On the Design of Sailplane Tail Surfaces

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Introduction

The wide variety of tail surface designs seen on modern sailplanes attests to the differences of opinion among designers as to the best combination of variables in the layout of these surfaces. In fact, it seems that greater variety is seen today than ever before. In addition to the range of differences in normal planform parameters such as taper, aspect ratio and sweep, and those of dimension such as tail size and length, there appears to be little agreement as to which type of configuration offers the best compromise; "Y", "T" and "V" type tails have been used on recent high-performance designs.

It is the purpose of this paper to examine some of the more important variables in terms of their effect on the efficiency of the surface as a stabilizing device and to present the results as a guide for sailplane designers.

Actually the tail surfaces serve three separate important functions—stability, control and damping. Fortunately, in many cases, these functions are so related that optimization of the surface as a stabilizing element also results in an optimum surface for the damping and control functions or very close thereto.

In the design of any sailplane the mutual interference effects of the various components must be given due consideration in determining the overall aerodynamic characteristics of the machine. This is true of the tail surfaces, in particular for the downwash and sidewash effects of the wing and

FIGURE 1. - MOMENT EFFECTIVENESS OF TAILS WITH VARIOUS TAPER RATIOS

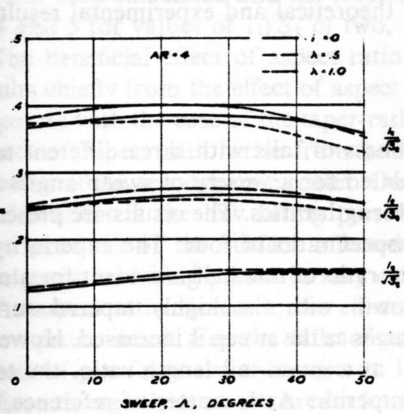


FIGURE 2. - LIFT-CURVE SLOPES VERSUS TAPER RATIO

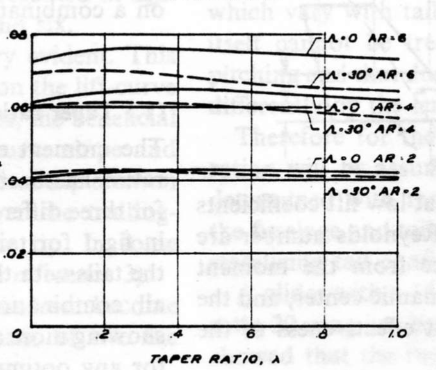
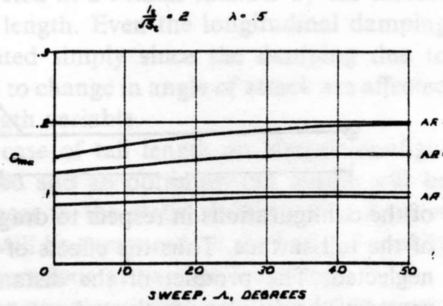


FIGURE 3. - EFFECT OF ASPECT RATIO



fuselage at the tail as well as the effective dynamic pressure across the tail. For an efficiently designed sailplane these effects should be of smaller magnitude than for airplanes and the differences in the magnitudes of these interferences with changes in tail design variables are of a smaller order, so that in studying major tail variables, the influence of interference effects may often be negligible.

Although it is obvious that, commensurate with good handling qualities, performance will be improved by minimizing the size of the fuselage and tail, this minimizing has, perhaps, more important indirect benefits. The weight of tail surfaces has a pronounced effect on longitudinal balance. If the pilot has to be placed quite ahead of the wing to achieve the proper balance, then the allowable center-of-gravity range must be greater for the same range of pilot weights, which, in turn, requires a large tail volume.

