An Index for predicting flight reliability of sailplanes in thermal soaring

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Summary

This paper attempts to relate, in a quantitative manner, the aerodynamic characteristics of sailplanes with the meteorological properties of thermal convections, so that the soaring efficiency and flight reliability of such aircraft can be explicitly predicted. Although the methods of analysis employed appear generally applicable to many forms of meteorological convections, the particular case of soaring in isolated vortex-shell thermals is given primary consideration.

A new flight procedure is presented by which data on the most important parameters governing the thermal properties can be quantitatively determined. This flight procedure is developed using previous theoretical and experimental work by the author on the structure and aerodynamics of isolated vortex shells. Following this, a statistical procedure is developed by means of which the thermal data acquired by the flight investigations can be reduced to a form directly applicable to the analysis of the soaring reliability of sailplanes. In particular, a "soaring reliability index" is developed which shows in explicit form how the size and spatial distribution of atmospheric thermals, and the dissipation altitude of the convections, govern the reliability of thermal soaring flight.

Finally, the effects of the thermal properties and the aerodynamic characteristics of sailplanes are integrated in such a manner that it becomes possible to predict an aircraft configuration which will possess high reliability in soaring while still maintaining the maximum allowable gliding and distance-flight performance capabilities. The various relations derived are analyzed in detail and are shown to yield a valuable insight into the various factors which govern the success of thermal soaring flights.

Introduction

A problem of fundamental concern to the sailplane designer is that of determining the optimum compromise of aerodynamic characteristics which will allow his craft to attain an adequate degree of soaring reliability, without unduly penalizing the other performance capabilities of the craft. The term "soaring reliability", as used here, refers to the relative probability or degree of certainty that a sailplane will intercept and be able to use a sufficient number of thermal convections that it can remain continuously airborne under the existing meteorological conditions. Whether a particular thermal is "usable" or not depends, of course, on the characteristics and efficiency of the sailplane in circling flight. This meteorological-aerodynamic interaction is discussed in detail in references 1 and 2. The task of designing for sufficient soaring reliability in sailplanes is obviously one of foremost importance since all of a craft's other performance attributes are meaningless unless sufficient use can be made of the available atmospheric energy sources to guarantee sustained flight.

In the past, sailplane designers have attempted to provide for adequate soaring reliability using little more than guesses guided by past experience. This procedure was necessitated, of course, by the fact that so little was known, quantitatively, about the structure and distribution of atmospheric thermals and about the primary meteorological-aerodynamic relationships which govern reliable sailplane design. Such an indefinite design procedure, however, leaves much to be desired and it is natural to seek a more rational approach to the problem of designing sailplanes which have adequate, but not excessive, soaring reliability. It is the purpose of this paper to suggest a method whereby, despite the extreme complexity and statistical nature of the problem, a rational and meaningful solution can be obtained in a reasonably simple way, at least for the particular cases where the convection structure and properties can be adequately described in mathematical form.

Symbols

A	aspect ratio
A_*	aspect ratio for γ_{max}
a	thermal core radius (fig. 1)
b	span length
C_{L_*}	lift coefficient for minimum $\dot{z}$ in circling
d	average horizontal distance between thermals
G	horizontal component of glide distance
h_*	maximum altitude of thermals
h_o	minimum altitude of thermals
k	thermal size factor
L/D	lift-drag ratio
N	total number of intercepted thermals
n	total number of glides
P_i	number of thermals within a given radius range
R	thermal radius
R'	radius of minimum size of usable thermal
R_o	radius of minimum thermal size measured
R_m	radius of maximum thermal size measured
$\triangle R$	radius interval
r	radial distance from thermal axis (fig. 1)
s	horizontal component of total glide distance
$\triangle s$	horizontal component of individual glide distance
$\triangle t$	time duration of glide
V	gliding airspeed
V'	velocity of ascent of thermal shell
v	vertical velocity in thermal (relative to core velocity)
v_c	velocity at thermal center (relative to core velocity)
ν_c	absolute vertical velocity at thermal center
$\dot{z}$	aerodynamic sinking velocity of sailplane
β_*	angle of bank for minimum $\dot{z}$
Γ'	thermal core circulation
γ	soaring reliability index
η	vertical distance in thermal (see fig. 1)

