TRANSACTIONS

of The American Society of Mechanical Engineers

JANUARY, 1934

VOL. 56, NO. 1

Published by **The American Society of Mechanical Engineers**
29 West Thirty-Ninth Street, New York, N. Y.

TRANSACTIONS

of The American Society of Mechanical Engineers

Published on the tenth of each month

Publication Office, 20th and Northampton Streets, Easton, Pa.
Editorial Department at the Headquarters of the Society, 29 West Thirty-Ninth Street, New York, N. Y.

Includes Applied Mechanics and Aeronautical Engineering

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Entered as second-class matter March 2, 1928, at the Post Office at Easton, Pa., under the Act of August 24, 1912. Price $1.50 a copy, $12.00 a year; to members and affiliates, $1.00 a copy, $7.50 a year. Changes of address must be received two weeks before they are to be effective on our mailing list. Please send old, as well as new, address.

Effect of Fillets on Wing-Fuselage Interference

By A. L. KLEIN,[1] PASADENA, CALIF.

Mutual interference of wing and fuselage has been the subject of many previous investigations, but these have been on a very small scale. A comprehensive investigation into the case of a low-wing monoplane was thought to have important possibilities, especially as this type of airplane was known to have some aerodynamical peculiarities. In a preceding investigation it had been found that the addition of large fillets to the intersection of wing and fuselage would cause a great improvement and it was decided to extend these tests and to include the case of a high-wing monoplane for comparison.

NUMEROUS investigations have been made on the mutual interference of wings and fuselages, but much of the preceding work has been done on a very small scale (ref. 1).[2] It was thought that a comprehensive investigation into the case of the low-wing monoplane might be of importance, especially as this type of airplane was known to have some aerodynamical peculiarities. In a preceding investigation it had been found that the addition of large fillets to the wing-fuselage intersection would cause a great improvement; it was therefore decided to extend these tests and to include the case of the high-wing monoplane for comparison.

The model used for the investigation was a $^1/_6$-scale model of the Northrop "Alpha," a Wasp-engined transport plane of approximately 5000 lb gross weight. The model had a span of 7 ft and a length of 52 in. The airfoil section was 18 per cent Clark-Y at the root and 12 per cent at the tip. The wing area of the model was 8.33 sq ft, and the root chord of the wing was 16.67 in. The wing was mounted with reference to the fuselage as shown in Fig. 5. The model as used consisted of a wing and fuselage only. This model was presented to the laboratory by the Northrop Aircraft Corporation, a unit of United Aircraft and Transport Company.

Experimental Methods

The investigation was carried on by two distinct methods. The set-up for force measurements was identical with that described in ref. 2, while in addition three combs of pitot tubes were mounted behind the model for exploration of the wake behind the wing. These combs can be seen in Fig. 1, and also some of the pitot tubes can be seen in Figs. 6 and 7. The total pressure orifices were made of $^1/_8$-in. brass tubing mounted on a steel tube. For static-pressure measurements, jackets containing side orifices were slipped over the total-pressure tubes. These tubes were connected to the multiple manometer, and observations were made of the wake distribution behind the set-up for various angles of attack. Records of the wake observations were made by taking shadowgraphs of the manometer on ozalid paper. These records were then reduced by plotting curves showing the loss of total head as percentage of the total head in the free stream. Figs. 2, 3, and 10 show curves of this type, and also show the relative position of the model and the combs. The position of the stabilizer and elevator for each angle of attack is indicated on the curves. The fillets used in the investigation were built up from physicists' soft wax, a compound of beeswax, Venice turpentine, and rosin, and modeled to templets. It was found that an almost glasslike surface could be given this wax by rubbing it with sandpaper dipped in kerosene.

Wake Observations

Fig. 2 shows the wake losses behind the wing tested alone. Noting first the wake losses in row 1, it is seen that as the angle of attack increases, the center of the wake moves downward, as one would expect. When the wing reaches an angle of attack of 15 deg, the center of the wake has reached its lowest point, near which it remains until the angle increases to 16.5 deg, after which the wake moves noticeably upward. If one now looks at the force-measurement curves for the wing alone (Fig. 8), one sees that the angle for maximum lift is 16.5 deg. In row 2 the behavior is similar to row 1; the downwash causes the wake to go downward until the angle of maximum lift is reached, after which the wake moves upward. In the case of row 3 an anomaly occurs; the downwash does not reach the maximum value at 16.5 deg, but continues to increase, and apparently stalling does not occur at this section of the wing until an angle of attack of approximately 20.5 deg is reached. The wake curves for small angles in rows 2 and 3 are omitted because the wake was smaller than the distance between the pitot tubes, so that no deductions could be drawn as to its magnitude and shape.

Below on the same figure is a similar set of observations for the model assembled as a low-wing monoplane with no fillet at the intersection between the wing and the fuselage. The maximum diameter of the fuselage was 9.5 in. Pitot comb 1 was mounted approximately halfway betweem comb 2 and the wing tip. The positions of the stabilizer and elevator are drawn in on the successive curves. It will be noticed that the wake curves for row 1 differ completely from those for the wing alone, while the wake curves in rows 2 and 3 are hardly distinguishable from those for the wing alone. The wake curves in row 1 are not only larger in area than those for the wing alone, but also the position of their center line indicates a much smaller downwash. It will be noticed that the center line of the wake never goes below the chord line, while for the case of the wing alone the center of the wake moves down below the chord line at small angles and remains there. These two conditions represent the limiting cases of the present investigation, the wing alone giving the condition for zero interference and the wing and fuselage with no fillet the case of maximum interference.

Now consider the case of a fillet that partly remedies the interference effect. Fig. 3 shows the wake distribution for what will be called the "wrong fillet." Fig. 4 is a photograph of this fillet, and its lines are shown in Fig. 5. In the case of the "wrong fillet," the wake curves in row 1 are similar to those for the wing alone up to an angle of 6 deg, but at and above an angle of 9 deg the wakes

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[2] See list of references at end of paper.

Contributed by the Aeronautic Division and presented at the Pacific Coast Aeronautics Meeting, Berkeley, Calif., June 9 and 10, 1932, of The American Society of Mechanical Engineers.