Another factor which deserves considerable attention is the size of the fuselage. That the fuselage detracts from performance is well appreciated and many cramped cockpits serve as signs of this fact. However fuselage length is important from more than the drag it causes. A designer may use a long fuselage with a poorly designed tail in order to achieve stability. This excess fuselage not only weighs a great deal, but, because of the effect on gross weight and the resultant increase in wing bending moments under accelerated flight conditions, the growth factor for the fuselage is much higher than for the wing. Also, the sailplane nose is destabilizing and constitutes a major factor in establishment of necessary tail volume, so that fuselage size ahead of the center of gravity is important in respect to stability and should be minimized.

It is hoped that the following studies will serve as a basis for improvement in the analysis of tailplane design from the point of view of the designer.

Notation

AR	Aspect ratio
b	Surface span, meters
C_L	Lift coefficient
$C_{L\alpha}$	Lift-curve slope, $dC_L/d\alpha$, per degree
$C_{m\alpha}$	Tail pitching-moment slope about the aircraft moment center, $dC_m/d\alpha$, per degree
c_d	Section drag coefficient
$c_{d\,min}$	Minimum section drag coefficient
$c_{l\,max}$	Maximum section lift coefficient
$c_{l\alpha}$	Section lift-curve slope, $dc_l/d\alpha$, per degree
c_r	Root chord, meters
c_t	Tip chord, meters
c	Mean aerodynamic chord, meters
D	Drag, kilograms
h_n	Chordwise position of the aerodynamic center with respect to the mean aerodynamic chord
K_h	Horizontal tail volume factor, $S_t\,x_t\,(1-d\epsilon/d\alpha)$, cubic meters
K_v	Vertical tail volume factor, $S_v\,x_t$, cubic meters

FIGURE 4.- EFFECT OF ASPECT RATIO

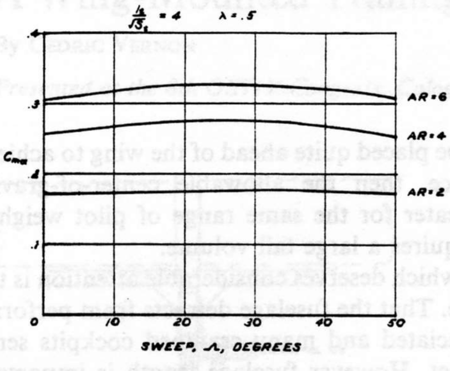


FIGURE 5.- EFFECT OF ASPECT RATIO

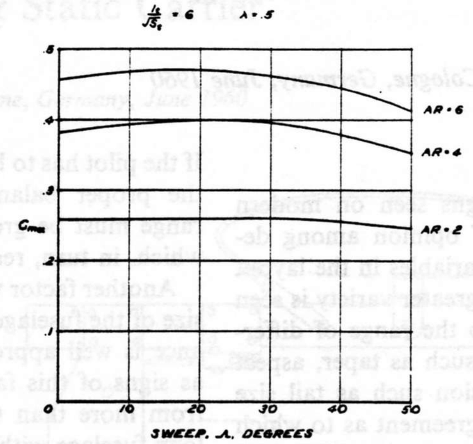
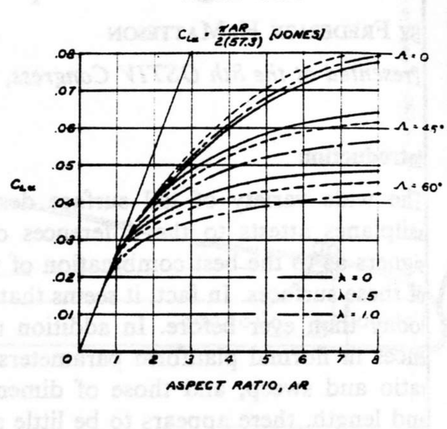