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θ	glide angle
σ	thermal interception frequency function

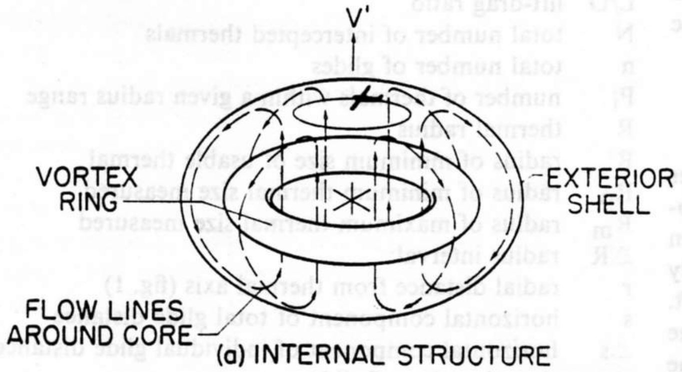
Subscripts:

max	maximum value
min	minimum value
opt	value for best gliding speed

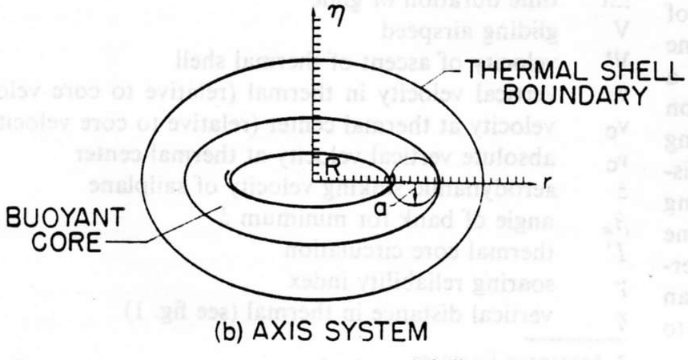
Meteorological-aerodynamic interactions in sailplane design

The first requirement of soaring flight is to remain continuously airborne, and this will be satisfied only to the extent that a soaring plane is properly designed to make adequately efficient use of the thermal conditions existing over an area to gain or maintain altitude. The important question thus arises as to what constitutes an adequately efficient soaring plane design. Obviously the answer depends entirely upon the form, structure, and distribution of the *local* thermal currents. If thermals were everywhere extremely large, powerful, and densely distributed, it would be best, for most purposes, to design sailplanes with the highest possible L/D and with high wing loadings. Then, not only would the craft possess the necessary soaring reliability, but distance, goal, and penetration capabilities would be maximized. Unfortunately, experience has shown that, except in a few ideal regions, thermals are actually relatively small and sparsely distributed, and their practical use requires an aircraft having quite different properties from those just outlined. The weaker the thermal conditions, the weaker the craft's distance, goal, and penetration capabilities must become, in general, if a high degree of soaring reliability is to be maintained (ref. 2).

Clearly then, if a soaring plane is to be truly optimized with respect to some desired aspect of performance while still maintaining adequate soaring reliability, it must be designed to best accommodate the thermal conditions prevailing over the particular geographical area where it is to operate. Designing for sufficient soaring reliability is critical, for unless a craft can intercept and *use* a thermal to gain altitude at the time when it is needed, all of the craft's other performance capabilities are meaningless. It is clear that for successful sailplane design an accurate knowledge of local thermal properties is mandatory.