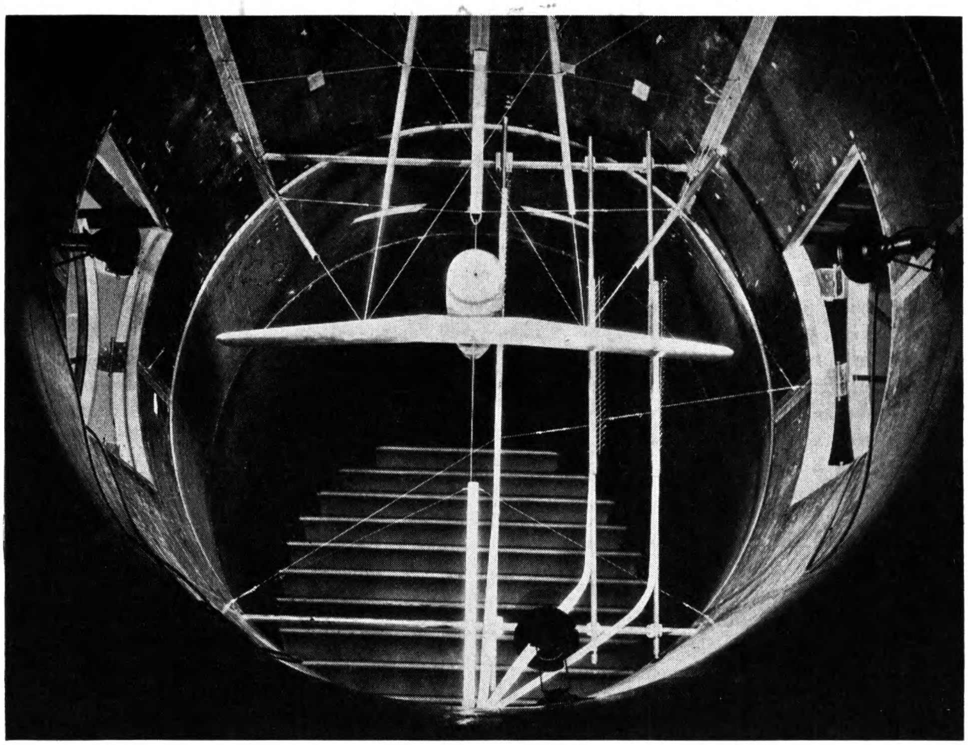

FIG. 1 VIEW OF MODEL AS A HIGH-WING MONOPLANE IN THE TUNNEL
(The three pitot-tube combs can be seen in the background.)

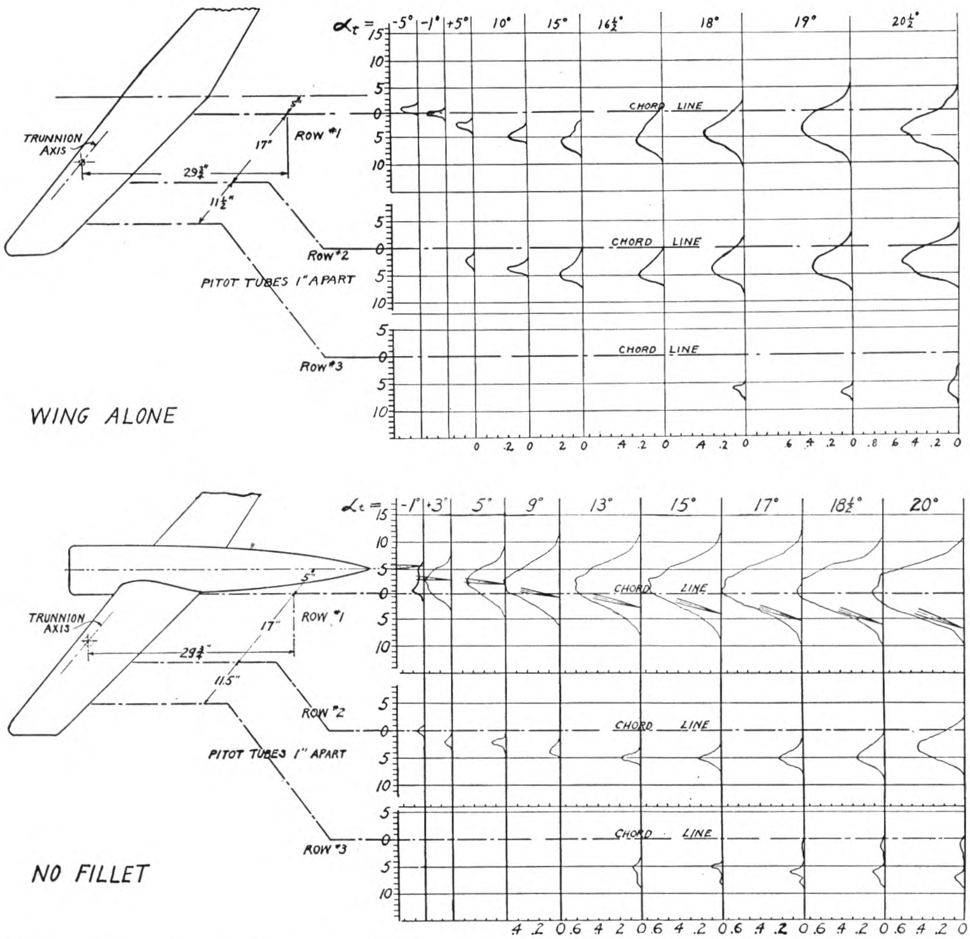

FIG. 2 WAKE DISTRIBUTION BEHIND THE WING ALONE AND THE WING AND FUSELAGE WITH NO FILLET
(The area between the vertical lines represents the energy lost.)

in this row are similar to those for the wing and fuselage with no fillet. The fact that this behavior is not observed at rows 2 and 3 indicates once more that the effect is largely localized in the region of the intersection of wing and fuselage. The force-measurement curves (Fig. 8) discussed later show that at the angle of 7 deg something happens to the flow. The change in the flow pattern from the wing-alone type to the no-fillet type is completely discontinuous. An observer watching the multiple manometer when the model is set at this critical angle sees either one pattern or the other, and the change from one to the other is sudden and complete. At this angle the manometer is in a very unsteady condition. The smaller flow pattern for the downwash and the larger for the trailing vortex replace each other rapidly on the tubes. There are no intermediate stable states; either the manometer is showing one pattern or the other, or it is changing rapidly. The method of watching the multiple manometer for the change in pattern was found to be extremely sensitive, as improvements could be made and the critical angle checked visually with an accuracy of $^1/_4$ deg. This made an exceedingly rapid method of observing the effect of modifications, as no computations were necessary, and all that was needed was to start the tunnel and to run the model through a range of angles of attack. The critical angles obtained in this manner checked very accurately with the breaks in the polar, lift, and moment curves. Fig. 3 shows the wake curves for a fillet of the optimum type. The critical angle in this case was 15.7 deg. The lines of this fillet are shown in Fig. 5, and it is illustrated in Fig. 7.

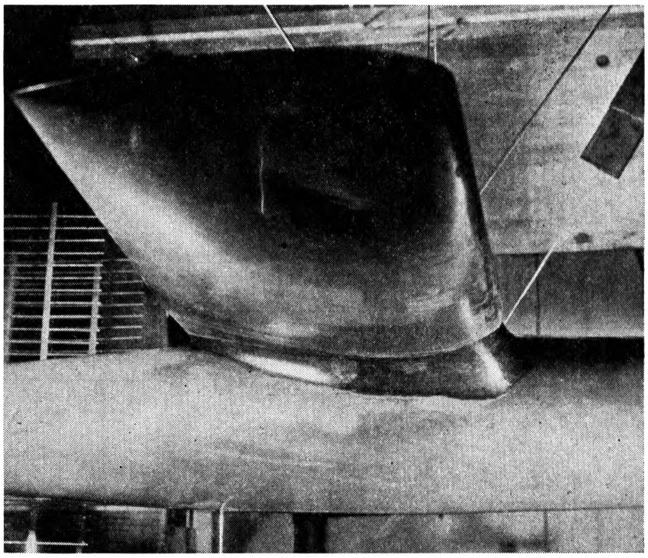

Fig. 4 The Wrong Fillet No. 2
(Note that the model is inverted and the pitot tubes can be seen in the background.)