FIGURE 6.- LIFT-CURVE SLOPE VERSUS ASPECT RATIO

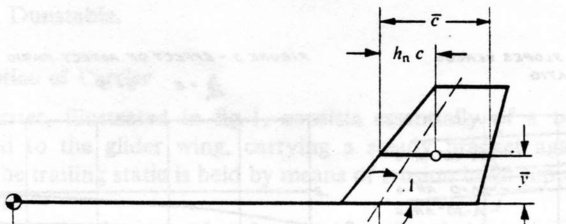


l_t	Distance from the intersection of the tail quarter-chord line and the aircraft centerline to the aircraft moment center, meters
q	Dynamic pressure, kg/m²
Re	Reynolds number
S_t	Horizontal tail area, square meters
S_v	Vertical tail area, square meters
t/c	Thickness-chord ratio
x_t	Distance from the aircraft moment center to the tail quarter mean aerodynamic chord point, meters
y	Lateral position of the mean aerodynamic chord, meters
α	Angle of attack, degrees
ε	Downwash angle, degrees
λ	Taper ratio, c_t/c_r
Λ	Sweep angle of the quarter-chord line, degrees

Discussion

(a) Planform

The planform parameters have been calculated for a group of horizontal tails of unit area. The assumption is made that the comparison on a unit area basis reflects the relative merit



of the configurations in respect to drag at low lift coefficients of the tail surface. Thus the effects of Reynolds number are neglected. The product of the distance from the moment center of the sailplane to the tail aerodynamic center, and the tail lift-curve slope then is the moment effectiveness of the isolated tail.

$$C_{m\alpha} = (l_t + y \tan\Lambda - c/4 + h_n c)\, C_{L\alpha}$$

For convenience the length term in the brackets is divided by a reference dimension of one meter to eliminate units. Since wing dimensions are not used for reference, the slope of the pitching-moment curve $C_m\alpha$ will, of course, be of a different magnitude than that normally associated with stability derivatives.

In order to compare parameters for different tail lengths, the ratio, $l_t/\sqrt{S_t}$, is introduced. It should be noted, however, that the term, l_t, is the distance to the intersection of the quarter-chord line with the centerline and for swept tails is thus not the normally defined tail length. This is done because the fuselage need be only long enough to support the tail and not to reach the quarter-chord point of the tail mean chord.

The lift-curve slopes have been taken from NACA Report 921 by De Young and Harper (Reference 1) and are derived from the Weissinger method. The chordwise positions of the aerodynamic center, h_n, are from the Royal Aeronautical Society Data Sheets as reproduced in Bernard Etkin's "Dynamics of Flight" (Reference 2). These data are based on a combination of theoretical and experimental results.

(1.) Taper ratio

The moment effectiveness of tails with three different taper ratios has been calculated for a variety of sweep angles and for three different tail length ratios. The results are presented in fig.1 for tails of aspect ratio of four. The superiority of the tails with the taper ratio of one half is evident for almost all combinations shown, with the highly tapered surface showing more advantages as the sweep is increased. However, for any optimum tail at a given tail length ratio, the taper ratio of one half is superior. As a matter of reference, tail

FIGURE 7.- EFFECT OF TAIL LENGTH

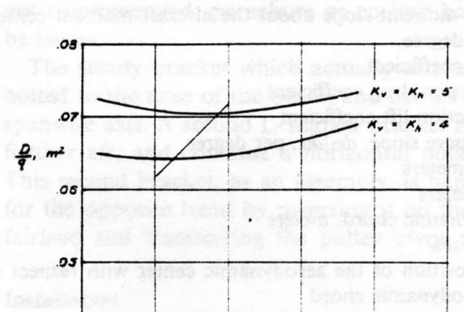


FIGURE 8.- EFFECT OF TAIL HEIGHT

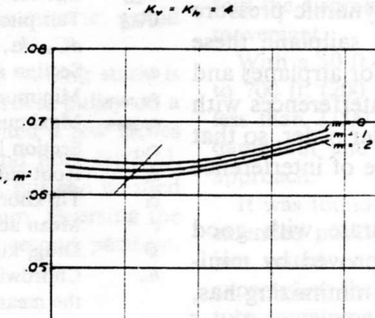
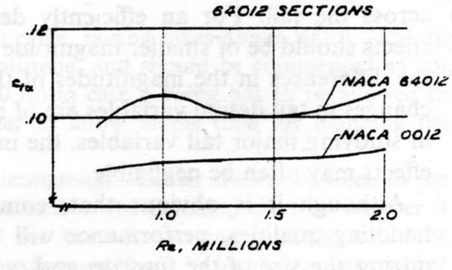