(a) INTERNAL STRUCTURE



(b) AXIS SYSTEM

Figure 1. Internal flow structure of a thermal shell

In the following sections I shall endeavor to outline a procedure by which the quantitative relations between the aerodynamic characteristics of a sailplane and its soaring reliability can be established, when sufficient data are available on thermal conditions. The discussion will be based upon the assumption that the thermals consist entirely of vortex shells (see fig. 1). The reason for using this particular convection form is twofold: First, it is one of the few types of thermal convections which can be adequately described in mathematical form and secondly, indications are that it is probably the most universally distributed of all thermal forms and hence is the form of most general importance in soaring flight. The author's theory of the vortex shell convection and its utilization in soaring is discussed in detail in references 1, 2, 3, and 4, and it will be assumed herein that the reader is familiar with the details of this form of convection. Although the analysis is based primarily upon the use of vortex shell convections, the general procedures developed can, of course, be extended to include treatment of various other convection forms or combinations of forms. The results of this analysis give a clear insight into many of the principal aerodynamic-meteorological relations governing soaring reliability in general, and provide a foundation upon which flight research and further theoretical work in this important area of soaring technology can be based.

Flight measurement of vortex shell properties

The first step in the development of a soaring reliability criterion is the investigation of the thermal shells existing over the particular geographical area of interest during the seasonal and daily time intervals considered appropriate for soaring. For this purpose use is made of a "thermal sailplane" (ref. 2) for collecting data on the Γ, R, and a values of the thermals and on the maximum useful altitude h_* to which the thermal shells rise. A knowledge of the values of R and h_* for the thermals is especially important in determining the soaring reliability, as will be evident later.

The theory of the vortex shell is developed in reference 1, where the thermal velocity field is approximated by that of a buoyant vortex-ring system (see fig. 1), and it is shown that when the effective values of Γ, R, and a of a thermal shell are known, the entire velocity field V of the flow can be calculated by induction theory. As discussed therein, nondimensional plots of the relative velocity field v/V' against (r/R, η/R), where v is the vertical component of the velocity relative to the vortex core, can be prepared for various values of the ratio R/a (see fig. 2), and when the actual values of Γ, R, and a are known the plot corresponding to the given R/a value can be converted to the dimensional form v(r, η), since

$$V' = \frac{\Gamma}{4\pi R}\left(\ln \frac{8R}{a} - \frac{1}{4}\right) \qquad (1)$$

Thus the relative vertical velocity field within the thermal shell becomes known for use in design analysis (ref. 2). The problem now is to find a means for measuring the values of Γ, R, and a of actual atmospheric thermals so that the dimensional velocity diagrams can be constructed.

To accomplish these measurements we employ a thermal sailplane which is capable of making turns of very small radius r with a low sinking velocity $\dot{z}$. The plane first enters the thermal and after proper orientation is assumed to establish *equilibrium* circling flight about the thermal's vertical axis. If then the craft's rate of climb is determined, the value of V' becomes known since the craft rises at the same rate as the thermal, under equilibrium conditions. After taking this reading, the radius of turn of the sailplane is smoothly and steadily decreased in such a manner that equilibrium with the thermal is essentially maintained at all radii (as evidenced by a constant rate of climb reading), while flying at the optimum values β_* and C_{L*} for minimum $\dot{z}$ (ref. 2). Under these conditions the plane will follow along its minimum $\dot{z}$ curve relative to the thermal core, as shown in figure 3. Ultimately, however, the plane will reach the condition denoted by point A, where $\dot{z}$ becomes greater than v, and the rate of climb will begin a rapid decrease. If at the onset of this loss in rate of climb, the value of $\dot{z}$, say $\dot{z}_A$, corresponding to the β_* and C_{L*} being flown at radius r_A is recorded, we then know the value of v, say v_A, at this radius since at equilibrium, $\dot{z}_A = v_A$. Furthermore, the value determined for v_A will correspond to the plane $\eta = 0$, since v has its maximum value in this plane. Physically, point A denotes the condition where the craft sinks out of the upper half of the thermal into the lower half. With sufficient practice in the interpretation of thermal motions, it should eventually become possible for pilots to recognize this point in flight and to record the appropriate data. These two simple measurements (V' and v_A) now allow us to calculate the values of the ratios Γ/R and R/a for the thermal as follows:

