Circling Performance of Sailplanes

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Abstract
Variable geometry in the form of high lift flaps has been proposed as a means of increasing the overall cross-country speed of a sailplane by providing a better compromise between cruise and climb performance. This paper gives an analysis of the circling performance of a sailplane with high lift flaps, keeping the main design parameters in the range dictated by operational considerations of straight glide performance and the characteristics of thermals encountered. The results show that a substantial increase in both climb performance and effective cross-country speed will result from the use of high lift flaps on sailplanes.

Introduction
The possibility of using high lift flaps to improve circling performance of sailplanes has recently been given serious consideration, and some sailplanes with high lift flaps have been built. The most notable example is the B.J. 2, 3, 4, series of sailplanes designed and built by Beatty and Johl in South Africa [1].
Flaps are intended to retain good low speed characteristics for thermaling while allowing the use of higher wing loading for better high speed performance with flaps retracted. This paper gives an analysis of the circling performance of sailplanes with high lift flaps keeping in mind other operational requirements which affect the choice of design parameters.
The basic equations for an analysis of circling flight were given by A.M. Lippish [2].
Sinking speed,

$$V_z = \frac{C_D}{(C_L \cos\varphi)^{1.5}} \sqrt{\frac{2W}{\varrho S}} \qquad (1)$$

Where

W/S is wing loading
φ is bank angle
ϱ is air density.
Turn radius, r, is given in terms of bank angle φ, C_L, and $\sqrt{\frac{2W}{\varrho S}}$ as

$$r = \frac{1}{g \sin\varphi\, C_L} \cdot \frac{2W}{\varrho S} \qquad (2)$$

where g = 32.2 ft/sec².

$$\text{From this, } \cos\varphi = \sqrt{1 - \left(\frac{2W}{rg\, C_L\, \varrho S}\right)^2}$$

$$= \sqrt{1 - N^2 / C_L^2}$$

$$\text{where} \qquad N = \frac{1}{rg} \frac{2W}{\varrho S}$$

Equation (1) can now be written as,

$$V_z = \frac{C_D}{\left(C_L \sqrt{1 - N^2 / C_L^2}\right)^{1.5}} \sqrt{\frac{2W}{\varrho S}} \qquad (3)$$

In order to evaluate sinking speed in circling flight using equation (3) the relationship between C_D and C_L will have to be determined. This relationship is given by the glide polar.

The Glide Polar
The glide polar can be represented by the equation,

$$C_D = C_{Do} + (K+B)\, C_L^2 \qquad (4)$$

This form is valid for sailplanes at moderate lift coefficients. Deviations from equation (4) occur at high lift coefficient due to flow separations and rapid thickening of turbulent boundary layers in adverse pressure gradients. Some recent measurements of glide polars on a number of current competition sailplanes [3] showed a linear relationship between C_D and C_L^2 up to $C_L = 1.0$ to 1.2. For a sailplane with a slotted flap it should be possible to extend this linear relationship to $C_L = 2.0$.
The glide polar for a particular sailplane configuration can be determined by considering the individual contributions of wing, fuselage, and empennage to C_D.
Wing drag is made up of profile drag and induced drag.
Considering induced drag first,

$$C_{Di} = \frac{C_L^2}{\pi A} (1+\sigma)$$

where A is aspect ratio, and σ is a factor taking into account deviations of spanwise lift distribution from the ideal elliptical shape.
The value $\sigma = 0.05$ will be taken for the purposes of this study, but it should be noted that it could be much larger if partial span flaps are used, or if flow separations occur at the wing-fuselage junction.
Wing profile drag can be determined directly from published aerofoil data [4], [5], [6], both for the case of a wing without flaps, and for a wing with flaps. A reasonable approximation for wing profile drag can be obained with the following equation,

$$C_{D\,profile} = C_{Do}' + B\, C_L^2 \qquad (5)$$

The constant B is chosen to fit the published aerofoil data up to the desired maximum circling lift coefficient. C_{Do}' is the profile zero lift drag coefficient.
For example, the profile drag for an aerofoil with a 0.25 chord slotted flap given in reference [6] can be closely approximated by equation (5) for all values of C_L up to $C_L = 2.5$ if $C_{Do}' = 0.006$ and $B = 0.004$.
Fuselage drag should be nearly independent of C_L, and will also be nearly independent of wing area. With this in mind, fuselage drag coefficient will be inversely proportional to wing area.

$$C_{D\,fus} = \frac{\text{fuselage drag}}{\frac{1}{2} \varrho V^2 S} \qquad (6)$$

