ANALYSIS OF WIND-TUNNEL INVESTIGATIONS OF
TRAILING-EDGE FLAPS ON SWEPT-BACK WINGS

A THESIS
Presented to
the Faculty of the Division of Graduate Studies
Georgia School of Technology

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Aeronautical Engineering

by
William Thomas Rowe
June 1950
ANALYSIS OF WIND-TUNNEL INVESTIGATIONS OF
TRAILING-EDGE FLAPS ON SWEPT-BACK WINGS

Approved:

Date Approved by Chairman June 30, 1950
ACKNOWLEDGMENTS

The author wishes to express his appreciation to Professor J. J. Harper, who proposed this thesis topic, for his valuable suggestions and for his generous contribution of time and effort throughout its prosecution.

The author should also like to express his gratitude to the Faculty of the Daniel Guggenheim School of Aeronautics, Georgia Institute of Technology, for their help and timely advice.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approval Sheet</td>
<td>ii</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>iii</td>
</tr>
<tr>
<td>Preface: Meaning of Symbols Used</td>
<td>v</td>
</tr>
<tr>
<td>List of Figures</td>
<td>vii</td>
</tr>
<tr>
<td>I. Summary</td>
<td>1</td>
</tr>
<tr>
<td>II. Introduction</td>
<td>3</td>
</tr>
<tr>
<td>III. Apparatus and Models</td>
<td>9</td>
</tr>
<tr>
<td>IV. Procedure</td>
<td>11</td>
</tr>
<tr>
<td>V. Accuracy of Data</td>
<td>13</td>
</tr>
<tr>
<td>VI. Results and Discussion</td>
<td>15</td>
</tr>
<tr>
<td>VII. Conclusions</td>
<td>24</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>26</td>
</tr>
<tr>
<td>APPENDIX I, Figures</td>
<td>28</td>
</tr>
</tbody>
</table>
### PREFACE

#### MEANING OF SYMBOLS USED

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>Section lift coefficient ($\text{airfoil section lift}$)</td>
<td>$\frac{\text{lift}}{q_c}$</td>
</tr>
<tr>
<td>$A$</td>
<td>Aspect ratio $\frac{b^2}{S}$</td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td>Span of wing measured perpendicular to plane of symmetry, feet</td>
<td></td>
</tr>
<tr>
<td>$c$</td>
<td>Local chord measured parallel to plane of symmetry, feet</td>
<td></td>
</tr>
<tr>
<td>$\bar{c}$</td>
<td>Mean aerodynamic chord, feet $\frac{\int_{0}^{b} c^2 , d , b}{\int_{0}^{b} c , d , b}$</td>
<td></td>
</tr>
<tr>
<td>$C_D$</td>
<td>Drag coefficient ($\frac{\text{drag}}{qS}$)</td>
<td></td>
</tr>
<tr>
<td>$C_L$</td>
<td>Lift coefficient ($\frac{\text{lift}}{qS}$)</td>
<td></td>
</tr>
<tr>
<td>$C_{L\infty}$</td>
<td>Slope of lift curve measured at zero lift $\frac{dC_L}{d\alpha}$</td>
<td></td>
</tr>
<tr>
<td>$C_m$</td>
<td>Pitching moment coefficient about $0.25S$ ($\text{pitching moment}$)</td>
<td>$\frac{\text{moment}}{qS^2}$</td>
</tr>
<tr>
<td>$L$</td>
<td>Lift, pounds</td>
<td></td>
</tr>
<tr>
<td>$q$</td>
<td>Dynamic pressure ($\frac{\rho V^2}{2}$), lbs/sq.ft.</td>
<td></td>
</tr>
<tr>
<td>$R_e$</td>
<td>Effective Reynolds number based on mean aerodynamic chord</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>Wing area, square feet</td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>Free stream velocity, ft/sec</td>
<td></td>
</tr>
<tr>
<td>$X$</td>
<td>Distance along chord from leading edge, $%$ chord</td>
<td></td>
</tr>
<tr>
<td>$Y$</td>
<td>Ordinate of wing measured perpendicular to chord, $%$ chord</td>
<td></td>
</tr>
</tbody>
</table>
\( \alpha \)  
Model angle of attack degrees

\( \mu \)  
Viscosity of air, \( \frac{\text{lb. second}}{\text{sq. ft.}} \)

\( \rho \)  
Mass density of air, slugs per cubic ft.

\( \lambda \)  
Taper ratio, \( \frac{\text{tip chord}}{\text{root chord}} \)