The absolute velocity $v_c(=v_c + V')$ of the air at the geometric center of the thermal shell ($r = 0$, $\eta = 0$) is by theory equal to ½ Γ/R, and since the velocity v varies only slightly with r near $r = 0$ (i.e., $v_c = \dot{z}_A$ as shown in fig. 3) we have

$$\frac{\Gamma}{R} = 2\left(\dot{z}_A + V'\right) \tag{2}$$

Then, by substituting this value of Γ/R and the measured value of V' into equation (1) and solving for R/a, we obtain

$$\frac{R}{a} = \frac{1}{8}\ \text{antiln}\left(\frac{2\pi V'}{\dot{z}_A + V'} + \frac{1}{4}\right) \tag{3}$$

These quantities, however, do not determine the absolute values of the thermal properties but only the characteristic ratios. There remains the need, therefore, of finding the actual dimensional value of R to fully determine the thermal's properties.

If immediately after the sailplane pilot has recorded the $\dot{z}_A$ value (or equivalent data) at point A, the radius of turn is quickly increased, the craft will again rise into the top half of the thermal and equilibrium can be re-established. Then, by steadily *increasing* the radius of turn under equilibrium conditions, point B will ultimately be reached, as noted in figure 3. Here the craft will again lose equilibrium and a decrease in the climb rate will again occur. At the onset of this condition, which also occurs in the $\eta = 0$ plane of the thermal, both $\dot{z}_B$ and r_B (the radius of turn at point B) are recorded. Thus, since $\dot{z}_B = v_B$ from the equilibrium condition, the ratio v_B/V' can be calculated for the radius r_B and the vertical level $\eta = 0$. Proceeding to the nondimensional thermal diagram corresponding to the known R/a value of the thermal, the measured value of v_B/V' can be located on the $\eta/R = 0$ curve and the corresponding value of $r/R(= r_B/R)$ determined, as in figure 4. The effective radius of the thermal then follows directly from

$$R = \left(\frac{R}{r_B}\right) r_B \tag{4}$$

Using the value of R thus determined, the corresponding values of Γ and a are obtained from equations (2) and (3) and the entire thermal velocity field and spatial dimensions become known.

Since the variation of v/V' and r/R is needed only in the plane $\eta/R = 0$ for purposes of determining the thermal radius R, the nondimensional thermal diagrams can be conveniently arranged in the form of a three-dimensional "surface of maximum thermal velocity" such as shown in

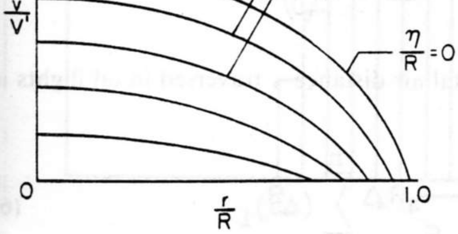


Figure 2. The thermal diagram (nondimensional)

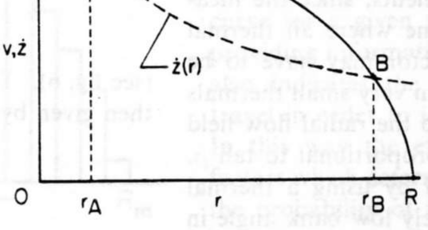


Figure 3. The circling performance diagram (dimensional)

