Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Optimum Flap Schedules and Minimum Drag Envelopes for Combat Aircraft

B. Rajeswari*
National Aeronautical Laboratory, Bangalore, India
and
K.R. Prabhu†
Kentron, Inc., Hampton, Virginia

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>aspect ratio</td>
</tr>
<tr>
<td>b</td>
<td>wing span</td>
</tr>
<tr>
<td>c(η)</td>
<td>local chord</td>
</tr>
<tr>
<td>C_D</td>
<td>total drag coefficient</td>
</tr>
<tr>
<td>C_DL</td>
<td>lift-dependent drag coefficient</td>
</tr>
<tr>
<td>C_DLM</td>
<td>minimum drag envelope</td>
</tr>
<tr>
<td>C_DPL</td>
<td>lift-dependent profile drag coefficient</td>
</tr>
<tr>
<td>C_DV</td>
<td>vortex drag coefficient</td>
</tr>
<tr>
<td>C_L</td>
<td>lift coefficient</td>
</tr>
<tr>
<td>C_La</td>
<td>wing lift curve slope with respect to angle of attack, leading-edge flap deflection angle, and trailing-edge flap deflection angle, respectively</td>
</tr>
<tr>
<td>C_d</td>
<td>sectional drag coefficient</td>
</tr>
<tr>
<td>C_dmin</td>
<td>minimum profile drag</td>
</tr>
<tr>
<td>C_i</td>
<td>section lift coefficient</td>
</tr>
<tr>
<td>C_i0</td>
<td>lift coefficient at minimum drag—also ideal lift coefficient</td>
</tr>
<tr>
<td>F</td>
<td>quantity proportional to C_DPL</td>
</tr>
<tr>
<td>K_P</td>
<td>lift-dependent profile drag factor</td>
</tr>
<tr>
<td>K_T</td>
<td>lift-dependent drag factor of minimum drag envelope</td>
</tr>
<tr>
<td>k</td>
<td>lift-dependent drag factor for a section</td>
</tr>
<tr>
<td>L/D</td>
<td>lift-to-drag ratio</td>
</tr>
<tr>
<td>S</td>
<td>wing area</td>
</tr>
<tr>
<td>y</td>
<td>spanwise station</td>
</tr>
<tr>
<td>α</td>
<td>angle of attack (with respect to wing chordal plane)</td>
</tr>
<tr>
<td>α_i0(η)</td>
<td>distribution of total induced angle of incidence</td>
</tr>
<tr>
<td>β</td>
<td>leading-edge flap deflection angle</td>
</tr>
<tr>
<td>γ</td>
<td>trailing-edge flap deflection angle</td>
</tr>
<tr>
<td>Τ(η)</td>
<td>spanwise loading</td>
</tr>
<tr>
<td>η</td>
<td>= y/(b/2)-nondimensional spanwise station</td>
</tr>
<tr>
<td>ΔC_P</td>
<td>chordwise loading</td>
</tr>
<tr>
<td>β_o</td>
<td>optimum leading-edge flap deflection angle</td>
</tr>
<tr>
<td>γ_o</td>
<td>optimum trailing-edge flap deflection angle</td>
</tr>
</tbody>
</table>

Introduction

WING leading- and trailing-edge flaps are usually deployed to improve the lifting ability of wings, especially during takeoff and landing. In recent times, however, these flaps have been used also during maneuver conditions to improve the aerodynamic efficiency (L/D). Some examples of aircraft using such devices are F-4E, F-8E, F-16, F-18, etc. During a maneuver, the flaps automatically follow a predetermined deflection schedule which is a function of Mach number and angle of attack. The flap deflection schedule is mainly determined through extensive wind-tunnel tests.

In this paper, a simple analytical method based on linear theory is developed to determine the optimum flap schedule for both leading- and trailing-edge flaps.

Problem Formulation and Method of Solution

If the drag polars are plotted for various flap deflections β and γ, then the envelope of these polars defines the minimum drag envelope. The corresponding deflections β_opt and γ_opt, which minimize the lift-dependent drag C_DL, define the optimum flap schedule.