\( \gamma \)  
Angle of sweepback measured at quarter chord axis, degrees

\( \gamma_{fl} \)  
Sweepback of flap hinge axis, degrees

\( \Delta \)  
Increment

\( \delta_F \)  
Flap deflection, degrees
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Plan Form Dimensions of 60° Swept Wing</td>
</tr>
<tr>
<td>2. Schematic Arrangement of Special Flaps - 60° Model</td>
</tr>
<tr>
<td>3. Plan Form Dimensions of 45° Swept Wing</td>
</tr>
<tr>
<td>4. Schematic Arrangement of Special Flaps - 45° Model</td>
</tr>
<tr>
<td>5. Variation of the Aerodynamic Coefficients With Angle of Attack for a 60° Swept-Back Wing With a Full-Span Split Flap</td>
</tr>
<tr>
<td>6. Variation of the Aerodynamic Coefficients With Angle of Attack for a 60° Swept-Back Wing With a Six-Step Flap</td>
</tr>
<tr>
<td>7. Variation of the Aerodynamic Coefficients With Angle of Attack for a 60° Swept-Back Wing With a Fowler Flap</td>
</tr>
<tr>
<td>8. Variation of the Aerodynamic Coefficients With Angle of Attack for a 60° Swept-Back Wing With a Rotated Fowler Flap</td>
</tr>
<tr>
<td>9. Variation of the Aerodynamic Coefficients With Angle of Attack for a 60° Swept-Back Wing With a Three-Step Split Flap</td>
</tr>
<tr>
<td>10. Variation of the Aerodynamic Coefficients With Angle of Attack for a 45° Swept-Back Wing With a Full-Span Split Flap</td>
</tr>
<tr>
<td>11. Variation of the Aerodynamic Coefficients With Angle of Attack for a 45° Swept-Back Wing With a Six-Step Flap</td>
</tr>
<tr>
<td>12. Variation of the Aerodynamic Coefficients With Angle of Attack for a 45° Swept-Back Wing With a Fowler Flap</td>
</tr>
</tbody>
</table>
13. Variation of the Aerodynamic Coefficients With Angle of Attack for a $45^\circ$ Swept-Back Wing With a Rotated Fowler Flap ................................................................. 41

14. Variation of the Aerodynamic Coefficients With Angle of Attack for a $45^\circ$ Swept-Back Wing With a Three-Step Split Flap ................................................................. 42

15. Variation of the Theoretical and Experimental Values of $C_{L_{\infty}}$ with Sweep Back ................................................................. 43

16. Variation of Maximum Lift Coefficients with Flap Deflection for the $60^\circ$ Swept Wing ................................................................. 44

17. Increment in Lift Coefficient with Flap Deflection for the $60^\circ$ Swept Wing ................................................................. 45

18. Increment in Drag Coefficient with Flap Deflection for the $60^\circ$ Swept Wing ................................................................. 46

19. Increment in Pitching Moment Coefficient with Flap Deflection for the $60^\circ$ Swept Wing ................................................................. 48

20. Variation of Maximum Lift Coefficient with Flap Deflection for the $45^\circ$ Swept Wing ................................................................. 50

21. Increment in Lift Coefficient with Flap Deflection for the $45^\circ$ Swept Wing ................................................................. 51

22. Increment in Drag Coefficient with Flap Deflection for the $45^\circ$ Swept Wing ................................................................. 52

23. Increment in Pitching Moment Coefficient with Flap Deflection for the $45^\circ$ Swept Wing ................................................................. 54
<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>24. Tuft Study of 60° Swept Wing</td>
<td>56</td>
</tr>
<tr>
<td>25. Tuft Study of 45° Swept Wing</td>
<td>57</td>
</tr>
<tr>
<td>26. Variation with Sweepback of the Experimental and Estimated Values of $\Delta C_L$ Resulting from a Split-Flap Deflection of 60 Degrees</td>
<td>58</td>
</tr>
<tr>
<td>27. 60° Model with Split Flap</td>
<td>59</td>
</tr>
<tr>
<td>28. 60° Model with Six-Step Flap</td>
<td>60</td>
</tr>
<tr>
<td>29. 60° Model with Fowler Flap</td>
<td>61</td>
</tr>
<tr>
<td>30. 60° Model with Rotated Fowler Flap</td>
<td>62</td>
</tr>
<tr>
<td>31. 60° Model with Three-Step Split Flap</td>
<td>63</td>
</tr>
<tr>
<td>32. 45° Model with Split Flap</td>
<td>64</td>
</tr>
<tr>
<td>33. 45° Model with Six-Step Flap</td>
<td>65</td>
</tr>
<tr>
<td>34. 45° Model with Fowler Flap</td>
<td>66</td>
</tr>
<tr>
<td>35. 45° Model with Rotated Fowler Flap</td>
<td>67</td>
</tr>
<tr>
<td>36. 45° Model with Three-Step Split Flap</td>
<td>68</td>
</tr>
</tbody>
</table>
ANALYSIS OF WIND-TUNNEL INVESTIGATIONS
OF TRAILING-EDGE FLAPS ON SWEPT-BACK WINGS

I SUMMARY

Tests on two swept-back wings were conducted in the Georgia Tech nine-foot-diameter wind tunnel. The wings were semi-span models of NACA 65A006 profile maintained parallel to the plane of symmetry, with aspect ratio of 4, span 46 inches, and taper ratio 0.6; they differed only in the angle of sweepback, one being swept 45 degrees and the other 60 degrees. Five different types of trailing-edge full-span flaps were tested on each model. The flaps were Split, Six-Step or Staircase, Fowler, Rotated Fowler, and Three-Step Split. Each flap tested was deflected through four angles: 15, 30, 45, and 60 degrees.

The purpose of the tests was to determine the effect of various trailing-edge flaps on the aerodynamic characteristics of the swept wings and to determine the optimum flap and flap angle of the flaps used.