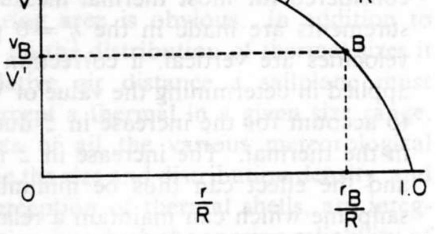


Figure 4. Method for determining the thermal radius R

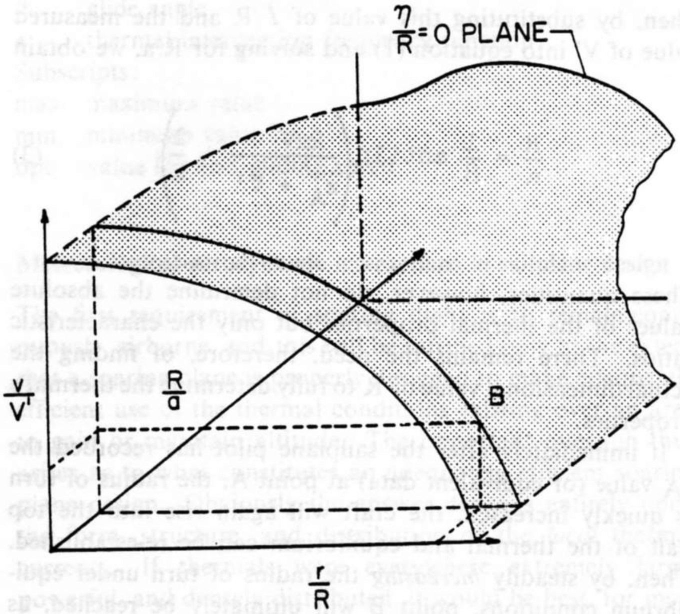


Figure 5. The surface of maximum thermal velocity

figure 5. Using this surface, the value of R can be obtained for any specified values of R/a, v_B/V', and r_B.

In addition to determining the internal properties of thermals, the measuring sailplane can remain with the thermal and can record the maximum useful altitude h_* to which it ultimately rises. This information is important for use in predicting the soaring reliability of sailplanes, as will be shown subsequently. By repeating the measurement sequence in the same thermal at various altitude intervals, information on the variation of thermal properties with time or altitude can also be obtained.

In practice, the entire set of data readings would be made rather rapidly, say within the period of a few minutes, and the actual thermal properties would, of course, be calculated later using the recorded data. The sinking velocities $\dot{z}_A$ and $\dot{z}_B$ can be determined in a number of ways, and the radius of turn r_B can be determined by use of a rate-of-turn indicator or a centrifugal accelerometer. Many of the measurements could of course be recorded automatically by use of proper recording instruments.

The critical importance of using a "thermal" sailplane for obtaining thermal data by the foregoing procedure is obvious. The validity of equation (2) rests upon the assumption that r_A is sufficiently small that v_A is essentially equal to v_c, and unless the measuring sailplane can get deep enough into the thermal, this assumption will not be satisfied. Also since we shall want to measure as wide a range of thermal sizes as possible, only a true thermal sailplane would be capable of obtaining data on the smaller thermals.

While only the effects of the vertical velocity field need be considered for most thermal measurements, since the measurements are made in the $\eta = 0$ plane where all thermal velocities are vertical, a correction factor may have to be applied in determining the value of V' in very small thermals to account for the increase in $\dot{z}$ due to the radial flow field in the thermal. The increase in $\dot{z}$ is proportional to tan β, and the effect can thus be minimized by using a thermal sailplane which can maintain a relatively low bank angle in small turns.

By making the indicated measurements, dimensional thermal diagrams of v against r can be prepared for the isolated vortex thermals of a given area, and these diagrams will give the soaring pilot a useful picture of the size, strength, and extent of these air currents in which his craft must operate. Even a first-order knowledge of the local thermal velocity fields should greatly aid pilots in making the most efficient use of such convections.

Spacing and size distribution of thermals

To collect the desired data on thermal sizes and distributions a thermal sailplane (or a series of such craft) is released at altitude and simply wanders about at random over the area, intercepting and measuring as many thermals as possible during the daily time interval of interest. During these flights an accurate barograph record is maintained and each thermal investigated is properly indexed on the barograph recording (fig. 6). The thermal properties will, of course, be functions of the type of terrain, heating rate, general air stability, and wind strength and direction, and thus will vary not only with different seasons of the year, but in the course of a single day. After many such flights have been made and much data accumulated, a systematic classification of the results can be commenced as follows.