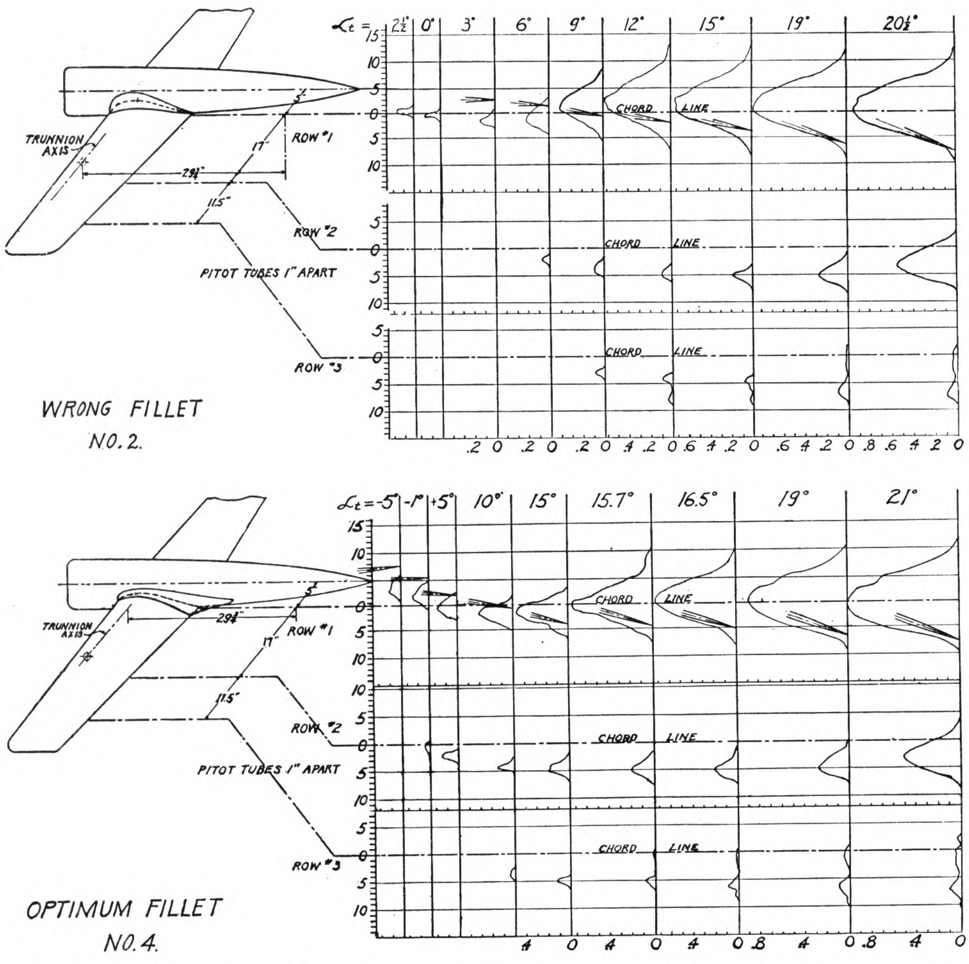

Fig. 3 Wake Distribution Behind Fillet No. 2 (Wrong Fillet) and Optimum Fillet No. 4

Force Measurements

The force measurements were made with the normal three-component set-up. The tests were run at a water head of 39.24 cm, and as the root chord of the model was 42.35 cm, the Reynolds number for the tests was approximately 2,100,000. The accuracy of the tests can be judged from the points shown on the enlarged section of the polar (Fig. 14). It is not believed that variations in the maximum-lift coefficient of the order of 2 or 3 per cent are of any significance, as it was found that almost imperceptible changes in the surface condition of the model would cause this much variation. This variation is in line with that found by the N.A.C.A. in large-scale tests (ref. 3).

Before beginning the investigation on the effect of fillets, lift, drag, and pitching moment, tests were run of the wing alone. These results furnish a convenient basis for the subsequent discussion.

Normal Low-Wing Configuration

Results of three component tests on the normal low-wing arrangement are shown in Fig. 8. Considering the curves in the case of no fillet, it is observed that at a C_L of 0.6 the polar starts breaking over sharply, the C_L against α-curve