FIGURE 9.- COMPARISON OF THE LIFT-CURVE SLOPES FOR THE NACA 0012 AND NACA 64012 SECTIONS



ngth ratios for modern sailplanes run from about 2½ to 6, so that the spread shown is relatively large. Still the optimum sweep is not less than 20 degrees and for the short tail the optimum seems to be in the neighborhood of 50 degrees.

For low angles of sweep the characteristics evidenced above are caused primarily by the differences in the lift-curve slope with taper ratio. Fig. 2 shows lift-curve slopes versus taper ratio calculated by the method of NACA Report 921. For zero sweep the differences are small, but the optimums occur between a taper ratio of 0.5 for the aspect ratio of two to about 0.3 for the aspect ratio of six. The optimum values for the 30 degree sweptback surfaces occur at lower taper ratios. As the sweep increases, the term h_n becomes increasingly important. The effect is to accentuate the advantage of the low taper ratios with increasing sweep. The effect of increasing aspect ratio on the effects of taper is to accentuate them.

FIGURE 10. - COMPARISON OF THE MINIMUM DRAG OF THE NACA 0012 AND NACA 64012 SECTIONS

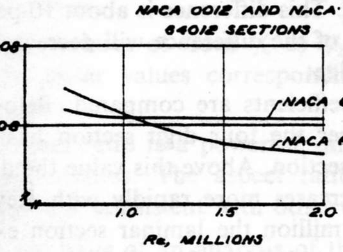


FIGURE 11. - RATIO OF LIFT-CURVE SLOPE TO MINIMUM DRAG COEFFICIENT FOR THE NACA 0012 AND NACA 64012 SECTIONS

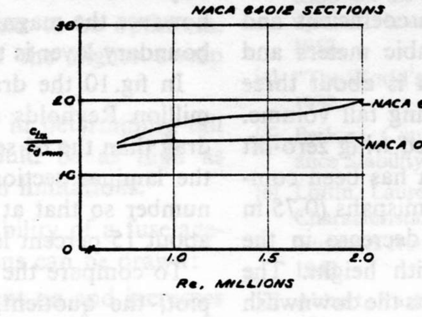
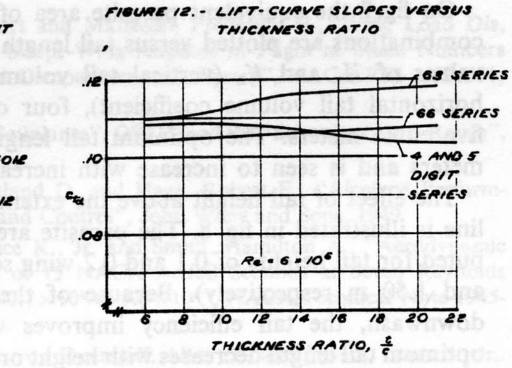


FIGURE 12. - LIFT-CURVE SLOPES VERSUS THICKNESS RATIO



(2.) Aspect ratio

The effect of aspect ratio for horizontal tails of taper ratio 0.5 has been calculated and the results are presented in figs. 3, 4 and 5 for values of $l_t/\sqrt{S_t}$ of two, four and six.

The beneficial effect of aspect ratio is very evident. This results chiefly from the effect of aspect ratio on the lift-curve slope. As with the case of the taper-ratio series, the beneficial effects of aspect ratio arise from both lift-curve slope and location of the aerodynamic center. One physical explanation of this effect is the low lifting pressures over the trailing-edge portions of the surface affected by the tip. In some cases negative lifting pressures may exist (see reference 3).