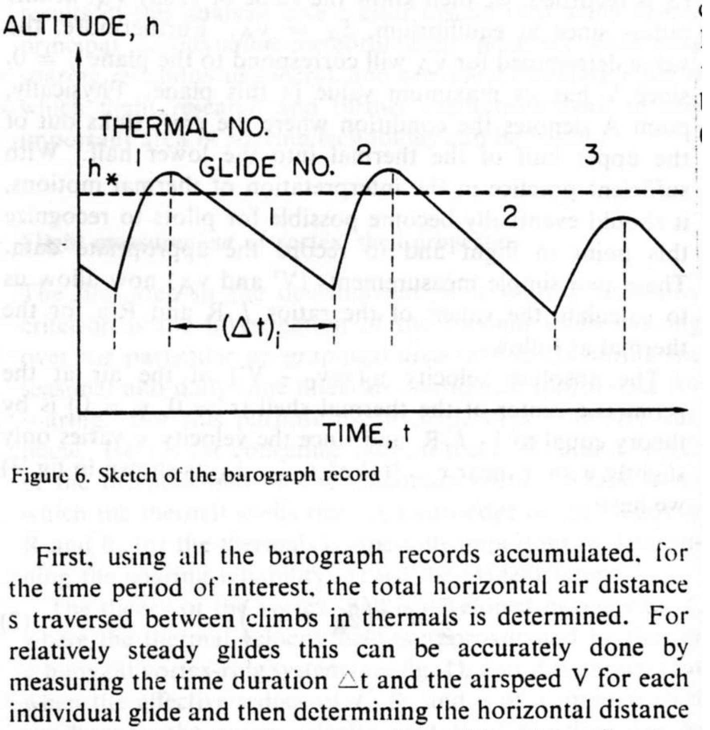


Figure 6. Sketch of the barograph record

First, using all the barograph records accumulated, for the time period of interest, the total horizontal air distance s traversed between climbs in thermals is determined. For relatively steady glides this can be accurately done by measuring the time duration Δt and the airspeed V for each individual glide and then determining the horizontal distance component Δs, using the appropriate L/D and $\dot{z}$ calibration curves for the sailplane. Thus,

$$\Delta s = \dot{z}\left(\frac{L}{D}\right)\Delta t \tag{5}$$

(see fig. 6). The total air distance s traversed in all flights is then given by

$$s = \sum_{i}^{n} (\Delta s)_i \tag{6}$$

where n is the total number of glides made in all the accumulated flights and i is the index identification of the individual thermals. As more flights are made and more data collected, n will of course increase. The average horizontal *air distance* between thermal interceptions is given by d = s/n,

$$d = \frac{\sum_{i}^{n} (\Delta s)_i}{n} \qquad (7)$$

and from the value of d we can gain some idea of the average spacing of thermals over the area.

Next, a size distribution graph, such as shown in figure 7, is prepared from the data. The abscissa, on which the thermal radius R is plotted, is divided into a number of equal intervals △R of suitable size (say △R = 10 feet, for example), and the minimum and maximum thermal radii which have been measured in flight marked at the points R_o and R_m, respectively. Denoting now by k the total number of thermals intercepted *per mile* of horizontal air distance traveled which have radii between $R_i - \frac{1}{2}(\triangle R)_i$ and $R_i + \frac{1}{2}(\triangle R)_i$, where R_i is the midpoint of any particular $(\triangle R)_i$ interval, we can plot k as shown for each △R interval and so obtain a size distribution graph of the type illustrated. Here the value of k for a particular interval, k_i, is obtained by dividing the total number of thermals P_i in each particular $(\triangle R)_i$ interval by s, the total air distance traversed between thermals (eq. (6)). Thus,