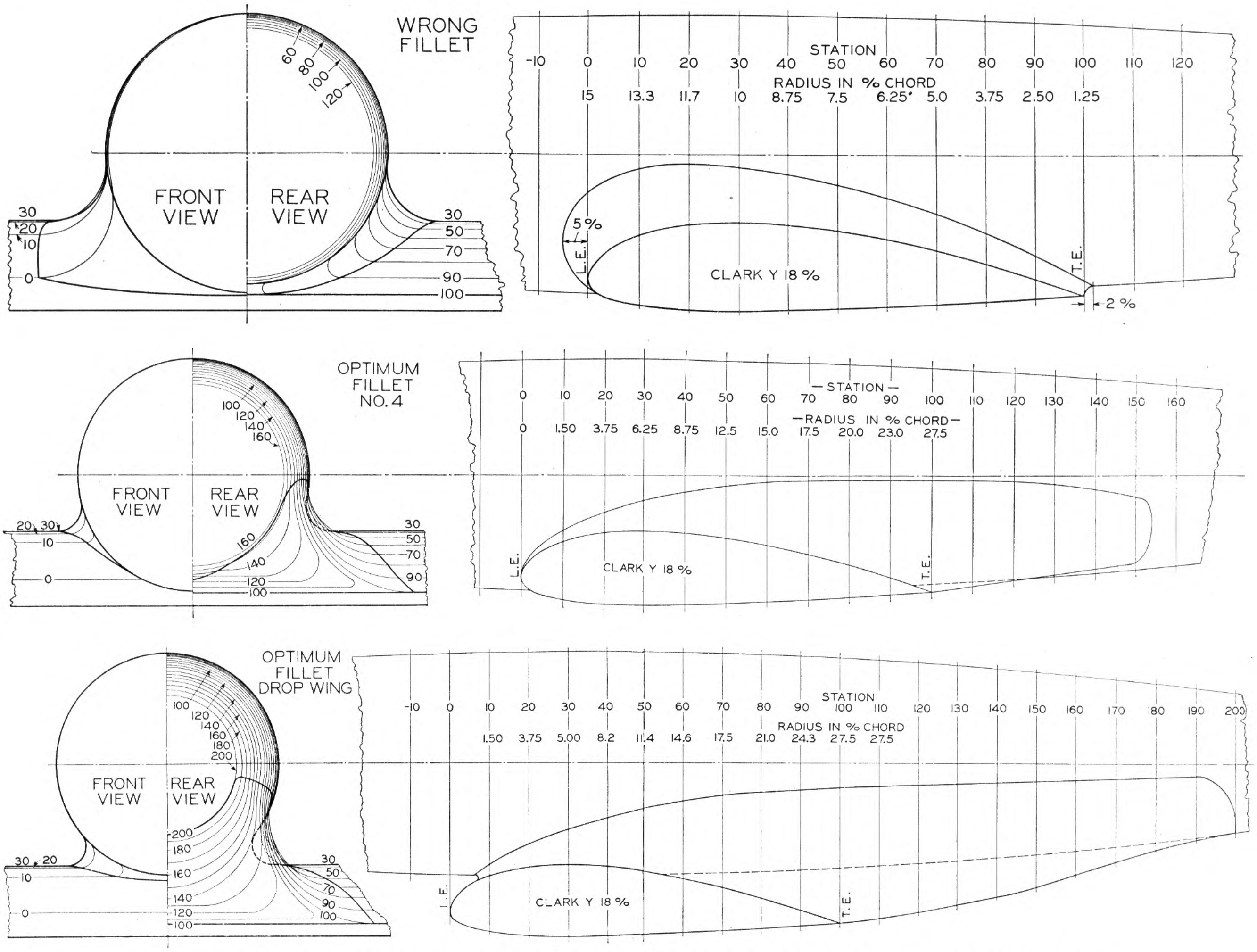

Fig. 5 Lines of the Wrong Fillet No. 2, Optimum Fillet No. 4, and Fillet *D* of the Dropped Wing

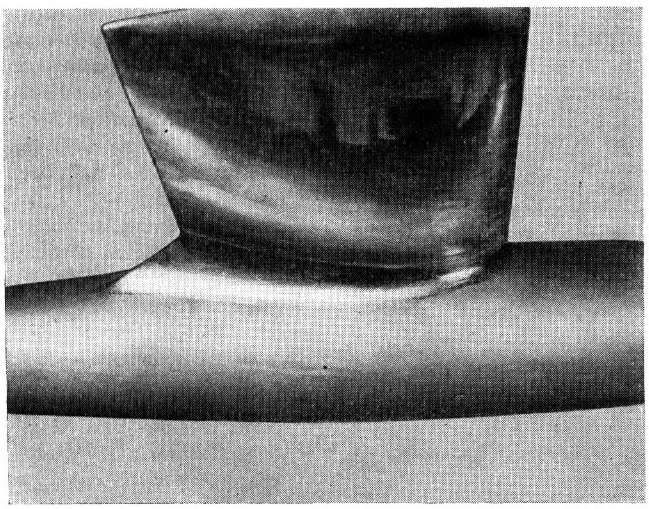

Fig. 6 Fillet No. 3

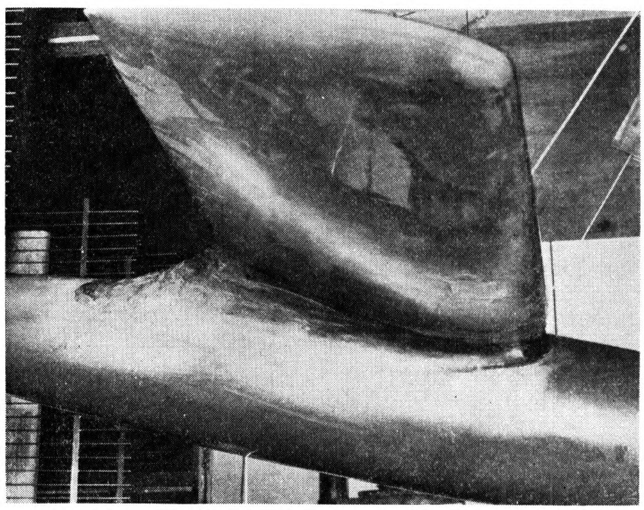

Fig. 7 Wrong Fillet No. 4

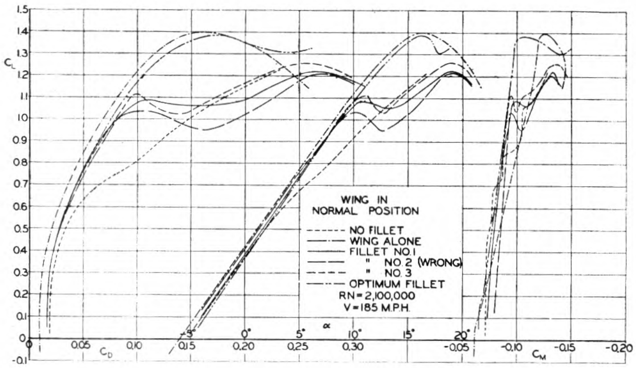

FIG. 8 NORMAL LOW-WING CONFIGURATION

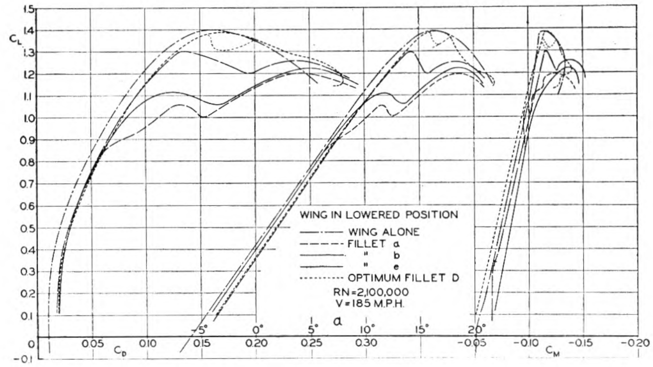

FIG. 9 DROPPED-WING CONFIGURATION

takes up a new slope, and the moment curve becomes irregular. Now referring to the wake-loss diagrams, it is seen that for an angle of 5 deg the downwash is much smaller for the wing and fuselage than for the wing alone. The wing-alone polar parallels the induced-drag parabola (aspect ratio 5.97). The polar curve of the wing-fuselage arrangement parallels the wing-only polar up to a C_L of 0.45, and then starts deviating from it. If one attempts to fit an induced-drag polar to this curve in the region from a lift coefficient of 1.0 to 1.2, one needs an aspect ratio of approximately 2.5, or somewhat less than one-half the aspect ratio of the complete wing. This leads one to suspect that the wing is acting as two monoplanes separated by the fuselage and that there is a trailing vortex on each side of the fuselage. The wake diagrams lead one to the same conclusion, as from them one sees that the downwash is practically the same at rows 2 and 3 as for the wing alone, while in row 1 the downwash has practically disappeared for all positive angles. It will then be assumed as a working hypothesis that the foregoing is correct and that the interference corresponds to the breaking up of the horseshoe lifting vortex into two side-by-side horseshoe vortices.

This aerodynamic picture enables one to account for the peculiar shapes of the various curves, and also shows why the minimum drag is not subject to much improvement.