The effects of deflecting flaps on the lift are similar to those for a straight wing, although the increments caused by deflecting the flap are less. The general shape of the pitching moment curves is not altered greatly by deflecting flaps; however, there are large variations in the moment coefficients which are not desirable.
The optimum flap selected from the consideration of the greatest increase in maximum lift is the Fowler flap—for both the 45° and 60° swept wings. The optimum flap angle is 45 degrees for the 45° swept wing and 20 degrees for the 60° swept wing.
II INTRODUCTION

Until the beginning of World War II most airplanes were built with conventional wings, frequently rectangular in shape and without sweepback. These airplanes were designed to fly at speeds well below the speed of sound, and the wings used were quite satisfactory in this speed range. The limited number of swept wings which were built were only slightly swept, and their purpose was to locate properly the center of gravity in relation to the aerodynamic center of the wing. As the war progressed, however, and the speeds of military aircraft were increased, it became evident that some radical changes would have to be made for velocities in the neighborhood of the speed of sound. These changes would be necessary in order to prevent drag increases and also to eliminate the control difficulties which were being encountered.

If the velocity of the air over the wing of an aircraft approaches the local speed of sound at a Mach number of from 0.75 to 0.85, depending on the particular section, a critical condition develops which causes a radical change in the aerodynamic characteristics of the wing. At this critical speed, now known as "force break" speed, shock waves appear on the wings and control surface; there is a sudden increase in drag; a decrease in lift; and also a sudden shift in the center of pressure on the airfoil. The increase in drag is most undesirable. The sudden change in center of pressure and the decrease in lift require considerable adjustment of control surfaces. In many
instances the controls become ineffective, making the airplane difficult to control or even uncontrollable until a lower speed is reached.

Many theoretical considerations have been given to the problem and Betz\(^1\) in Germany and Jones\(^2\) in the United States proposed that the critical speed could be increased by giving the wings a fixed angle of sweepback.

In order to improve the characteristics of the wing in the vicinity of sonic speed, certain difficulties which need further study arise in the low-speed range. It is in this region of speeds that the present investigations are made.

The use of sweep is based on the concept that, for a wing with parallel leading and trailing edges, the lift—that is, the pressures which result in lift—is generated only by the velocity component perpendicular to the leading and trailing edges. Therefore when such a wing is yawed or swept, the velocity normal to the leading edge is reduced in proportion to cosine \(\Lambda\), or to the cosine of the yaw angle relative to the resultant velocity. Then the lift can be written as a good approximation

\[
L = \frac{1}{2} \rho V^2 \left( C_{L\alpha} \right)_{\Lambda=0} \propto \cos^2 \Lambda
\]

---


and 
\[ C_L = \frac{L}{\alpha} = (C_{L\alpha})_{\alpha=0} \propto \cos^2 \Lambda \]

making 
\[ (C_{L\alpha})_\Lambda = (C_{L\alpha})_{\alpha=0} \cos \Lambda \]

This theoretical value of \( C_{L\alpha} \) does not occur exactly in experiment, since the theory is not strictly applicable to tapered and finite-span wings. However, experiments in both Germany and the United States show that while the full gain indicated by theory is not attained, a swept wing does offer considerable advantage over an unswept wing. It has been found that at the wing center the sweepback effect does not completely occur, and also there is a three-dimensional flow about the wing tips causing a decrease in the effect of sweepback\(^3\), particularly for low aspect ratio.

From lifting line theory the slope of the lift curve with sweepback and aspect ratio corrections added that appear to give the best agreement with values obtained by experiment is:

\[ (C_{L\alpha})_\Lambda = \frac{(A+1) \cos \Lambda}{A+2 \cos \Lambda} \quad (C_{L\alpha})_{\alpha=0} \]

where
\[ (C_{L\alpha})_{\alpha=0} = \frac{A \alpha_0}{A+2} \]

\(^3\)Durand, op. cit., p. 97.

is the slope of lift curve for unswept wings. The slope of the lift curve is therefore reduced as the angle of sweepback is increased, providing the other parameters of the wing are held constant. This really amounts to an increase in the angle at which the wing stalls as the angle of sweepback is increased. Two disadvantages arise from this reduction in the lift curve slope due to sweep. First, the take-off run of swept-wing aircraft will of necessity have to be longer in order that the required lift for flight can be obtained. Second, the main landing gear must be made excessively long in order for the aircraft to obtain a reasonable landing speed.

It seems necessary to use some type of flaps to obtain maximum lift at a reasonable angle of attack. Several types have been suggested and these fall into two general groups; namely, leading-edge and trailing-edge flaps. For the present investigation only the trailing-edge types are considered.

Several types of trailing-edge flaps are used successfully on straight wings. Probably the two most commonly used types are the split and Fowler flaps. They are constructed and mounted so that the flap chord is a constant percentage of the chord of the wing, and when the wing is swept back the hinge line of the flap is swept back also. Since the lift coefficient of a swept wing is reduced due to sweepback, then the effectiveness of the flap likewise will be decreased.

---

as the effective flap deflection angle \( \Delta_\varphi = \int \cos \alpha \, \Delta \zeta \),

where \( \Delta_\varphi \) is the effective deflection angle measured in the plane of symmetry.\(^6\) Thus the present experiments are concerned with testing the conventional-type flaps and then taking out, or at least reducing, the sweep of the flap hinge axis.

