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Effect of Asymmetric Drag Polar Characteristics on Minimum Trimmed Drag

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Nomenclature

$\mathcal{R}$	= aspect ratio
b, b_t	= wing span, tail span
C_D	= drag coefficient
C_L	= lift coefficient
C_m	= pitching moment coefficient
e	= Oswald's efficiency factor, $k=1/(\pi e \mathcal{R})$
e_{rel}	$=e_{wb}/e_t$
h, h_{opt}	= center of gravity (c.g.) position in chord length, optimum c.g. position
h_t, h_{wb}	= aerodynamic center in chord length for tail, wing-body combination
k	= lift-dependent drag, $C_D=C_{D_0}+k(C_L-C_{L_0})^2$
S, S_t	= wing area, tail area
$\bar{\epsilon}_\infty$	= downwash angle at downstream infinity
ϵ_0^*, ϵ_L^*	= downwash factors

Subscripts

t	= tail
wb	= wing-body combination

In recent papers,[1-10] the problem of reducing trimmed drag of the airplane has been investigated and it has been shown how lift must be distributed between the wing and tail in order to obtain the minimum of trimmed drag. The drag polars used in analytical relations for minimum trimmed drag are of the following type

$$C_D=C_{D_0}+kC_L^2 \qquad (1)$$

As illustrated in the left part of Fig. 1, this expression can be characterized as a form which is symmetric with respect to the C_D axis. In many cases, however, the actual drag polars significantly deviate from this form and are as shown in the right part of Fig. 2. This type can be qualified as a drag polar with asymmetric characteristics. It may be analytically expressed as

$$C_D=C_{D_0}+k(C_L-C_{L_0})^2 \qquad (2)$$

As can be seen, the quantity C_{L_0} provides a measure for the kind of asymmetric characteristics which are to be considered in the following.

There may be different reasons for the asymmetry addressed. One reason is camber of wing profile or, equivalently, flap deflection. An example is shown in part A of Fig. 2. From this it follows that drag polar asymmetry can be quite significant, being increased the more camber and/or flap angle is introduced. This effect may be of particular interest in regard to more recent designs utilizing new techniques such as "automatic maneuver flaps" or "variable wing camber." Here, leading- and trailing-edge flaps or variable camber are used to reduce drag at high lift in order to improve the maneuver performance of the aircraft. This is achieved by automatically operating the high-lift devices such that the highest lift drag ratio possible at each lift coefficient is obtained for the wing. However, wing drag polar asymmetry introduced by flap deflection or variable wing camber may have quite a significant effect on overall trimmed drag and may even influence the optimum tail contribution to minimum trimmed drag to a considerable extent. Moreover, the c.g. position related to minimum trimmed drag is also affected since, as will be shown, it is sensitive to the drag asymmetry addressed.

Another reason for asymmetric drag polar characteristics is wing twist. This is illustrated in part B of Fig. 2, which shows

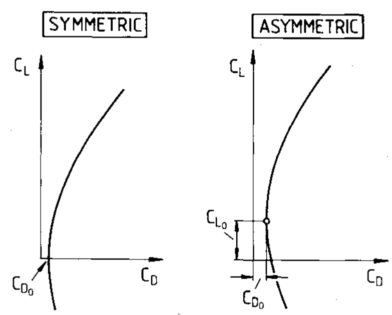
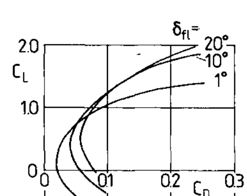
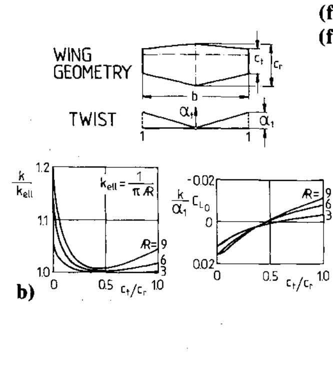


Fig. 1 Symmetric and asymmetric drag polar.



a)



b)

Fig. 2 Drag polar asymmetry: a) Effect of flap deflection δ_{fl} (from Ref. 11); b) Effect of twist (from Ref. 12).