Three fillets were then tested to determine the best type. These fillets all had a radius of 15 per cent of the root chord. Fillet 1 was a uniform fillet of this radius throughout. Fillet 2 (wrong) had a 15 per cent radius at the nose and tapered aft; its lines are shown in Fig. 5. Fillet 3 had a small nose and a radius of 15 per cent at the trailing edge, and was of the same type as the optimum fillet shown in Fig. 5. A photograph of fillet 3 is shown in Fig. 6. All three of these fillets were a marked improvement over the unfilleted condition, fillet 3 having the greatest maximum lift and the greatest slope of its lift curve. As all of these fillets were a great improvement over no fillet, an elaborate program was undertaken to develop fillets of various types. It soon appeared that fillets 1 and 2 could not be much improved, while fillet 3 could be developed with considerable success. Numerous variations of this type were constructed, and the following rules were deduced from the tests:

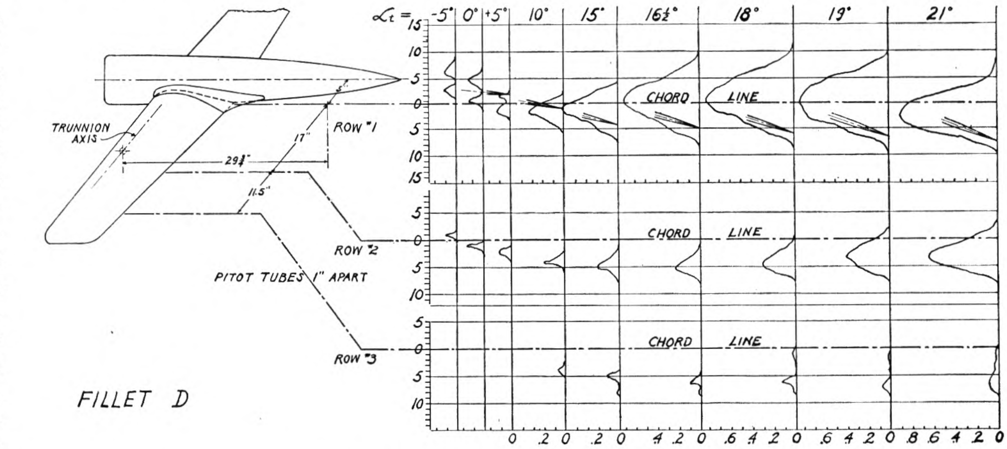

FIG. 10 WAKE DIAGRAM FOR OPTIMUM FILLET D

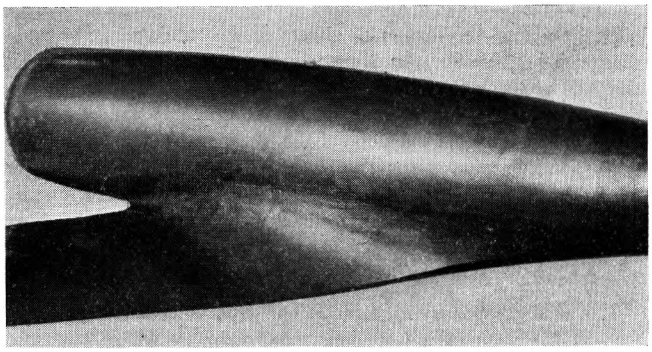

FIG. 11 OPTIMUM FILLET D (WING LOWERED)

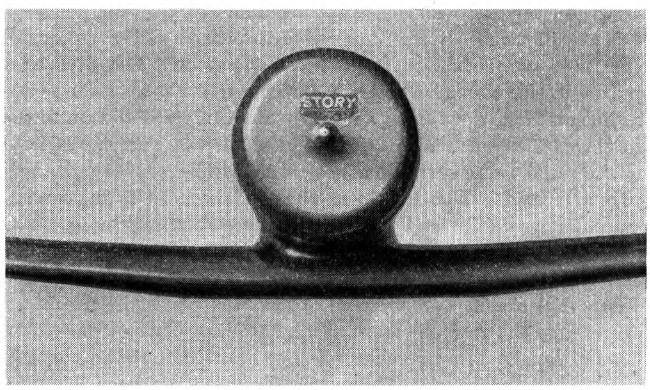

FIG. 12 OPTIMUM FILLET D (WING LOWERED)

1 Increasing the trailing-edge radius improves the maximum lift and prevents induced-drag losses at medium-lift coefficients; excessive trailing-edge radii increase the drag
2 Increasing the radius at the nose increases the drag and decreases the maximum lift
3 The fillet should taper as uniformly as possible from the nose to the trailing edge, and its maximum size should be as close to the trailing edge as possible
4 The fillet should be washed out smoothly to the fuselage.

Fillet 4 is an optimum design of this type. Maximum lift has been sacrificed for low drag, and it will be noticed that there is only a trace of the former ill effects of the fuselage. The wake diagrams for this fillet are shown in Fig. 3, and it will be noticed that the break in the downwash does not occur until over 15 deg, while in fillet 3 the break occurred at 10 deg. It will be noticed also that with fillet 4 the slope of the lift curve is steeper than the corresponding curves for the wing alone. This effect can be easily explained, as in this case the fuselage contributes some lift, and the coefficients are calculated neglecting this effect.

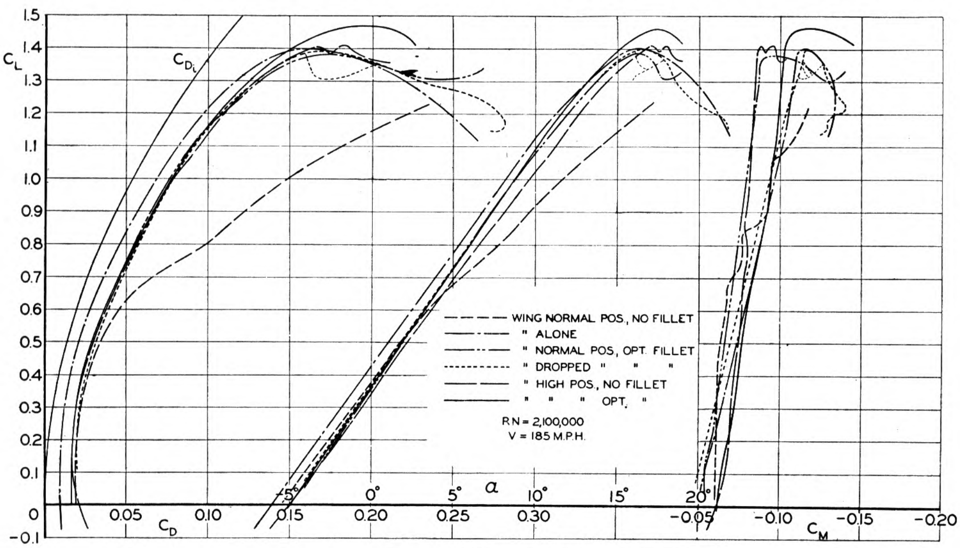

Fig. 13 Curves for Various Configurations

Low-Wing Configuration, Wing Lowered

It was suggested by an aircraft constructor that an investigation of the case of a low-wing monoplane in which the wing passes entirely below the cabin floor would be of great interest. Accordingly, a block 2 in. thick was made and placed between the wing and the fuselage. This corresponded to lowering the wing 1 ft at full scale. It was impossible to take any observations of the unfilleted condition for this arrangement. The first fillet put on in this configuration had a 20 per cent chord trailing-edge radius and had the nose of the wing faired forward and up to the fuselage. The results are plotted as fillet *a* in Fig. 9. Fillet *b* in the same figure corresponds to a similar fillet with the leading edge cut back. The fillet was then enlarged to 27.5 per cent trailing-edge radius and the nose was undercut still more. The lines of this fillet *D* are given in Fig. 5. Fillet *D* was found to be the optimum for this configuration. Fillet *e* was an endeavor to secure still greater improvement. The fillet was hollowed out by decreasing the radii in front of the trailing edge of the wing. This hoped-for improvement was not realized, but the curve is included in the figure. The curves for case *D* and for the wing alone illustrate how perfectly the pernicious effect of the wing-fuselage intersection can be eliminated; it will be noticed on the polar that the profile drag is practically independent of the lift coefficient. It was found that, as in the case of the normal low-wing configuration, the radius at the nose should be a minimum.