The split flap selected had a chord equal to 0.3c the chord of the models, and the trailing edge of the flap was mounted flush with the trailing edge of the wings. The sweepback of the quarter chord \( \Delta \zeta /c \) of the wings is 45 degrees and 60 degrees and the flaps are mounted at a constant 0.7c, making the sweepback of the hinge axis \( \Delta \zeta \) 41.75 and 58.3 degrees, respectively. After the tests were completed, each split flap was separated into three segments and then remounted with the sweep angle of the hinge line of the flap reduced for each model. For the 45° model it was 0 degrees, and for the 60° model it was 41.75 degrees.

The Fowler flap selected was of NACA 4412 profile with a chord equal to 0.3c of the wing. The flap was mounted at the optimum location on each wing as determined for rectangular wings.\(^7\) The sweepback \( \Delta \zeta \) of the Fowler flap was also the same as that of the wing on

---


which it was mounted. To slightly reduce $\Lambda_{k}$ for the flap, the outboard end was rotated, giving $\Lambda_{k}$ of 34 degrees for the 45° model and $\Lambda_{k}$ of 52 degrees for the 60° model.

One other flap, called a step or staircase flap, was next tested. It consisted of six segments which were mounted with $\Lambda_{k} = 0$ degrees for both models. For a complete description of this type refer to Figures 2 and 4.

The five flaps were tested to determine their effect on the aerodynamic characteristics of the swept wings and to determine the optimum flap and flap angle for swept wings with trailing-edge flaps.
III APPARATUS AND MODELS

The tests were conducted in the nine-foot-diameter wind tunnel at Georgia Tech. The tunnel is a single-return type with a closed jet and is capable of speeds of approximately 125 miles per hour. The power is furnished by a 2300-volt synchronous motor connected to a constant speed propeller, and the velocity through the test section is varied by changing the pitch of the propeller. The wind velocity is accurately held at the desired range by calibrating a double piezometer ring against the velocity in the test section.

The test models were constructed of aluminum spars covered with 1/8-inch sheet aluminum alloy, with the exception of the leading edge ahead of the 0.25c station which was made of laminated mahogany. Both models were semi-span with NACA 65A006 profile parallel to plane of symmetry, with aspect ratio 4, span 48", and taper ratio 0.6. The only difference in the models was the sweep angle—one being swept back 45 degrees and the other being swept back 60 degrees.

A total of five flaps was tested on each model. The full-span split flap was constructed of 1/8-inch sheet aluminum alloy. The flap had a chord equal to 0.30 the chord of the model, and when mounted the trailing edge was flush with the trailing edge of the model as shown in Figures 27 and 32.

The step or staircase flap consisted of six small flap segments. These also were made of 1/8-inch sheet aluminum alloy. The details of mounting are shown in Figures 2 and 4.
A Fowler flap made of laminated mahogany and NACA 4412 profile was tested next. The flap had a chord equal to 0.30 of the chord of the model and was mounted at \( X = 100\% \) and \( Y = -2.5\% \). This position was selected as it gives the optimum location for the Fowler flap on rectangular wings \(^1\). (See Figures 29 and 34).

The other two flaps were modifications of the split and Fowler flaps. The split flap was cut into three segments and each segment was mounted as shown in Figures 2 and 14. The Fowler flap was rotated on the wing (See Figures 2 and 14) to a position corresponding to a position of smaller angle of sweepback.

Each model was mounted flush on a circular disc which is at the same level as the floor of the tunnel. The mount was rigidly clamped to the balance support. Readings of lift, drag, and moment were taken for all tests by means of the electronically controlled balance system which is installed in the wind tunnel.

\(^1\)Platt, op. cit., p. 2.
Before any tests were started, the tunnel, with open jet and with the model out, was calibrated for the variation of velocity through the jet against the height of the liquid in the manometer which was attached to the double piezometer ring. In addition, a longitudinal velocity survey was conducted to insure that the variation in velocity through the section where the model was mounted would not be great enough to affect the accuracy of the results. Then the model was mounted in the test section and a test was made.

The model was removed; the test section was erected; and the same calibration was repeated. Then the model was replaced and another test completed. The purpose of both the open and closed jet runs was to determine, if possible, the effect of the jet boundary on the swept wing.

The 60° model was tested first. A support wire was fastened to this model and to the disc for the purpose of preventing excessive deflections caused by the unusually large pressure forces on the model at high angles of attack. Part of the tests was made at a dynamic pressure of 36.79 lbs. per sq. ft. and the remainder at 25.4 lbs. per sq. ft. corresponding to an effective Reynolds number of $3.9 \times 10^6$ and $3.25 \times 10^6$, respectively. These figures are based on the mean aerodynamic chord of 24.5".

The procedure for testing was in the following order: (1) A base run was obtained for the wing alone. (2) A flap was placed on
the model and then four additional runs were made at the four flap-
deflection angles of 15, 30, 45, and 60 degrees. In all runs the lift, drag, and moment were read for all angles of attack, including the stall, while the velocity over the model was held constant.