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the characteristics of trapezoidal wings. Twist angle distribution denoted by α_t is assumed here to be linear. In this context, an additional point may be mentioned. This is related to wing zero-lift downwash, which is an effect also caused by wing twist and is considered to have a significant influence on minimum trimmed drag.[3,5] The drag polars used in investigations on the influence of wing zero-lift downwash are supposed to be symmetric according to the form described by Eq. (1). However, wing zero-lift downwash is usually combined with an asymmetric drag polar because both together are the result of wing twist. This means that, in order to account fully for the effect of wing zero-lift downwash, it is necessary to apply an asymmetric drag polar.

For the subsequent analysis, it is appropriate to express the equation of overall drag of the airplane in the following form:

$$C_D = C_{D_{0_{wb}}} + k_{wb}(C_{L_{wb}} - C_{L_{0_{wb}}})^2 + (S_t/S)[C_{D_{0_t}} + k_t(C_{L_t} - C_{L_{0_t}})^2 + \bar{\epsilon}_\infty C_{L_t}] \tag{3}$$

Subscripts wb and t have been added in order to identify the contributions of the wing-body combination and the tail. The product $\bar{\epsilon}_\infty C_{L_t}$ represents interference drag between the wing and the tail, with $\bar{\epsilon}_\infty$ denoting wing downwash at downstream infinity (for details, see Ref. 3). The downwash $\bar{\epsilon}_\infty$ is considered to consist of two parts where one is a constant and the other a linear function of wing lift. It may be expressed as

$$\bar{\epsilon}_\infty = \bar{\epsilon}_0 + \frac{\partial \bar{\epsilon}_\infty}{\partial C_{L_{wb}}} C_{L_{wb}} \tag{4}$$

The constant part $\bar{\epsilon}_0$ represents wing zero-lift downwash, the effect of which is to be investigated in combination with drag polar asymmetry since both together are caused by wing twist.

The overall drag expression of Eq. (3) is now evaluated for constant total lift $C_L = \text{const}$, while retaining the aircraft in trim $C_m = 0$. The coefficients C_L and C_m may be written as

$$C_L = C_{L_{wb}} + (S_t/S)C_{L_t} \tag{5}$$

$$C_m = C_{m_{0_{wb}}} + C_L(h - h_{wb}) - (S_t/S)C_{L_t}(h_{wb} - h_t) \tag{6}$$

Furthermore, the following relations are applied

$$C^*_{D_0} = C_{D_{0_{wb}}} + (S_t/S)(C_{D_{0_t}} + k_t C^2_{L_{0_t}})$$

$$\epsilon^*_L = (\partial\bar{\epsilon}_\infty/\partial C_{L_{wb}})/(2k_{wb})$$

and

$$(S/S_t)k_t/k_{wb} = e_{\text{rel}}(b/b_t)^2$$

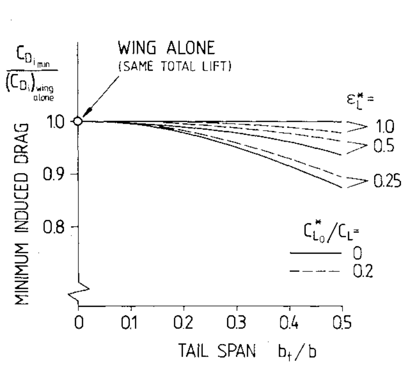

Fig. 3 Effect of $C^*_{L_0}$ on minimum trimmed drag.