$$k_i = \frac{P_i}{\sum_{j}^{n} \left(\dot{z} \cdot \frac{L}{D} \cdot \Delta t \right)_j} \qquad (8)$$

where P_i is the total number of intercepted thermals having radii within the particular $(\triangle R)_i$ interval. When the total number of measured thermals is relatively small, the height of the various strips will vary erratically, of course, with many intervals having k = 0. As more data become available, however, it is to be expected that the bars will begin to vary in height according to some definite pattern, for some chosen value of the interval △R, and should become distributed on either side of a maximum value of k as indicated in figure 7. The pattern thus obtained will be specifically characteristic of the particular geographical area during the time period of interest.

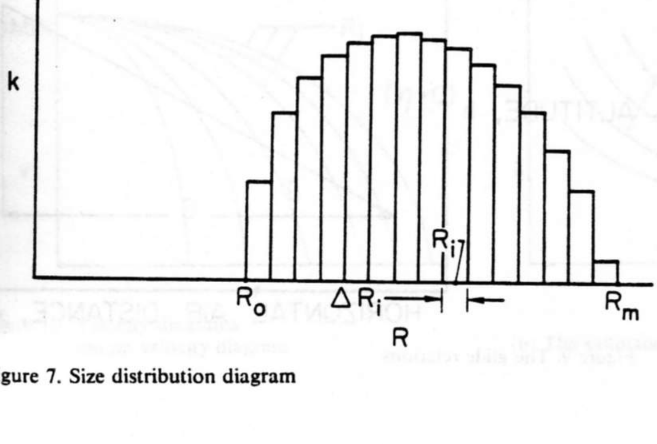


Figure 7. Size distribution diagram

Frequency of thermal interceptions

We can now construct a new graph by dividing the value k_i of each interval of the size distribution graph by the radius interval $(\triangle R)_i$ of the strip, and plotting this new value, denoted by σ, on the ordinate in place of k as shown in figure 8(a). The factor σ will be defined as the thermal *interception frequency* and is given by

$$\sigma_i = \frac{k_i}{(\Delta R)_i} \qquad (9)$$

The resulting graph is the thermal *interception frequency diagram*. When data on a sufficiently large number of thermals are available for preparing such a graph, the value of △R may be made small; the stepwise variation of σ with R can then be approximated by a continuous curve drawn through the midpoints of the steps, as shown by the dashed curve in figure 8(a). The resulting curve is the graph of the interception frequency function σ(R) (fig. 8(b)).

If now N is defined as the total number of thermals intercepted *per mile*, having radii between an arbitrary radius R' and R_m, then as is obvious from the bar graph of figure 8(a),

$$N = \sum_{i=m}^{R'} \sigma_i (\Delta R)_i \qquad (10)$$

or from the continuous curve of figure 8(b),

$$N = \int_{R_m}^{R'} \sigma \, dR \qquad (11)$$

The value of N is thus numerically equal to the area under the interception frequency curve between R_m and R', and hence is a function of the variable limit R'. The total number of thermals intercepted per mile obviously increases as R' decreases. Therefore, if R' denotes the radius of the minimum size thermal within which a given sailplane can circle in equilibrium, then for a high probability of intercepting a *usable* thermal it is desirable that R' for the sailplane be as small as possible, especially if the magnitude of σ is small.

