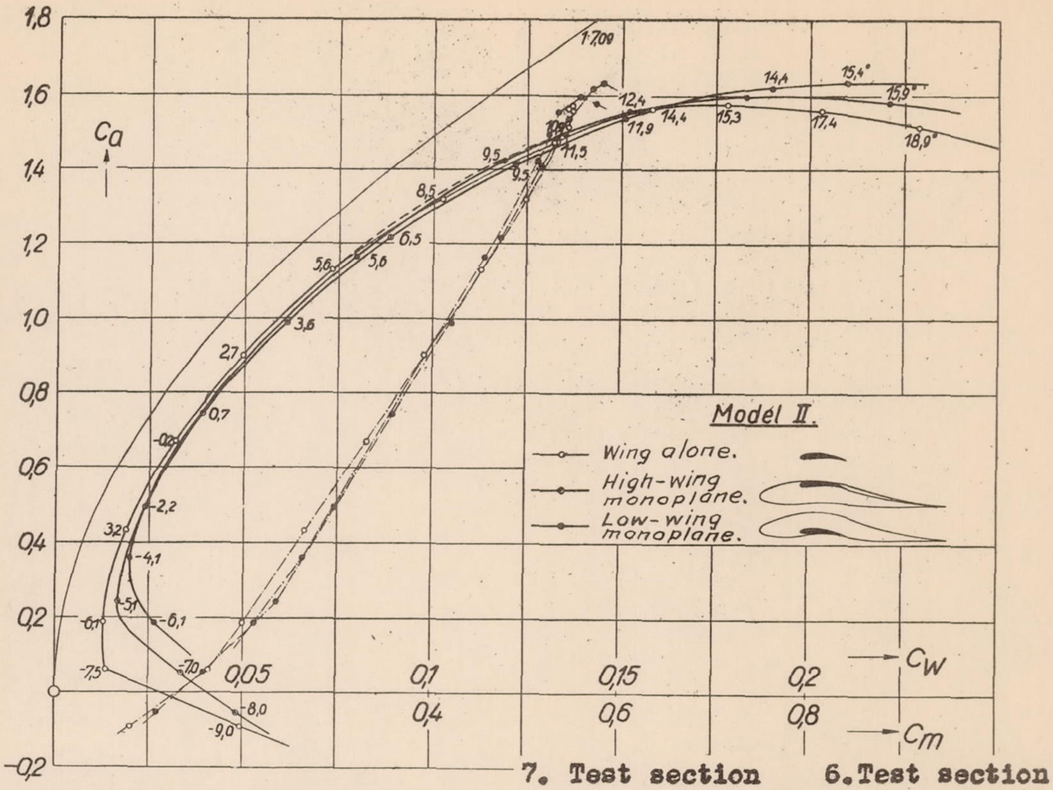


Figure 26.-Polar diagrams of "wing alone" and of high and low wing.

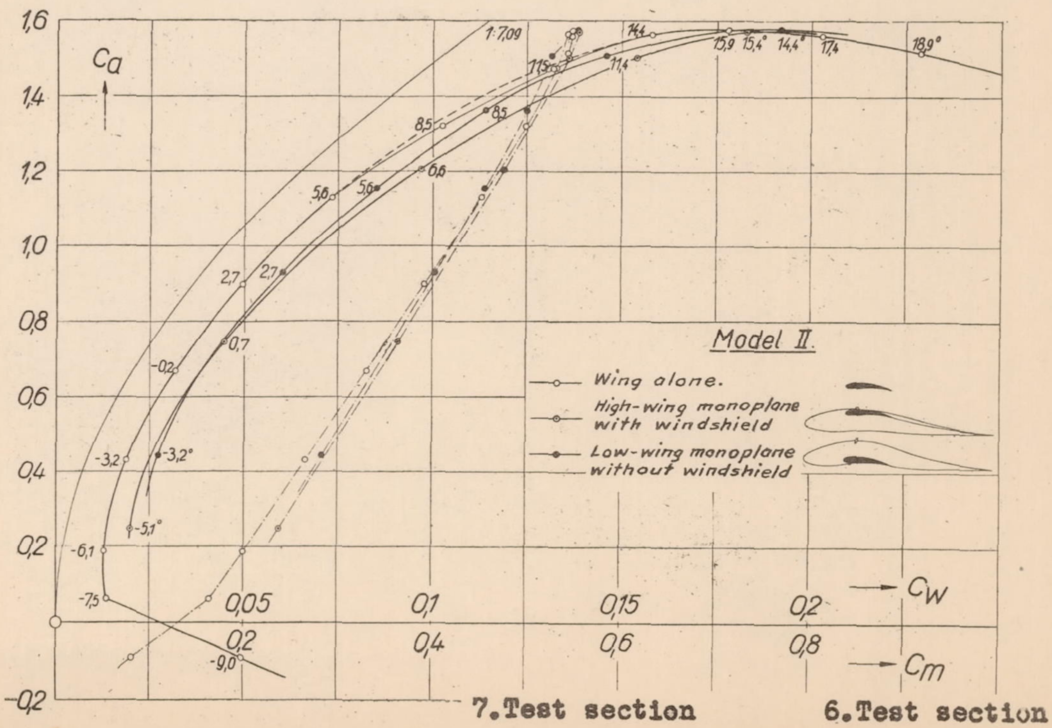


Figure 27.-Polar diagrams of "wing alone" and high and low wing with windshield.