As aspect ratio increases, the effects of planform become more pronounced. For the tails of aspect ratio of two the effects of planform are unimportant.

Even though these results are for horizontal tails, the trends and conclusions are applicable to vertical surfaces if corrections are applied to account for the effective aspect ratio. These corrections depend on the size and location of the horizontal tail and fuselage. If a horizontal tail is situated at the base of the vertical tail, and the fuselage is large in terms of the tail height, these elements may serve as a good reflection plane and the effective aspect ratio of the vertical tail may be doubled. Generally this is not the case for sailplane tail surfaces where the horizontal tail is often ahead or behind the vertical, and the fuselage diameter is relatively small. So, it is expected that, for many present-day sailplanes, the effective aspect ratios of the vertical surfaces may be closer to the geometric aspect ratios. These geometric aspect ratios have been low. A group of 13 single seat sailplanes from the OSTIV "The World's Sailplanes" had an average vertical tail aspect ratio of about 1.5. In fig. 6, which is taken directly from NACA Report 921, is shown the lift-curve slope versus aspect ratio. It is quite apparent that higher aspect ratios would result in an almost proportionately higher vertical-tail effectiveness. It is the author's opinion that most sailplanes have vertical surfaces with aspect ratios that are too small, and that flying qualities, particularly in circling flight, suffer therefrom.

(b) Tail location

The tailplane planform parameters have been analyzed for isolated tail surfaces, and it is supposed that conclusions so obtained on this simplified basis are applicable to complete aircraft. The tail length is a very important quantity in the design, however the interference effects are known to be too dependent on this variable to permit a valid study on the basis of the isolated surface. The criterion also cannot be treated in a general manner because stability, control and damping are not affected in a similar manner by the factors which vary with tail length. Even the longitudinal damping itself cannot be treated simply since the damping due to pitching and that due to change in angle of attack are affected differently by the length variable.

Therefore for the case of tail length an aircraft configuration will be assumed and an optimum tail length will be determined with respect to the static stability. The drag of the fuselage and tail will be compared on the basis of equally stabilizing tail configurations at various locations.

A glider with a 15 meter span, taper ratio of 0.3 and aspect ratio 20 wing has been chosen. A study of single place gliders showed that the fuselage cross-section area averaged about one half square meter and that the tail length for the horizontal tail averaged about 55 percent of the overall fuselage length. Such a fuselage layout has been selected for this study. The vertical and horizontal tail lengths have been taken as equal. For the vertical tail the tail volume is taken as the measure of weathercock stability, and for the horizontal tail the product of the tail volume and the term $(1 - d\varepsilon/d\alpha)$.

$$K_v = S_v x_t$$
$$K_h = S_t x_t \, (1 - d\varepsilon/d\alpha)$$

slope of downwash.

The fuselage drag was computed from the data of Perkins and Hage for fineness ratios of six to ten. The zero-lift drag coefficient of the tail surfaces was considered as a constant at 0.008 based on the area.