After the tests on the 60° model were completed, the 45° model was placed in the tunnel and mounted in the same position. This model was tested at a dynamic pressure of 36.79 lbs. per sq. ft., which corresponds to an effective Reynolds number of 3.9 x 10^6. The tests were conducted in the same manner as those on the 60° model.

In addition to the flap studies, visual observations were made of the flow pattern over each wing at angles of attack to the stall by placing tufts at regular intervals along the span and chord of the wing.
V ACCURACY OF DATA

Since no data were available for the boundary corrections of swept-back panel models (with reflection plane), corrections similar to those for unswept reflection plane models were applied to the drag coefficient and angle of attack. The corrections applied are

\[ \Delta C_{D_i} = 0.0130 \ C_L^2 \]
\[ \Delta \alpha = 0.742 \ C_L \]

The data have also been corrected for the drag of the endplate and support wire (which was used on the 60° model only).

It is doubtful that the absolute values of the coefficients can be considered correct for the 60° model, but the incremental values of \( C_L \), \( C_D \), and \( C_m \) should be relatively independent of the endplate tare, wall effect, and interference. The data obtained at angles of attack greater than 30 degrees with the 60° swept model may be less accurate since, at high angles of attack, the tip of the wing was close to the tunnel wall and no additional corrections were applied for this condition. However, the absolute values of the coefficients for the 45° model, as well as the incremental values, are believed to be well within the range of experimental accuracy.

---


2 Ibid.
The model angle of attack was set within \( \pm 0.1 \) degree and flap angles are accurate to within \( \pm 0.5 \) degree. The extremely low lift coefficient developed at zero angle of attack for both models indicates that inaccuracies in model contours are negligible.
Plain Wing. The shape of the lift and pitching moment curves for the 45° and 60° swept wings are not linear (Figures 5 and 10) as are those of wings without sweep. The 60° wing shows a slight increase in the slope of the lift curve at a lift coefficient of approximately 0.2, and the 45° wing shows an increase at a lift coefficient of approximately 0.5. This increase in slope is attributed to an increase in the lift at the wing tip. Tuft observations of the wing at this point also show that there is a roughness developed in the flow all along the leading edge, with the exception of that portion of the wing near the root.

At a lift coefficient of 0.5 for the 60° wing and 0.7 for the 45° wing, the lift curve rounds out and begins to decrease. The pitching moment curve which has been stable up to this point suddenly shifts and turns in the unstable direction. This instability has been shown to be a function of aspect ratio and taper ratio in addition to the angle of sweepback. Considering taper to be of secondary importance, large aspect ratios generally give unstable pitching moment curves on wings with large amounts of sweepback. The decrease in lift curve slope is caused by the tip of the wing stalling; the decrease in stability follows directly because, as the tip stalls, the center of pressure moves forward causing the tail heavy moment. The center of pressure is

---

measured with respect to the normal c/h reference. A tuft study (See Figures 24 and 25) in this region substantiates the reasoning that the instability is a direct effect of shifting of the load inboard and thus forward. A tuft study indicated that the tip was stalled and that the flow over practically the entire upper surface was parallel to the leading edge.

The lift curve slope continually decreases from lift coefficients of 0.5 and 0.7 for the two wings until maximum lift is reached. The value of the lift coefficient at maximum lift is 1.0 for the 60° wing at an angle of attack of 42 degrees, and for the 45° wing the maximum lift coefficient is 1.1 at 28 degrees.

After reaching the maximum lift coefficient, the lift curves for the swept wings show another distinct difference from wings with no sweep. For a wing without sweep the curve usually breaks suddenly, and two or three degrees after maximum lift has been reached the lift coefficient is probably only half that of maximum lift. However, since the separation for the swept wings occurs gradually and is not as violent as that for the plain wing, the lift coefficients adjust themselves and are only slightly lower than maximum lift for several degrees after the stall.

A comparison of the experimental and theoretical values of the slope of the lift curves with angle of sweepback is given in Figure 15. The value of the lift curve slope, measured at $\alpha = 0$ for the 60° wing, is 0.042 as obtained from Figure 5, and for the 45° wing a value of 0.054 is obtained from Figure 10. Calculation of the slope by use of the lifting line theory
\[ (C_{L\infty})_{\Lambda} = \frac{(A+2)(C_{\infty})_{\Lambda}}{A^2(C_{\infty})_{\Lambda}} \]

yields 0.043 for the 60° wing and 0.056 for the 45° wing. Both the experimental and calculated values are in good agreement with values obtained by Letko\(^2\).

**Wing With Various Types of Trailing-Edge Flaps.** In an attempt to increase the maximum lift coefficient and also to decrease the angle at which the wing stalls, a series of five different types of trailing-edge flaps were tested.

The effect of deflecting each of the flaps from 0 to 60 degrees on the aerodynamic coefficients of the 45° and 60° swept-back wings is shown in Figures 5-14. The effects on lift are similar to those for a straight wing, although the increments caused by deflecting the flap are less. At the higher flap deflection angles, the maximum lift coefficient is less than that obtained at smaller deflection angles. Maximum lift occurs also at a slightly lower angle of attack for the wing with flap deflected. The general shape of the pitching moment curve is not greatly altered due to deflecting flaps, as can be seen from the graphs, the inflections remaining at about the same points; however, the absolute values of \( C_m \) are increased negatively.