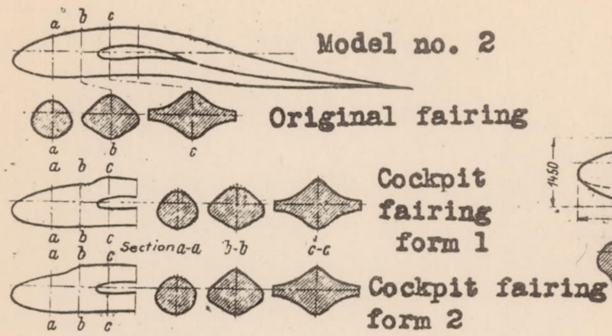


Figure 28.-Model no.2 with cockpit fairing.

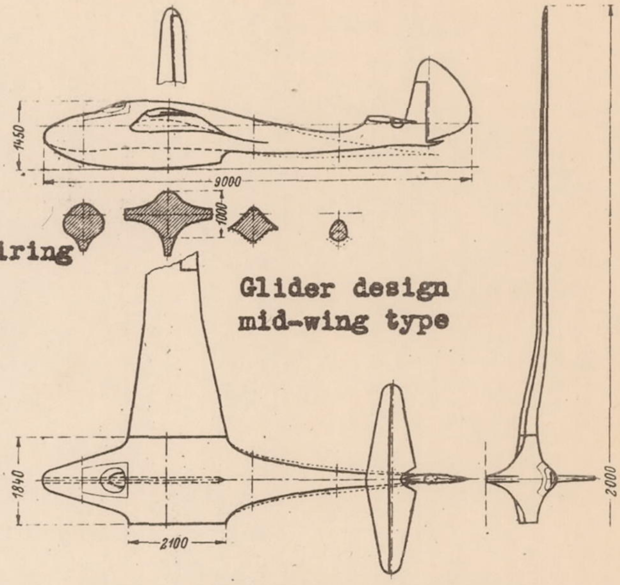


Figure 30.-Design of glider (mid-wing type) with fuselage adapted to flow around the wing.

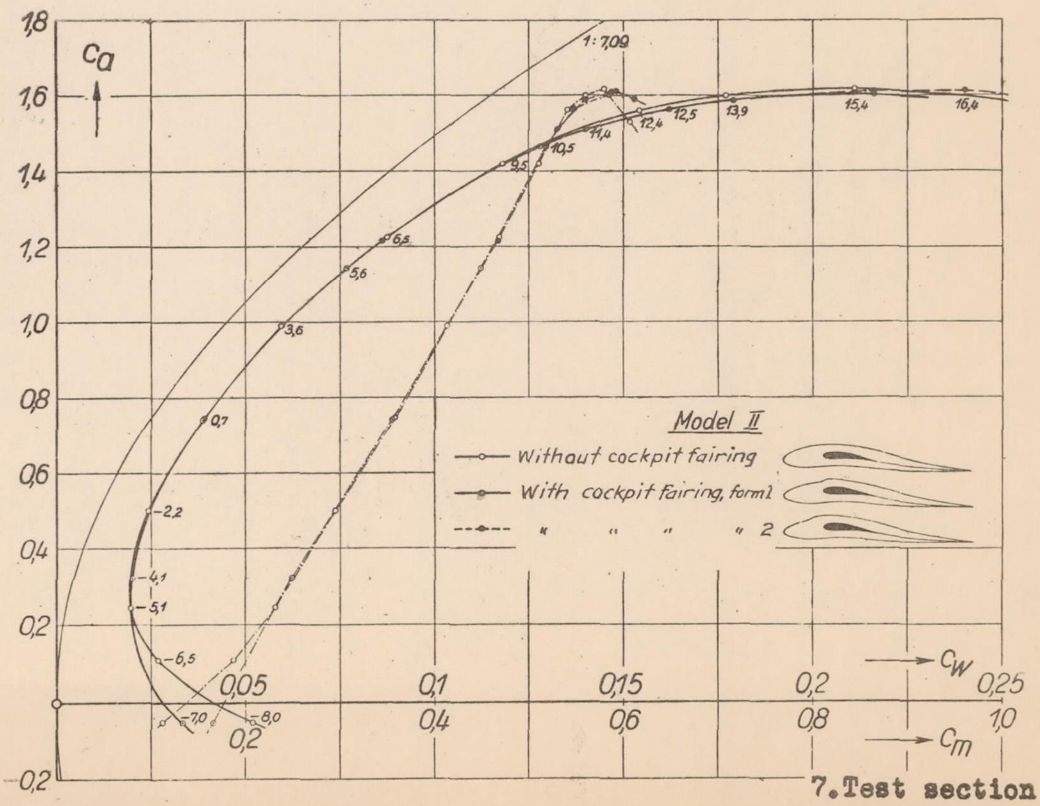


Figure 29.-Polar diagrams of model no. 2 with and without cockpit fairings.