FIGURE 13.- MINIMUM DRAG COEFFICIENTS FOR THREE AIRFOIL SERIES

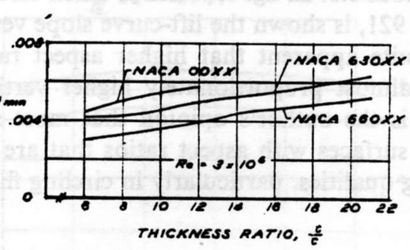


FIGURE 14.- RATIO OF LIFT-CURVE SLOPE TO MINIMUM DRAG COEFFICIENT FOR THREE AIRFOIL SERIES

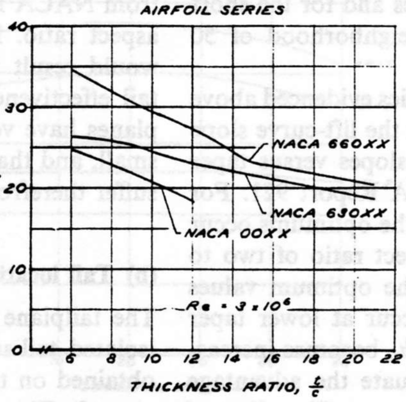
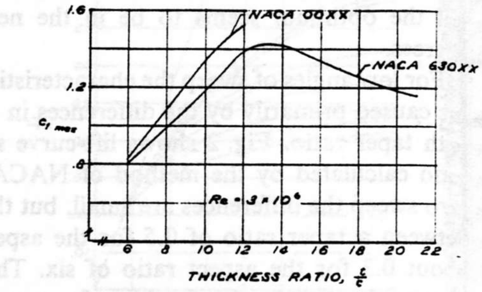


FIGURE 15.- MAXIMUM LIFT COEFFICIENTS FOR TWO AIRFOIL SERIES



The downwash was extrapolated from the curves of Perkins and Hage. These curves are for tail locations outside the wing wake.

On fig. 7 the equivalent parasite area of the fuselage tail combinations are plotted versus tail length for two different values of K_v and K_h (vertical tail volume coefficient and horizontal tail volume coefficient), four cubic meters and five cubic meters. The optimum tail length is about three meters and is seen to increase with increasing tail volume.

The effect of tail height above the extended wing zero-lift line is illustrated in fig. 8. The parasite area has been computed for tail heights of 0.1 and 0.2 wing semispans (0.75 m and 1.50 m respectively). Because of the decrease in the downwash, the tail efficiency improves with height. The optimum tail length decreases with height or as the downwash decreases. Similar variations could be expected from other changes affecting the downwash such as wing taper ratio or aspect ratio. For the optimum cases, the values of $x_t/\sqrt{S_t}$ are about 2.3 to 2.4, which are at the lower end of the range for typical sailplanes. The absolute values are probably not too significant considering the number of variables and assumptions, however the trends are believed to be correct.

If the optimization had been conducted with respect to weight, the optimum tail lengths would have been shorter because of the greater dependence of fuselage weight than drag on the length.

(c) Airfoils

A variety of symmetrical airfoil sections are used in today's sailplanes. The NACA 4-digit series (e.g. NACA 0008, NACA 0015, etc.) are fairly common and the NACA 6 series (e.g. NACA 63009, NACA 65012, etc.) are being seen on more recent high-performance machines. A survey of 23 representative single seat sailplanes showed that total tail surface area averaged over 20 percent of the wing area, with extremes ranging from 16 to 30 percent. It is apparent that the tail surfaces can be a source of sizeable performance loss if care is not exercised in their design.

The presence of a hinge and gap on a tail surface may cause transition of the boundary layer if it is laminar and thus change the lift and drag characteristics from those for the section without the movable surface. In the limit for a well faired and sealed surface, however, the section characteristics might be considered to approach those of an unbroken surface. The following data are taken from tests of plain airfoil surfaces in wind tunnels since little systematic data exist for sections with controls.

In fig. 9 the lift-curve slopes of the NACA 0012 and NACA 64012 airfoils are plotted versus Reynolds number from NACA Technical Note 1945. The laminar section has a higher lift-curve slope and is superior throughout the Reynolds number range. This difference is about 10 percent, however the magnitude of the difference will decrease if the boundary layer is turbulent.

In fig. 10 the drag coefficients are compared. Below one million Reynolds number the four digit section has lower drag than the 64 series section. Above this value the drag of the laminar section decreases more rapidly with Reynolds number so that at two million the laminar section exhibits about 15 percent less drag than the four digit section.

To compare the lift and drag characteristics on the same plot, the quotient, $c_{l\alpha}/c_{d\,min}$, has been plotted in fig. 11. The NACA 64012 section is superior at all the Reynolds numbers for which the data has been shown. The quotient is 25 percent less for the four digit section at two million Reynolds number.