Lift-Dependent Profile Drag

For a cambered airfoil, the drag polar can be fairly well represented by the relation

\[ C_d = C_d_{\text{min}} + k(C_i - C_i0)^2 \]

(1)

To a first approximation, C_i and C_d can be taken to be functions of camber alone. Extending these arguments to each spanwise section of a three-dimensional wing (i.e., assuming that the wing is composed of a series of two-dimensional airfoils of varying camber and thickness), the lift-dependent profile drag C_DPL can be determined by integrating Eq. (1) across the span and is written as

\[ C_{DPL} = \frac{1}{S} \int_{-b/2}^{b/2} K_P (C_i - C_i0)^2 c dy = K_P F \]

(2)

where K_P is a constant (being independent of camber), and

\[ F = \frac{1}{S} \int_{-b/2}^{b/2} (C_i - C_i0)^2 c dy \]

(3)

For a wing at an incidence α, C_i(α) and C_i0 can be expressed in accordance with linear theory as

\[ C_i(α) = a_1 α + a_2 β + a_3 γ \]

(4)

\[ C_i0 = a_4 β + a_5 γ \]

Fig. 1 Flap schedule of F-18 aircraft.
where \( a_1, \ldots, a_6 \) are constants. Substituting these in Eq. (3) and carrying out the integration, \( F \) can be expressed as a quadratic in \( C_L, \beta, \) and \( \gamma \):

\[
F = A_1 C_L^2 + A_2 \beta^2 + A_3 \gamma^2 + A_4 \beta C_L + A_5 \beta \gamma + A_6 \gamma C_L
\]

Here, \( C_L = C_L, \alpha + C_L, \beta + C_L, \gamma \) for small \( \alpha, \beta, \) and \( \gamma \).

The lift-dependent profile drag factor \( K_p \) is determined by the use of data correlation curves given in Refs. 1 and 2. The ideal lift coefficient \( C_L \) and zero lift incidence on stations of wing with deflected flaps are calculated using the local loading \( \Delta C_p \) and \( C_L (\eta) \) formulae given in Ref. 3 modified to include a leading-edge flap. The details of these calculations are given in Ref. 4.

### Vortex Drag

McKee's method\(^3\) for calculation of spanwise load distribution on wings with spanwise discontinuities in angle of incidence and/or wing chord has been adopted here for wings with plain leading- and trailing-edge flaps. Once the load distribution \( \Gamma(\eta) \) is known, the spanwise distribution of local lift \( C_l(\eta) \) is related to \( \Gamma(\eta) \) by

\[
C_l(\eta) = (2b/c) \Gamma(\eta)
\]

The total lift and vortex drag coefficients are

\[
C_L = A \int_{-1}^{+1} \Gamma(\eta) \, d\eta
\]

\[
C_{DV} = A \int_{-1}^{+1} \Gamma(\eta) \alpha_0(\eta) \, d\eta
\]

Within the limits of linear theory, \( C_{DV} \) can be expressed as a quadratic

\[
C_{DV} = B_1 C_L^2 + B_2 \beta^2 + B_3 \gamma^2 + B_4 \beta C_L + B_5 \beta \gamma + B_6 \gamma C_L
\]

where \( B_1, B_2, \ldots, B_6 \) are constants.

### Total Lift-Dependent Drag

Since both \( C_{DV} \) and \( F \) are quadratic in \( C_L, \beta, \) and \( \gamma, \) the total lift-dependent drag is also a quadratic and can be expressed as

\[
C_{DL} = C_{DV} + K_p F = C_L C_L^2
\]

\[+ C_3 \beta^2 + C_4 \gamma^2 + C_5 \beta C_L + C_6 \beta \gamma + C_7 \gamma C_L \]

where \( C_1, C_2, \ldots, C_6 \) are constants.

### Flap Schedule and Minimum Drag Envelope

To get the flap schedule, \( C_{DL} \), Eq. (10) is minimized with respect to \( \beta \) and \( \gamma \) for a given \( C_L \). The first derivatives of \( C_{DL} \) with respect to \( \beta \) and \( \gamma \) are equated to zero. The resulting values of \( \beta_{opt} \) and \( \gamma_{opt} \) are substituted in Eq. (10), and the minimum drag envelope is given by

\[
C_{DLm} = K_T C_L^2
\]

where \( K_T \) is a constant and the constants \( C_1, C_2, \ldots, C_6 \) are determined by knowing the total lift-dependent drag coefficient for various values of \( \beta \) and \( \gamma \).

### Results

Figure 1 gives a comparison of leading- and trailing-edge flap schedules and Fig. 2 the resulting minimum drag envelope for F-18 aircraft.\(^5\) The comparison of flap schedules between theory and experiment for the F-18 aircraft (Fig. 1) does not seem to be very good. A possible reason for this could be the relative insensitivity of the drag coefficient to flap deflection angle, at least around the flap angles for minimum drag and at the lift coefficients under consideration.