To determine the optimum flap and flap angle for the 60° swept wing, the increment in the maximum lift \( \Delta C_{L_{\text{max}}} \) with flap deflection

---

\(^2\) William Letko and Alex Goodman, *Preliminary Wind-Tunnel Investigation at Low Speed of Stability and Control Characteristics of Swept-Back Wings*, (U. S. National Advisory Committee for Aeronautics, Technical Memorandum No. 1046, April 1946), Figure 36.
\( \sigma_F \) for each flap is given in Figure 16. The greatest increment in maximum lift of 0.4 is obtained from the Fowler flap when it is deflected 20 degrees. The rotated Fowler flap reaches the next highest value of 0.35 at the same flap deflection angle of 20 degrees. It appears, on the basis of these tests, that rotating the outboard end of the Fowler flap to decrease the effective sweepback gives no advantages over the plain Fowler flap. The flow over the tip portion of the wing is probably disturbed by the junction of the two surfaces (Figure 2), causing the decrease in lift.

The six-step flap shows an increase in the maximum lift coefficient of 0.0014 as compared with the wing alone, and the three-step split flap is totally ineffective, giving a decrease in maximum lift coefficient for all flap deflection angles. Both of these flaps are impractical on the 60° wing, considering the fact that they show no advantage over the wing alone in lift, and also from the structural standpoint they would be difficult to incorporate in the wing. This same conclusion was reached for the same type flaps in Germany; however, their experiments were conducted on extremely small models at low Reynolds numbers.³,⁴

The split flap indicates a relatively small \( \Delta C_{L_{\text{max}}} \) of 0.05;


⁴H. Luetgebrune, Contributions to Sweep-Back Research, (Translation, Headquarters Air Materiel Command, Wright Field, Dayton, Ohio, December 1946), p. 44.
but the deflection angle at which this occurs is approximately 45 degrees, giving a high $C_D$, the angle of attack for maximum lift having been reduced to 39 degrees. Other test data show that a half-span split flap on a 60° swept wing produces no increment in $C_{L_{\text{max}}}$. On the basis of the possibility that the effectiveness of the split flap could be improved and since from the structural standpoint no problems are presented, the split flap may not be entirely useless. In other experiments, although the flap gave no $\Delta C_{L_{\text{max}}}$, the belief was expressed that the effectiveness of this type of flap could be improved by increasing the depth of the flap up to 0.4c and by choosing better flap hinge locations.

At zero angle of attack the Fowler flap shows an appreciable increment in lift ($\Delta C_L$) over the wing alone, although the step flap shows the largest increment at this angle for all flap deflections (Figure 17). Figure 7 again shows that at the optimum deflection angle up to and including $C_{L_{\text{max}}}$ the Fowler flap gives the largest increments in lift at angles of attack greater than zero.

Figures 18a and 18b show the variation in drag ($\Delta C_D$) with flap deflections at various angles of attack. At the larger angles, corresponding to the probable landing range, the Fowler flap gives the largest $\Delta C_D$ in the region of the optimum deflection angle. It is considered desirable to have as large a value of $D/L$ as possible since $D/L$ is the tangent of the angle of glide, consequently allowing the

---

airplane to make steeper and shorter approaches.

The increment of the pitching moment coefficient \( \Delta C_m \) due to flap deflection for the various flaps is given in Figures 19a and 19b at selected constant angles of attack. At angles of attack of zero and 12 degrees the rotated Fowler flap gives the largest variation with flap deflection, but for 24 and 30 degrees the Fowler flap exhibits the largest increments in \( \Delta C_m \). This variation in the moment due to deflecting the flap is highly undesirable, as the control movement required to trim out this moment would be excessively large and would also vary greatly with flap deflection. Of course if the wing is considered on an actual airplane, the tail would change the pitching moment with flap deflection. However, the practice at the present time is to try to select a configuration which will give the least possible moment coefficient as the flap is deflected to a given angle. Thus it may be necessary to select other than the Fowler flap to obtain better pitching moment characteristics.

To determine the optimum flap and flap angle for the 45° model, the increment in maximum lift (\( \Delta C_{L\text{\_max}} \)) for each flap and each deflection angle is plotted in Figure 20. The greatest value obtained is from the Fowler flap, although the deflection angle is somewhat larger than that obtained for the 60° wing with the same flap. A \( \Delta C_{L\text{\_max}} \) of 0.54, with the flap deflected 45 degrees, is obtained in this case. At zero angle of attack the Fowler flap shows the largest increase in lift over the wing alone (Figure 21) for all deflection angles, and the same is true for all angles of attack, including the stall. The
rotated Fowler flap reached the next highest \( \Delta C_L \max \) of 0.42 at the same deflection angle. The split flap gives a \( \Delta C_L \max \) of 0.19 at a flap deflection of 30 degrees, the six-step flap 0.095 at 45 degrees, and the three-step split flap is again totally ineffective. The only experimental data which can be found as a comparison for any of these flaps for a 45° swept wing show that a 0.2c half-span split flap deflected 60 degrees gives a \( \Delta C_L \max \) of 0.1 as compared to 0.04 for the present experiment at the same flap deflection.\(^7\)

Figures 22a and 22b show the increment in drag (\( \Delta C_D \)) due to flap deflection for the 45° model. It is noted that the variation at all angles of attack is more uniform than that of the 60° wing. At maximum lift the Fowler flap gives the greatest value of D/L and indicates that the 45° wing with this type flap would give the greatest glide angle.