High-Wing Configuration

The model was next arranged as a high-wing airplane, the wing being mounted so that it had the same angle of incidence as in the case of the low wing and so that its trailing edge was just touching the fuselage. The curves for the high wing with no fillet and high wing with fillets are shown in Fig. 13. The fillet had quite a large trailing-edge radius (20 per cent) and was of the tapered type. The lift obtained with this fillet was the highest found, but was associated with a slight increase in drag. Fillets of intermediate radius and of various types, large at the front, small at the rear, constant radii, etc., caused very little change. The curves for intermediate radii, and in fact for all of the other variations, lie between the two curves mentioned. The most remarkable point in this group is the behavior of the polar of the no-fillet case in the vicinity of zero lift. It will be noticed that this curve departs markedly from the wing-only polar in the same manner, for negative angles, as does the low-wing no-filet polar at small positive angles. This illustrates the extreme sensitivity of the suction side of the wing.

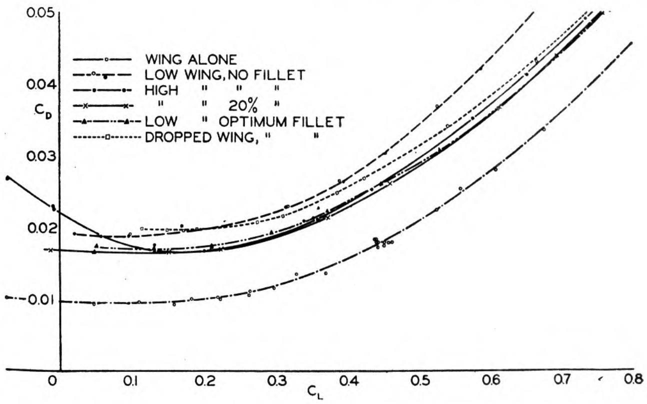

Fig. 14 Comparison of Various Configurations in the High-Speed Region Showing the Experimental Scatter

General Discussion

It has been seen from the foregoing that the aerodynamic disadvantages of the low-wing monoplane can be almost completely eliminated by proper design of the wing-fuselage intersection. The maximum-lift coefficient of the wing alone can be attained with either a high-wing or a low-wing configuration. The differences in drag between the high wing and the normal low wing are inappreciable.

In the case of the dropped low wing there is found to be some drag increase, but it is thought that this difference could be reduced by further investigation. The size of the optimum fillet in the case of a low-wing design can be decreased by the following means:

1 Making the fuselage small
2 Keeping the distance of the trailing edge of the wing below the bottom of the fuselage small
3 Using an airfoil of small top camber.

The minimum drag of the fuselage-wing combination can be best decreased by making the fillet at the leading edge of the wing as small as possible.

Buffeting. For the purposes of discussion, buffeting will be defined as follows: Buffeting is a violent shaking of the airplane and tail surfaces by aerodynamic forces at angles below the stall. Buffeting in this sense has been observed in the case of almost all low-wing monoplanes. If one considers the wake measurements and notices the critical angles, there is no difficulty in seeking what occurs.

The buffeting seems to be due to these three causes: first, the lift over the center section of the wing disappears, causing a decrease in the total lift available; second, the wake jumps from one side of the stabilizer to the other; and third, the stabilizer is then in the trailing vortex formed at the side of the fuselage. The position of the stabilizer is indicated on each of the wake drawings.

Mr. H. J. Steiger (ref. 4) has suggested that buffeting could be eliminated by cutting away the wing root and reducing the angle of attack at the fuselage. It is dubious if any such attempt would be satisfactory, as it would inevitably result in trailing vortices forming near the fuselage, and these vortices might cause a dangerous or uncomfortable tail vibration, in addition to their pernicious effect on the induced drag. It is easily seen that for a properly designed junction between the wing and the fuselage the lift must carry entirely across the span, since if there were no lift over that portion of the wing covered by the fuselage, the polar curve for the wing and fuselage would of necessity differ more from that of the wing alone than it actually does.

Acknowledgments

The author wishes to acknowledge his gratitude to the entire staff of the laboratory for their assistance in performing the tests and in preparing this report. He is especially indebted to Dr. C. B. Millikan, Mr. W. H. Bowen, Mr. W. B. Oswald, and Mr. N. B. Moore for their efforts.

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2 Clark B. Millikan and Arthur L. Klein, "Description and Calibration of 10-Ft Wind Tunnel at California Institute of Technology."

3 R. F. Anderson, "The Aerodynamic Characteristics of Airfoils at Negative Angles of Attack," N.A.C.A. Technical Note 412.

4 H. J. Steiger, address before the Royal Aeronautical Society, April 7, 1932.

Discussion

E. Ower.[3] The author's results entirely confirm the ideas formed from some similar, although not so comprehensive, work for which the writer was responsible some time ago. An account of this work was given in a lecture read to the Royal Aeronautical Society in January, 1932,[4] and the writer thinks that the explanation he then put forward of the type of interference for which fillets are found to be beneficial is worth repeating. He suggested that this interference occurs when the air stream has to expand at more than a certain rate if it is to remain in contact with the body and wing surfaces. A certain rate of expansion can be tolerated, but if the surfaces diverge from one another too rapidly, the flow detaches itself from them and a region of turbulence is set up which leads to a loss of lift and an increase of drag. A well-known analogous case is that of the outlet cone of a venturi tube—if the angle of this cone is too great, it does not "run full;" that is, the flow breaks away from the walls, with the resulting loss of efficiency of reconversion of the kinetic energy into static pressure.

This hypothesis was confirmed by the various tests made to investigate its truth, and it explains the author's results with fillets. For in his case the geometry was such, as indeed it is in most practical body-wing combinations, that the rate of expansion increased progressively from the maximum camber of the wing toward the trailing edge. Hence, as the author found, the best fillet increases in radius toward the rear of the wing. The writer's experiments were made with fillets of constant radius, but he did in fact predict that fillets of increasing radius toward the trailing edge would be preferable. The same line of reasoning indicates why fillets on the under surface of a high-wing combination are found to have very little effect; the divergence between the surfaces of the body and the wing is much less in such a combination than it is in low-wing positions. Moreover, in the high-wing position the pressure gradient along the lower wing surface is such as slightly to assist the flow to adhere to the surfaces, whereas in the low-wing position the pressure gradient on the upper surface tends powerfully in the opposite direction.

The author mentions the importance of preserving as far as possible the normal lift distribution along the span of the wing. This again agrees with views that the writer has expressed. This principle, together with that of avoiding regions of divergent flow, will be found to be of the utmost importance to the designer in his efforts to build high-performance aircraft. The designer is always more interested in direct proof than in speculation, and the author has provided such proof, whereas the writer, mainly through lack of time, was content to put forward ideas which needed corroboration by facts before they could be accepted with complete confidence.