Figure 2 shows that for the undeflected flap case, the estimated drag departs from the experimental one for \( C_L > 0.4 \), indicating the limits of the linear theory. However, with the flaps deflected (both leading and trailing edge), the agreement between experiment and estimation is remarkably good even for \( C_L \) of about 0.9. This can possibly be attributed to the ability of the leading-edge flaps in maintaining attached flow at these high \( C_L \) values.

A comparison of the drag envelope for the F-16 aircraft with and without programmable leading-edge flaps was made. The decrease in \( C_{DL} \) when flaps are employed is quoted as 18% in Ref. 6, which compares well with about 15% obtained from the present method. Figure 3 displays another comparison between theory and tests conducted at the National Aeronautical Laboratory on an aircraft model (aspect ratio \( A = 3.2 \)) at a Mach number of 0.5. These tests were done with and without trailing-edge flaps deflected. Figure 3 shows that the trailing-edge flap deflection schedule is predicted reasonably well by the theory.
Conclusions

A simple method based on linear theory has been developed for the determination of trailing- and leading-edge flap deflection schedules to obtain minimum lift-dependent drag (or equivalently maximum lift-to-drag ratio). The resultant lift-dependent drag polar can also be determined. Extensive comparisons with available experimental results have proved the general validity of the method. It is expected that this method would be useful in the preliminary design phase of an aircraft and also in reducing later on the quantum of wind-tunnel testing needed to determine flap schedules.

Acknowledgments

The first author wishes to acknowledge Dr. K. Yegna Narayan and Dr. H.N.V. Dutt for valuable suggestions and encouragement during the preparation of this paper.

References

1 Subsonic Lift Dependent Drag Due to Boundary Layer of Plane Symmetric Section Wings, ESDU, Royal Academy of Engineering, 60031-32, 1966.
2 RAE Data Sheets, Aerodynamics, Vol. 2, Wings, Royal Academy of Engineering, 01.01.01, 1953 and 01.01.05, 1955.

Bombing Error Sensitivities Using a Simplified Aerodynamic Trajectory

William D. Siuru Jr.*  
University of Colorado at Colorado Springs  
Colorado Springs, Colorado

Nomenclature

\( C_D \) = drag coefficient of bomb  
\( C_I \) = crossrange impact point  
\( C_R \) = crossrange release point  
\( d \) = diameter of bomb  
\( D_I \) = downrange impact point  
\( D_R \) = downrange release point  
\( E \) = exponential constant  
\( h_o \) = altitude at bomb release  
\( g \) = gravitational constant  
\( K_D \) = drag factor  
\( m \) = mass of bomb  
\( R_B \) = ballistic range  
\( T_f \) = time of fall  
\( V_o \) = airspeed of bomb at release  
\( V_{ave} \) = average velocity during time of flight

Introduction

Errors in determining the initial conditions at bomb release, i.e., airspeed, altitude, vertical velocity, drag coefficient and density, can greatly affect the accuracy at which a bomb reaches the desired impact point. Sensitivity coefficients determined from the solution of the equations of motion define how errors in initial conditions propagate in errors in the downrange and crossrange impact point. Because of the drag term, the equations of motion are nonlinear and thus are not amenable to analytic solutions. However, by using a simplified aerodynamic trajectory (SAT) where the drag term is linearized the sensitivity coefficients can be determined in closed form.

Approach

Referring to Figure 1, the downrange and crossrange impact points respectively can be determined by

\[
D_I = D_R + V_g T_f - (V_a T_f \cos \theta - R_B) \cos \delta  
\]

and

\[
C_I = C_R + V_g T_f + (V_a T_f \cos \theta - R_B) \sin \delta  
\]

By taking the differentials of Eqs. (1) and (2), the total downrange and crossrange error in the impact point can be determined based on the contributions of individual errors in initial conditions. For the downrange impact point

\[
\Delta D_I = \Delta D_R + \Delta R_B + (\Delta V_g T_f + \Delta V_a T_f \cos \theta) T_f  
\]

and for the crossrange

\[
\Delta C_I = \Delta C_R + \Delta V_g T_f + (\Delta V_a T_f \cos \theta - R_B) \Delta \delta  
\]

Fig. 1 Coordinate system and geometry for impact prediction.