Figures 23a and 23b show the increment in moment at selected angles of attack due to flap deflection for the 45° wing. At all angles of attack the Fowler flap gives the largest variation in moment when the flap is deflected to a given angle. The rotated Fowler flap shows the next largest variation. The moment variation for the split flap is small and does not vary as greatly as that for the Fowler-type flaps. Again as in the case of the 60° wing the moment is of major concern when selecting a flap configuration for a swept wing.

All of the flaps, with the exception of the three-step split type, verify the theoretical consideration that \( \Delta C_L \max \) and \( \Delta C_L \)

\(^7\)Letko and Goodman, op. cit., Figure 18a.
decrease with increasing angles of sweepback. As a comparison between theory and experiment, Figure 26 is presented giving calculated and experimental results for the split flap deflected 60 degrees against the angle of sweepback. Values of $\Delta C_L$ at $\alpha = 0$ for the $45^\circ$ and $60^\circ$ wings are 0.50 and 0.275, respectively. (Figures 5 and 10) The value of $(\Delta C_L)_{\alpha=0} = 1.3$, corresponding to a wing without sweep, is obtained from sectional data for a NACA 65-006 profile. From the theoretical consideration

$$\Delta C_L = (\Delta C_L)_{\alpha=0} \cos^2 \Lambda$$

gives values of 0.65 and 0.325 for the $45^\circ$ and $60^\circ$ wings, respectively.

The experimental values of $\Delta C_L \max$ obtained from the present tests are also presented in Figure 26. As a comparison, one other experiment recorded an increase in $\Delta C_L \max$ of 12% for a $45^\circ$ swept wing with the same type flap. Using this value a $\Delta C_L \max$ of 0.13 is predicted, as compared to the value of 0.04 obtained.

The decrease in flap effectiveness is found to be even greater than that predicted by theory; however only the split flap could be compared as no data on the other flap configurations are available on rectangular wings with the NACA 65A006 profile. Some of the discrepancies in the present calculations may be accounted for also as 65-006 data

---


9 Betz and Buseman, op. cit., p. 31.
were used. There is a possibility that the effectiveness of the split flap on the swept wing may be increased to a closer agreement with theory by further experiments on this type of flap, varying the chord and hinge location as the angle of sweepback is varied.

As a result of the present investigation it may be possible to improve the effectiveness of some of the flaps tested, especially the rotated Fowler and the split flaps. If it were structurally possible to rotate the Fowler flap so that the tip would be free of the wing tip, then some of the theoretical effectiveness might be obtained. On the 60° wing with the split flap deflected (Figure 27), there is a possibility that the inboard end of the flap can be sealed to prevent the air from going behind the flap. This experiment was attempted and a considerable gain in lift was obtained at moderate angles of attack; however, $C_{L_{max}}$ was not increased.
VII CONCLUSIONS

From the results of the present investigation, the following conclusions are drawn:

1. The maximum lift of swept-back wings decreases as the angle of sweepback is increased from 45 to 60 degrees. In the present tests a maximum lift coefficient of 1.1 is obtained for the 45° swept wing and 1.0 for the 60° swept wing. The Reynolds number is the same for both tests.

2. Flap effectiveness on swept wings decreases with increasing sweepback. For sweep angles as great as 60 degrees the conventional split flap, for instance, gives an increase in maximum lift over the wing alone of only 0.035 and for the 45° model the same flap gives an increase of 0.189.

3. From the consideration of increase in maximum lift, the Fowler flap is the optimum configuration for both the 45° and 60° swept wings tested. The optimum flap angle is found to be 45 degrees on the 45° model and 20 degrees for the 60° model.

4. The stability of the swept wings is satisfactory in the low angle of attack ranges, with and without trailing-edge flaps. At approximately an 8° angle of attack for the 45° and 60° wings, the stability decreases giving tail heavy moments for both wings.
5. As a result of the present investigation it may be possible to improve the effectiveness of some of the flaps tested, especially the rotated Fowler and the split flaps.

6. Because of the extremely thin airfoils which were used for the present investigation, it may be more advantageous to use the plain split flap in view of the fact that there are no structural difficulties encountered and the variation in moment due to flap deflection is not excessively large, even though the increase in maximum lift is not as great as might be desired.
BIBLIOGRAPHY


APPENDIX I

Figures
Fig. 1 Planform dimensions of 60° swept wing.
Fig. 2 Schematic arrangement of special flaps - 60° model.
Fig. 3 Planform dimensions of 45° swept wing.
Fig. 4 Schematic arrangement of special flaps - 45° model.
VARIATION OF THE AERODYNAMIC COEFFICIENTS WITH ANGLE OF ATTACK FOR A 60° SWEPT-BACK WING WITH A FULL-SPAN SPLIT FLAP
VARIATION OF THE AERODYNAMIC COEFFICIENTS WITH ANGLE OF ATTACK FOR A 60° SWEPT-BACK WING WITH A SIX-STEP FLAP
VARIATION OF THE AERODYNAMIC COEFFICIENTS WITH ANGLE OF ATTACK FOR A 60° SWEPT-BACK WING WITH A FOWLER FLAP
VARIATION OF THE AERODYNAMIC COEFFICIENTS WITH ANGLE OF ATTACK FOR A 60° SWEPT-BACK WING WITH A ROTATED FOWLER FLAP
FIGURE 9