Richard M. Mock.[5] This is believed to be the most interesting piece of aerodynamic research in America published during 1932, outside of that of the N.A.C.A. It is unfortunate that the tests were not made with a running model propeller, as it is possible and likely that the slipstream affects the flow around the fuselage and especially over the wing-fuselage intersection. Therefore it is believed that the comparative drag figures are somewhat questionable. During take-off and climb with high angles of attack, the same would be true as affecting the lift coefficients,

[3] Aerodynamics Department, National Physical Laboratory, Teddington, Middlesex, England.

[4] See *Jour. Royal Aero. Soc.*, 1932, vol. 36, p. 531. Also, Reports and Memoranda no. 1480 of the Aeronautical Research Committee, E. Ower, "Some Aspects of the Mutual Interference Between Parts of Aircraft."

[5] Aeronautical Engineer, A. H. G. Fokker, New York, N. Y. Jun. A.S.M.E.

while for landing the propeller effect is negligible. The comparative maximum lift coefficients, without propeller, are very valuable, as this is applicable to the landing condition.

The writer differs from the author regarding his comparison with the high-wing monoplane. The high-wing monoplane which he used as a comparison showed almost 6 per cent more maximum lift and about 3 to 4 per cent less drag than the best low-wing arrangement. However, the writer is under the impression that a high-wing design, rather than have the wing resting on top of the fuselage with its trailing edge just touching the fuselage, will have less drag if the wing is sunk into the fuselage, so that the top of the fuselage meets the top of the wing about one-third or one-half chord back from the wing leading edge and the combination is carefully filleted. The top of the fuselage might be lowered in front of the wing to allow a clean leading edge, and the portion of the fuselage above the rear portion of the wing might have fillets of very large radius. This should reduce the frontal area and the drag still below that of the combination used, and if the leading edge is carefully faired, should not affect the lift other than increase it by directing the flow from the fuselage over the upper surface.

Regarding the best position for the low wing, it would be interesting to raise the wing, as on the Gee Bee racer, rather than lower it as was done. As the fuselage decreases in width near the bottom and the wing is cambered on top, a pocket or cavity is formed between upper surface of the wing, just in front of the trailing edge, and the lower surface of the fuselage. The air passing over the wing and over the fuselage must fill this pocket, causing eddies and consequently drag. Therefore it is logical that by fairing over this cavity, as the author has done, the drag of the combination will be reduced. This could also be done by raising the wing slightly to where the fuselage is wider and then using a fillet, and also perhaps by changing the fuselage cross-section slightly so that an excessive fillet will not be necessary. Another means would be to have the wing, in front view, curve upward at the root, meeting the fuselage side at a right angle.

Of course, if the landing gear is attached to the wing, the wheel supports will be longer if the wing is raised. The increased length means slightly greater weight, and if the undercarriage is not retractable, the frontal area and consequently the drag will be increased. Lowering the wing from the optimum (filleted) low-wing position to the optimum (also filleted) dropped-wing position (Fig. 14) means an increase in drag of approximately 17 per cent. With a fixed external landing gear, the two shorter wheel supports with the dropped-wing position might partially offset the increased wing-fuselage drag. With a fully retractable landing gear, the landing-gear resistance could be neglected, and only the best wing-fuselage arrangement considered, with the tail location and fillet varied to eliminate buffeting.

The effect of lift-increasing trailing-edge flaps on buffeting would be interesting.

The writer would appreciate having the author's opinion of the meaning of the double curve near the maximum-lift coefficient of the dropped-wing combination with optimum fillet *D*. He also would appreciate an opinion of the double wake behind the fuselage at —5 deg, zero, and +5 deg for the same wing-fuselage combination. Another pilot combination between 1 and 2 and still within the stabilizer span would have been interesting. The writer would like to know the drag coefficient of the fuselage at the various angles of attack so that it can be added to the drag of the wing alone and compared with the drag of the combination.

G. J. Klein.[6] The early investigations into body-wing interference were, it is true, conducted at rather low values of Reynolds' number. However, they disclosed very interesting results, particularly in the case of the low-wing monoplane, and certainly showed the need for further research at higher Reynolds' number. In this connection, the present paper, together with an extensive series of experiments at the N.P.L. (R. & M. 1480 and R. & M. 1300), form a valuable extension and show that the general conclusions reached in the earlier work still hold at much higher values of Reynolds' numbers. When we consider all these researches together, we get a fairly accurate picture of the subject.

[6] Junior Research Physicist, National Research Council, Ottawa, Ont., Canada. Jun. A.S.M.E.

It is now definitely established that detrimental interference is due to burbling caused by an attempt to expand the airstream too rapidly in the angle between the side of the body and the surface of the wing. It is true that the presence of the body does change the lift grading of the wing and thus increases the induced drag, but unless this burbling occurs, this effect is very small. Actually the wings so modify the flow about the body that the body contributes appreciably to the total lift of the combination, and the resulting lift grading is not very different from the lift grading of the wing alone.

For the foregoing reasons it is sufficient to confine this discussion to the case where burbling occurs and to consider the factors involved. Obviously, the worst case would be a low-wing monoplane without fillets, having a highly cambered wing root and a body of small fineness ratio and of such a cross-sectional shape that the angle between the side of the body and the upper surface of the wing is small compared with 90 deg. This combination forms a pocket between the body and the wing near the trailing edge of the latter, into which the airstream cannot expand, even at the zero lift angle of attack of the combination. Increasing the angle of attack increases the difficulties in expanding the airstream, thus causing increased burbling. There are several methods of suppressing this burbling:

(1) The wing can be raised to a higher position on the body to eliminate the pocket effect.

(2) The body can be given flat sides, making an angle of 90 deg with the wing surface, as was done in the Schneider Trophy Racer S5.

(3) A fillet of increasing radius toward the trailing edge can be employed, as was done in the present paper.

In short, anything that eliminates this pocket effect over the useful range of angle of attack will result in a combination of body and wing that will be free of any undesirable interference effects.

An interesting result brought out by the paper is that the "double stalls" found in the earlier work at low values of Reynolds' number are still present at much higher values. Undoubtedly the recovery from the first stall is due to a decrease in the extent of the burbling caused by the downwash from the nose of the body.

Probably the most important point brought out by the paper is that a properly designed low-wing monoplane can be just as efficient as a high-wing monoplane.

Author's Closure

Replying to Mr. Ower, the low-wing fillet described was first developed in our wind tunnel in May, 1931, and test-flown in June of the same year. The second Northrop Beta and all succeeding Northrop ships have carried this device. The author agrees entirely with Mr. Ower's statements as to the necessity of eliminating most of the expansion of the wing fuselage intersection, as was first pointed out by Muttray (loc. cit.).