With the use of these relations and Eqs. (5), (6), and by introducing

$$C^*_{L_0} = C_{L_{0_{wb}}} - C_{L_{0_t}} k_t/k_{wb} \tag{7}$$

the minimum of trimmed drag can be expressed as

$$C_{D_{\min}} = C^*_{D_0} + C_{D_{i_{\min}}} \tag{8a}$$

where

$$C_{D_{i_{\min}}} = k_{wb}\left\{(C_L - C_{L_{0_{wb}}})^2 - C_L^2 \frac{[1 - \epsilon^*_L - (\epsilon^*_0 + C^*_{L_0})/C_L]^2}{1 + e_{\text{rel}}(b/b_t)^2 - 2\epsilon^*_L}\right\} \tag{8b}$$

There are two effects of asymmetric drag polar characteristics. The first effect, which is represented by the term

$$k_{wb}(C_L - C_{L_{0_{wb}}})^2$$

refers to wing drag polar only, the properties of which need no further explanation. The second effect is related to the combination of the wing and the tail. This may become more evident when considering the drag of the wing/tail combination as compared with the wing alone (when having the same total lift as the wing/tail combination). Since in the latter case $C_{L_{wb}} = C_L$, the drag of the wing alone is given by

$$(C_{D_i})_{\substack{\text{wing}\\\text{alone}}} = k_{wb}(C_L - C_{L_{0_{wb}}})^2 \tag{9}$$

In comparison with Eq. (8b), it follows that the wing/tail combination has less lift-dependent drag [when, as usual, $\epsilon^*_L + (\epsilon^*_0 + C^*_{L_0})/C_L > 0$]. This reduction is influenced by $C^*_{L_0}$. As illustrated in Fig. 3, positive values of $C^*_{L_0}$ which may represent the case usually existing increase the drag reduction when downwash is large. For small downwash, the opposite is true.

Drag polar asymmetry does not only affect the minimum of trimmed drag but also the related c.g. position, which may be called the optimum c.g. position. From the preceding analysis, it follows that the optimum c.g. position can be expressed as

$$h_{\text{opt}} = h_{\text{opt}_0} - C_{m_{0_{wb}}}/C_L \tag{10}$$

The term h_{opt_0}, which accounts for all effects except wing-body zero-lift moment, is affected by asymmetric drag polar characteristics denoted by $C^*_{L_0}$. It may be written as

$$h_{\text{opt}_0} = h_{wb} + \frac{1 - \epsilon^*_L - (\epsilon^*_0 + C^*_{L_0})/C_L}{1 + e_{\text{rel}}(b/b_t)^2 - 2\epsilon^*_L}(h_t - h_{wb}) \tag{11}$$

Here again, the effect of $C^*_{L_0}$ may be significant. The example presented in Fig. 4 shows that positive values of $C^*_{L_0}$ move the optimum c.g. position forward. This is a stabilizing effect, because the neutral point is not altered. Thus, $C^*_{L_0}$ may contribute to moving the optimum c.g. position to a location which would yield a suitable margin for inherent stability.

From Eq. (10), it also follows that the effect of $C_{m_{0_{wb}}}$ is dependent on lift coefficient C_L. As a result, the optimum c.g. position is not constant, but varies with airspeed and altitude. This effect, however, can be neutralized by $C^*_{L_0}$ together with ϵ^*_0, which both are connected with C_L in the same manner as $C_{m_{0_{wb}}}$. Thus, it is possible to make the optimum c.g. position

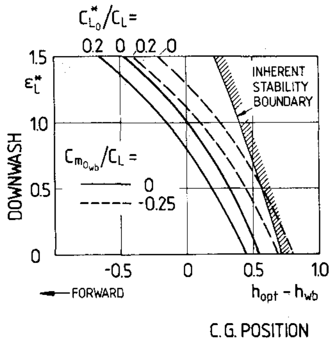

Fig. 4 Effect $C^*_{L_0}$ on optimum c.g. position ($AR = 7.5$, $S/S_t = 4.0$, $b/b_t = 2.5$).

independent of airspeed and altitude. This is the case if

$$C^*_{L_0} + \epsilon^*_0 = -\frac{1 + e_{\mathrm{rel}}\,(b/b_t)^2 - 2\epsilon^*_L}{h_t - h_{wb}}\, C_{m0_{wb}} \tag{12}$$

For nonvanishing values of $C^*_{L0_{wb}}$ this may be the only way of keeping the optimum c.g. position constant. This applies not only to aircraft designs with inherent stability, but also to designs which utilize new techniques such as CCV (Control Configured Vehicles) or ACT (Active Control Technology).

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