VARIATION OF THE AERODYNAMIC COEFFICIENTS WITH ANGLE OF ATTACK FOR A 60° SWEEPBACK WING WITH A THREE-STEP SPLIT FLAP
VARIATION OF THE AERODYNAMIC COEFFICIENTS WITH ANGLE OF ATTACK FOR A 45° SWEPT-BACK WING WITH A SPLIT FLAP
Variation of the aerodynamic coefficients with angle of attack for a 45° swept-back wing with a six-step flap.
VARIATION OF THE AERODYNAMIC COEFFICIENTS WITH ANGLE OF ATTACK FOR A 45° SWEPT-BACK WING WITH A FOWLER FLAP
VARIATION OF THE AERODYNAMIC COEFFICIENTS WITH ANGLE OF ATTACK FOR A 45° SWEEP-BACK WING WITH A ROTATED FOWLER FLAP
FIGURE 114

VARIATION OF THE AERODYNAMIC COEFFICIENTS WITH ANGLE OF ATTACK FOR A 45° SWEPT-BACK WING WITH A THREE-STEP SPLIT FLAP
LEGEND "A"

1. ○ Theoretical
2. ▲ Experimental

FIGURE 15

VARIATION OF THE THEORETICAL AND EXPERIMENTAL VALUES OF $C_{L\infty}$ WITH SWEEPBACK
VARIATION OF MAXIMUM LIFT COEFFICIENTS WITH FLAP DEFORMATION FOR THE 60° SWEPT WING
INCREMENT IN LIFT COEFFICIENT WITH FLAP DEFLECTION FOR THE 60° SWEPT WING
FIGURE 18a
INCREMENT IN DRAG COEFFICIENT WITH FLAP DEFLECTION FOR THE 60° SWEPT WING
FIGURE 18b

INCREMENT IN DRAG COEFFICIENT WITH FLAP DEFORMATION FOR THE 60° SWEPT WING
**FIGURE 19a**

INCREMENT IN PITCHING MOMENT COEFFICIENT WITH FLAP DEFLECTION FOR THE 60° SWEPT WING
FIGURE 19b

INCREMENT IN PITCHING MOMENT COEFFICIENT
WITH FLAP DEFLECTION FOR THE 60° SWEPT WING
VARIATION OF MAXIMUM LIFT COEFFICIENT WITH FLAP DEFLECTION FOR THE 45° SWEPT WING
Figure 21

Increment in lift coefficient with flap deflection for the 15° swept wing.
FIGURE 22a

INCREMENT IN DRAG COEFFICIENT WITH
FLAP DEFLECTION FOR THE 45° SWEEP WING
FIGURE 22b

INCREMENT IN DRAG COEFFICIENT WITH FLAP DEFLECTION FOR THE 45° SWEPT WING
FIGURE 23a
INCREMENT IN PITCHING MOMENT COEFFICIENT
WITH FLAP DEFLECTION FOR THE 45° SWEPT WING
Figure 23b
Increment in Pitching Moment Coefficient with Flap Deflection for the 45° Swept Wing
$\alpha = +5$

$\alpha = 10$

$\alpha = 15$

$\alpha = 20$

$\alpha = 25$

$\alpha = 30$

1. SMOOTH
2. ROUGH
3. PART. STALL
4. STALL

FIG. 24 TUFT STUDY 60° MODEL
LEGEND "A"

1. ○ $\Delta C_L$ FROM THEORY
2. △ $\Delta C_L$ FROM EXPERIMENT
3. □ $\Delta C_L_{\text{max}}$ FROM EXPERIMENT

VARIATION WITH SWEEPBACK OF THE EXPERIMENTAL AND ESTIMATED VALUES OF $\Delta C_L$ RESULTING FROM A SPLIT-FLAP DEFLECTION OF 60 DEGREES
FIGURE 27. 60 DEGREE MODEL WITH SPLIT FLAP
FIGURE 28. 60 DEGREE MODEL WITH SIX-STEP FLAP
FIGURE 29. 60 DEGREE MODEL WITH FOWLER FLAP
FIGURE 30. 60 DEGREE MODEL WITH ROTATED FOWLER FLAP
FIGURE 31. 60 DEGREE MODEL WITH THREE-STEP SPLIT FLAP
FIGURE 32. 45 DEGREE MODEL WITH SPLIT FLAP
FIGURE 33. 45 DEGREE MODEL WITH SIX-STEP FLAP
FIGURE 34. 45 DEGREE MODEL WITH FOWLER FIAP
FIGURE 35. 45 DEGREE MODEL WITH ROTATED FOWLER FLAP
FIGURE 36. 15 DEGREE MODEL WITH THREE-STEP SPLIT FLAP