Reference 6 has limited data for the lower Reynolds numbers so that the comparison for different thickness ratios has had to be made at Reynolds numbers somewhat higher than those common to sailplane tail surfaces. Data for this study is from NACA Report 824 by Abbott, von Doenhoff and Stivers and NACA Technical Note 1945. In fig. 12 are shown the lift-curve slopes for the NACA 4 and 5 digit, 630XX and 660XX type airfoils at a Reynolds number of six million. These curves are approximately correct for a Reynolds number of three million. The laminar sections improve with increasing thickness ratio, whereas the four and five digit sections do not. The 630XX airfoils may be seen to have the highest lift-curve slopes.

The minimum drag coefficients for the NACA 4-digit, 630XX and 660XX series are plotted in fig. 13 at a Reynolds number of three million. All series show the same trend in drag with thickness ratio. The drag of the laminar sections is less than for the four digit series; the more severe 66 series is superior in this regard.

The quotient, $c_{l\alpha}/c_{d\,min}$, is shown on figure 14 for the same series. Insofar as the quotient is a measure of the relative merit of different sections, the thinner sections are definitely superior. The laminar sections are again better than the conventional airfoils. The 660XX sections have higher quotients than the 630XX series; however, the region of low drag is spread over a smaller range of lift coefficients. As Reynolds numbers decrease these ranges increase; however, no systematic data are available for comparison.

In some cases the maximum lift and the stalling characteristics of the tail may be of interest. The use of very thin sections would aggravate this problem. In fig. 15 the maximum lift coefficients are shown for thefour digit symmetrical sections and the 630XX series. The optimum thickness ratio is between 12 and 15 percent for the 630XX series and may be expected to be similar for the four digit sections. The four digit sections are advantageous both in respect to maximum lift coefficients, and, since the lift-curve slopes are lower, particularly in the angle for stall. It would appear that there is little aerodynamic reason to use thick airfoils for tail sections.

Conclusions

On the basis of a simple analysis of the stability of isolated tail surfaces the following conclusions can be drawn:

(1.) The use of sweepback will improve the tail efficiency. The optimum sweep increases with decreasing tail length. The optimum becomes better defined as the aspect ratio increases.

(2.) Taper ratios of from ¼ to ½ appear to be optimum, the lesser values corresponding to the higher sweep angles.

(3.) Aspect ratio is a powerful variable in determining tail effectiveness. The aspect ratio should be as high as possible consistent with other design limitations.

On the basis of an analysis of the stability of a fuselage-tail combination the following conclusions can be drawn:

(1.) The optimum tail length is dependent on and increases with the tail volume.

(2.) Tail effectiveness improves somewhat as the horizontal tail is raised with respect to the wing and the corresponding optimum tail length decreases.

Based on comparisons of airfoil data for symmetrical sections without control surfaces, the following conclusions can be drawn:

(1.) NACA 6 series airfoils are superior to the four digit series as stabilizing surfaces, particularly at high Reynolds numbers.

(2.) Thin airfoils are superior for stabilizing surfaces except where stalling is a problem, where thickness ratios of from 12 to 15 percent may be optimum.

References

[1] De Young, John and Harper, Charles W., "Theoretical Symmetric Span Loading at Subsonic Speeds for Wings Having Arbitrary Planform", NACA Report 921, 1948.

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[6] Loftin, Laurence K., Jr. and Smith, Hamilton A., "Aerodynamic Characteristics of 15 NACA Airfoil Sections at Seven Reynolds Numbers from 0.7×10^6 to 9.0×10^6", NACA Technical Note 1945-1949.

[7] Abbott, Ira H., von Doenhoff, Albert E. and Stivers, Louis S., Jr,. "Summary of Airfoil Data", NACA Report 824, 1945.

Erratum

The angle Λ in the sketch near the middle of the second page of this paper should be the angle between the vertical line and the quarter chord.