Replying to Mr. Mock, as he says, it is unfortunate that the tests were not made with a running propeller. The laboratory has under development a fuselage, in which is included an electric motor with complete dynamometer, for repeating the preceding investigation with a slipstream. The model when finished will have the proper scale horsepower and the proper ratio of propeller diameter to span. However, the author does not believe that the drag differences will be large in the case with slipstream and without, as the laboratory has been rather successful in predicting the performance and especially the high speed of the airplanes which it has tested. In a paper by Drs. Th. von Kármán and Clark B. Millikan[7] there are described the methods used by this laboratory in estimating the performance of the actual airplane. Due to the successful checks which have been secured, it is not very probable that the discrepancies in drag between power off and power on will be large.

Since the investigation of the fillet was undertaken as an engineering study rather than as a scientific investigation into the configuration for minimum drag of the wing and fuselage alone, we did not consider several of the cases mentioned by Mr. Mock, as the lowering of the wing in the case of a high-wing monoplane or the raising of it in the case of a low-wing monoplane would require a larger fuselage in order to maintain the headroom in the cabin.

The reduction in frontal area in the cases mentioned by Mr. Mock would be more apparent than real, as it would necessitate, if his suggestions were carried out, the enlarging of the fuselage in order to accommodate the passengers or other loads. The raising of the wing any great distance was impossible in this particular case as it would bring the floor level too high. The consolidation of a stressed-skin wing into beams in order to enable the passengers to place their feet below the top surface of the wing is exceedingly extravagant of weight, and it also causes the cabin to be encumbered with structural members which interfere with the free circulation of passengers or the stowing of freight.

The author does not believe that the position of the wing with reference to the fuselage is a vital matter, as what is gained in one place is lost in another. In the multimotor transport field there is a very interesting case. There are two modern low-wing bimotor transports of the same power loading and span loading, one with the wing passing completely below the cabin floor and the other with the wing beams passing through the cabin. The airplane with the wing completely below the cabin floor is much faster, in the neighborhood of 25 mph, than its competitor. The difficulties of designing a retractable landing gear increase with at least the square of the length of the members as does also its weight. The raising of a wing 6 in. or 8 in. farther above the ground will often make a satisfactory retractable landing gear almost impossible. The addition of lower surface flaps has been found in this laboratory to have no effect on the buffeting of a well-filleted airplane. The author believes that the double peak of the curve for the optimum fillet *D* is probably due either to asymmetries of the model or to asymmetries of the air stream. The model was known to have developed some aerodynamic twist. This twist raised the angle of attack of one side of the model above that of the other, and consequently one side stalled in advance of the other. This effect has also been found in the laboratory a number of times in rolling-moment tests. The author believes that the two peaks in the wake diagrams shown in Fig. 10, at —5 deg. and +5 deg, can be explained as follows: The upper one is probably the wake of the fuselage and the lower one that of the wing. When the downwash becomes large, the fuselage wake becomes merged into that of the wing. The drag coefficient of the fuselage has never been measured separately, so that Mr. Mock's question on this point cannot be answered.

Replying to Mr. G. J. Klein, he is completely correct in his statement as to the three methods of eliminating the burbling in the wing-fuselage intersection. However, in the case of a straight-sided fuselage, the burble is not completely absent. The author would like to cite Fig. 15 as evidence in this case. The results in this figure were obtained with the Douglas transport fuselage, which is straight-sided in the region in contact with the wing and for a considerable distance aft of the trailing edge. The wing

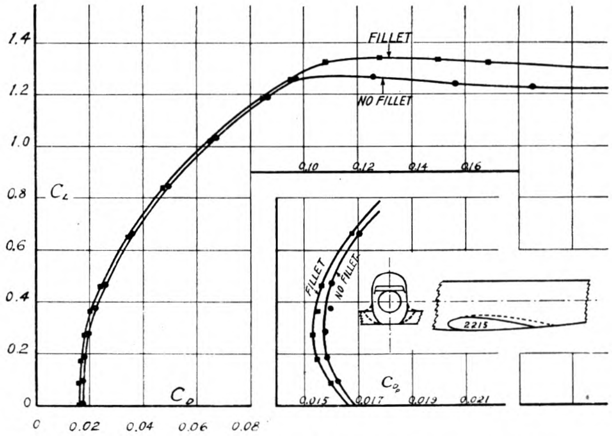

FIG. 15 LIFT AND DRAG POLAR CURVES FOR THE CASE OF A FUSELAGE WING COMBINATION IN WHICH THE FUSELAGE IS STRAIGHT SIDED

(Note: The separation in drag between the curves on the larger plot has been increased to permit satisfactory reproduction. The real separation is shown on the smaller plot.)

section used in this transport is the N.A.C.A. 2215. This section is of only 15 per cent thickness, has a very small camber (2 per cent), and furthermore the point of maximum camber is only 20 per cent aft from the leading edge. This wing has therefore probably the smallest top camber of any section in common use.

Nevertheless, in the tests shown, the difference between fillet and no fillet is quite perceptible. The model was tested with tail surfaces but less nacelles. The separation between the two curves shown on the larger plot in the figure has been exaggerated in the region of low lift coefficient in order to enable the two curves to appear separately on the reproduction. The smaller plot shows the experimental points in their true separation. In the low drag region the addition of the fillet reduced the minimum drag for the model approximately 1.8 per cent and raised the maximum lift coefficient as shown from 1.27 to 1.34. For very high angles not shown in the plot, the curves cross each other, an effect the author is unable to explain, but at all usable angles of attack the filleted case is superior to that of the unfilleted.

The discussion of why some of the lift curves have double peaks has been included in the reply to Mr. Mock. However, the double stalls in the other sense, i.e., of curves that come to a maximum and then go on to a further maximum, are apparently due to the local burbling of the wing in the center, while outboard portions of the wing do not stall as soon, but continue to work at larger and larger angles of attack. These restricted portions of the span can then go to larger lift coefficients, as it is well known that wings of small aspect ratio can reach larger lift coefficients than normal wings. It has been found in our laboratory that the characteristic sharp break in the lift curve can be explained as an effect of this kind. We always find the sharp break in untapered wings. Tapered wings usually show the rounding top which we think means that the center of the wing stalls before the outboard portions. Evidence for this can be seen in Fig. 2 on the wake diagrams for the wing alone. In one very interesting case the laboratory found that this sharp drop-off of the lift curve was obtained with a tapered wing in which an auxiliary

[7] Th. von Kármán and Clark B. Millikan, "The Use of the Wind Tunnel in Connection With Aircraft Design Problems," *Aeronautical Engineering*, 1933.

airfoil was used only over a part of the center section. In this case the sharp drop in the lift curve was obtained, not only in the laboratory but also in flight, while the airplane without the auxiliary airfoil stalled in the more usual manner. We therefore think that in this case the auxiliary airfoil held the flow on the center section to a higher lift coefficient than that which it would normally reach, and when it stalled, the entire wing stalled at once.

Since the foregoing paper was written, two confirmations[8,9] have been published of the results, and numerous airplanes have been designed and flown with these devices.

[8] Biechteler, Curt, "Versuche zur Beseitigung von Leitwerkschutteln," Z.F.M., vol. 24, no. 1, Jan. 14, 1933.

[9] Hood, Manley J. and White, James A., "Full-Scale Wind-Tunnel Research on Tail Buffeting and Wing-Fuselage Interference of a Low-Wing Monoplane," Technical Note no. 460, May, 1933.