A value of $C_{Dfus} = 0.002 \times \frac{136}{S}$ will be taken here as being a value roughly comparable to that of current sailplanes.
Tailplane drag coefficient will be of the order of $0.15 \times C_{Do}'$ and this value will be assumed to be constant.
While the glide polar produced using the above assumptions may not be quantitatively accurate, it will be a sufficiently representative model to show the effects of variations of the main design parameters. In fact, when applied to the geometrical characteristics of known sailplanes, the above assumptions will result in polar curves in good quantitative agreement with published data.
The final equation representing the glide polar is:

$$C_D = C_{Do} + (K+B)\, C_L^2 \qquad (4)$$

where $C_{Do} = C_{Do}' + C_{D\,fus} + C_{D\,tail}$.

$$K = \frac{1.05}{\pi A},$$

and B is chosen to represent the aerofoil data.
Equation (4) should be valid for a sailplane with a full span slotted flap

provided wing profile drag can be adequately represented by equation (5).

Reynold Number

The Reynolds number based on chord length tends to be the order of 1.0×10^6 for an average sized sailplane in low speed flight. The wing profile drag is higher, and the maximum lift coefficient is lower than they would be at higher Reynolds numbers. If data on profile drag are available for a range of Reynolds numbers, as they are in references [4] and [5], the information can be incorporated into constant B of equation (5).
Most of the test data available for aerofoils with flaps were taken at a relatively high Reynolds number, 5.1×10^6 in reference [6], and 2.5×10^6 in the case of reference [8]. Vesely [7] gives some results of wind tunnel tests at lower Reynolds number. The performance calculations have been made keeping these Reynolds number effects in mind and allowing for them as well as available experimental data permits.

Circling Performance

Minimum sinking speed as a function of turn radius can be taken to be a measure of circling performance. In Addition to turn radius, sinking speed depends on the geometrical characteristics of the sailplane and the lift coefficient at which it is flown. The use of high lift flaps is intended to extend the range of C_L available.

Fig. 1. Circling performance with high lift flaps.

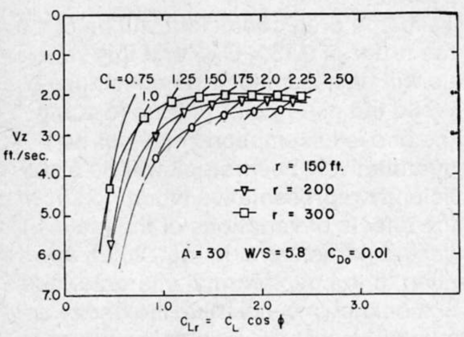
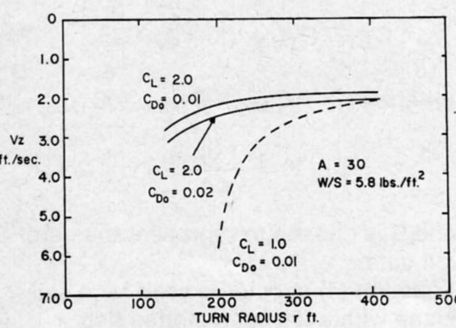


Fig. 2. Effect of lift coefficient and C_{Do} on sinking speed.



Sinking speed in terms of C_L can be obtained by substituting the expression for glide polar given in equation (4) into equation (3). Turn radius is also incorporated into this equation in the constant $N = \frac{1}{rg} \frac{2W}{\varrho S}$.

Equation (3) becomes

$$V_z = \frac{C_{Do} + (K+B)\, C_L^2}{\left(C_L \sqrt{1 - N^2 / C_L^2}\right)^{1.5}} \sqrt{\frac{2W}{\varrho S}} \quad (7)$$

Differentiating with respect to C_L and solving for the optimum value gives,

$$C_{L\,opt} = \left[4N + \frac{3\,C_{Do}}{K+B}\right]^{\frac{1}{2}} \quad (8)$$

The optimum value of C_L depends strongly on wing loading and turn radius which appear in the constant N. Values of W/S and r chosen on the basis of operational requirements tend to make N of the order of 1.0.
Circling performance can best be illustrated graphically. The following characteristics are chosen as an example of a sailplane with high lift flaps:

$$\begin{aligned} W/S &= 5.8\ \text{lb/ft}^2 \\ A &= 30 \\ C_{Do} &= 0.01 \\ B &= 0.004. \end{aligned}$$

This choice of variables results in performance approximately equivalent to the Schemp-Hirth Cirrus for C_L less than 1.0, giving a possible basis of comparison with current competition sailplanes.
Sinking speeds based on equation (7) and the above sailplane characteristics are plotted against

$C_{Lr} = C_L \sqrt{1 - N^2 / C_L^2}$ in figure 1.

The curves in figure 1 show that minimum sink occurs at quite high values of C_L, particularly for the 150 and 200 foot radius circles. If this sailplane were to be flown with flaps retracted, maximum circling lift coefficient would be limited to approximately $C_L = 1.0$ because of low Reynolds number. As a result, it would not be able to fly on a 150 foot radius circle, and would have considerably increased rate of sink compared to the case with high lift flaps even on the 200 and 300 foot radius circles.

Figure 2 shows the minimum sinking speed against turn radius for a sailplane with high lift flaps operating at $C_L = 2.0$, and for a sailplane without flaps flown at $C_L = 1.0$. These results are taken from the data presented in figure 1. The relatively low values of circling C_L were chosen because of the effect of low Reynolds number on

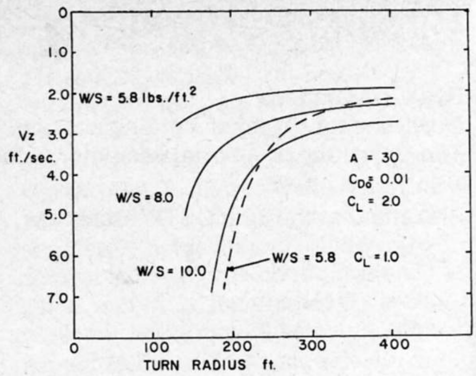


Fig. 3. Effect of wing loading.

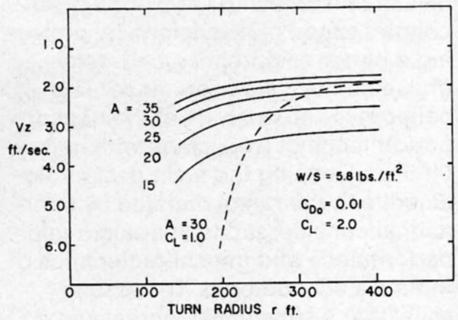


Fig. 4. Effect of aspect ratio.

maximum lift coefficient, and to allow a reserve necessary for control in gusty conditions.
The assumption regarding wing profile drag may be somewhat optimistic in that mechanisms to hold the slotted flap will cause extra drag. While this extra drag will increase the sink rate, it is not a very serious consideration compared to the large values of induced drag generated at high lift coefficient.
To see the effect of an increment in C_{Do}, a calculation of sinking speed as a function of turn radius was made for a sailplane with $C_{Do} = 0.020$ instead of 0.010. The result is shown in figure 2 along with the curve for $C_{Do} = 0.010$ for comparison.
The increased rate of sink is about 0.25 ft/sec for all turn radii, which would not make a noticeable difference to an average rate of climb of 5 to 10 ft/sec.
Figure 3 shows the effect of wing loading on circling performance. Compared to circling performance without flaps ($C_L = 1.0$) the sailplane with high lift flaps has better circling performance at a wing loading of 8 lb/ft², and even at 10 lb/ft² the rate of sink is only increased by about 0.5 ft/sec over that of the sailplane without flaps at a wing loading of 5.8 lb/ft².
Aspect ratio is important in controlling induced drag when operating at high lift coefficient. Just how important it is for circling flight performance is

shown in figure 4 where a change in aspect ratio from 35 to 15 results in approximately doubling the sinking speed.

Relationship to Operating Conditions

As mentioned previously, the shape and size of thermals to be encountered will have an important influence on the relative climb performance of sailplanes with and without flaps. In addition to this, circling performance should be related to overall cross-country speed in order to determine the best compromise between low wing loading for circling flight and high wing loading for fast cruise between thermals.

Experience in soaring indicates that thermal updraft velocities increase toward the center of the thermal «core» and that the area of strong lift is usually only 600 to 1200 feet in diameter.

The following model is a convenient mathematical representation of thermal size and strength based on the above general observations.

$$V_{th} = V_o \cos \frac{\pi r}{d}$$

where

V_{th} is updraft velocity at radius r
V_o is maximum updraft velocity
r is turn radius
d is thermal diameter (i.e. diameter at which updraft velocity is zero)

Fig. 5. Rate of climb in weak narrow thermals.

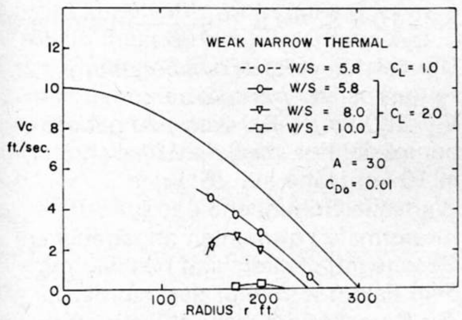
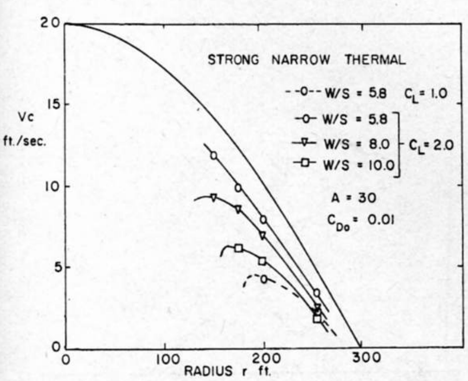


Fig. 6. Rate of climb in strong narrow thermals.



Values of V_0 and d can be chosen to represent a range of possible strength and size. The following values have been chosen:

(a) strong narrow thermal
$V_0 = 20$ ft/sec, $d = 600$ ft
(b) weak narrow thermal
$V_0 = 10$ ft/sec, $d = 600$ ft
(c) wide thermal
$V_0 = 15$ ft/sec, $d = 1200$ ft

these model thermals are approximately the same as those chosen by Bruce Carmichael [9] for a similar study.

The shape of updraft distribution, together with rates of climb for the high lift sailplane with a range of values of wing loading are shown in figures 5, 6, and 7. The calculated rates of climb for the same sailplane at $C_L = 1.0$ and a wing loading of 5.8 lb/ft² are also shown for comparison.

If real thermals are similar in shape to the assumed model, the ability to fly a small radius circle will far outweigh changes in rate of sink due to moderate variations in C_{Do} and aspect ratio.

Average cross-country speed can be calculated using a well known graphical construction [10] if rate of climb and the glide polar are given. Figure 8 shows the variation of cross-country speed with wing loading determined from the best rate of climb in each of the three thermal types. Average cross-country speed appears to be rather insensitive to wing loading, but with an optimum for the narrow thermals of between 6 and 8 lb/ft².

Average speeds for the sailplane without flaps, flying at a wing loading of 5.8 lb/ft², are shown for comparison. Since both the climb and straight glide performance of this configuration are approximately the same as the present generation of competition sailplanes, this comparison shows the expected gain in performance by the use of high lift flaps.

The sailplane without flaps will not climb at all in the weak narrow thermal, while the high lift sailplane with the same wing loading will average 46 miles per hour.

The use of high lift flaps results in about 50% increase in speed in the case of the strong narrow thermal and 20% increase in speed for the wide thermal.

Conclusions

High lift is more important than low drag for circling performance. It will be an advantage to use a slotted flap to get the highest possible lift coefficient rather than camber changing flaps that produce moderate increases in C_{LMax} with a minimum increase in profile drag.

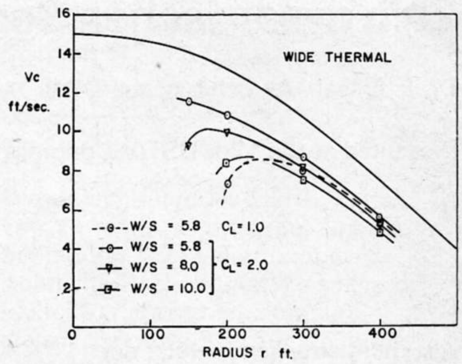


Fig. 7. Rate of climb in wide thermals.

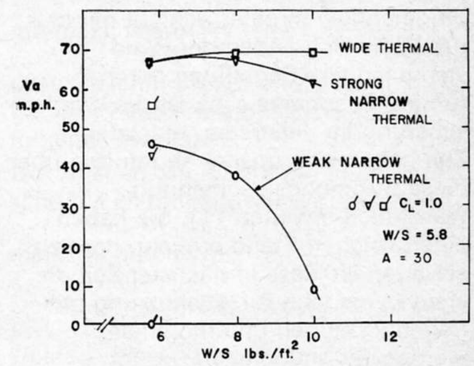


Fig. 8. Cross-country speed as a function of wing loading.

The use of high lift flaps will allow an increase in wing loading from 6 lb/ft² to 8 lb/ft² with the same or better circling performance.

Cross-country speed is not very sensitive to wing loading. For the type of thermal and sailplane characteristics assumed in this study, the best wing loading is approximately 8 lb/ft².

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