The value to soaring of an accurate interception frequency curve for a given soaring area is obvious. In addition to providing information on the distribution of thermal sizes it also indicates the relative air distance a sailplane must travel in order to intercept a thermal in a given size range. In this way the effects of all the various meteorological factors which determine the size and distribution density, and the probability of interception of thermal shells, are integrated into a single function by which the soaring reliability of a sailplane can be predicted. The function σ(R) will, of

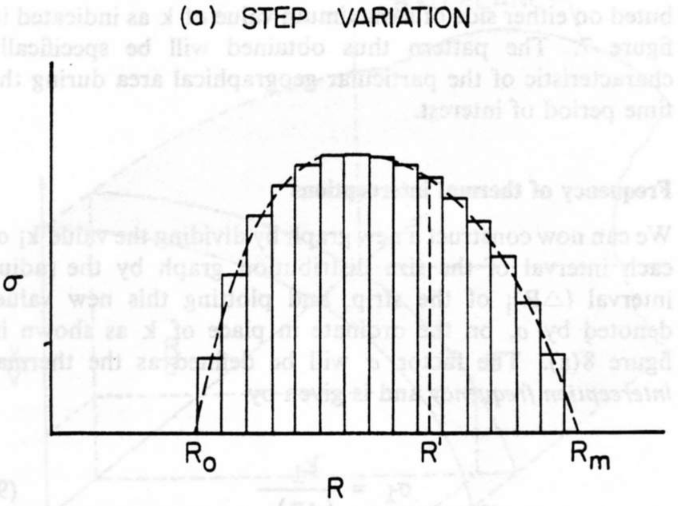


Figure 8. Interception frequency diagram (a)

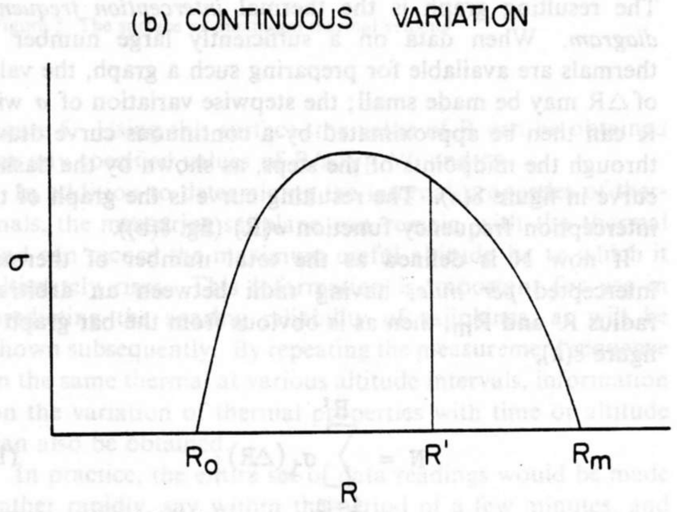


Figure 8. Concluded (b)

course, depend very much upon the meteorological conditions prevailing during the collection of the data. The influence of these various conditions will allow us, however, to prepare selective $\sigma(R)$ curves which will apply to periods when specific types of meteorological conditions exist, such as particular types of weather, wind conditions (speed and direction), daily and seasonal time periods, and highly localized terrain effects. For example, selective $\sigma(R)$ curves could be established for, say, two-hour intervals throughout the day for particular months of the year so as to determine the effects of the heating rate variation during the day on soarability of the air, for different times of the year. In a similar manner specific $\sigma(R)$ curves could be prepared for very narrow regions of terrain within a broader geographical area to determine the local variations of soarability. These, of course, are but a few of the many specialized $\sigma(R)$ functions which could be prepared from the thermal measurements.

To some extent the $\sigma(R)$ curve will be influenced by the capabilities of the pilot in gathering accurate data on the thermals but a more basic factor is the sailplane itself. Unless a true thermal sailplane (ref. 2) is used for the data collection, the value of R_o may lie so close to that of R_m that the range of the $\sigma(R)$ curve is too short to be of value; that is, a conventional sailplane cannot be used to measure very small thermals so that only the smallest *measurable* thermal size would appear on the graph. In addition, large, but weak, thermals would not be measurable with anything but a thermal sailplane since equilibrium flight in the thermal could not otherwise be established.

The soaring reliability index

There now remains the final problem of quantitatively relating the interception frequency curve to the soaring reliability of sailplanes. In order to develop this relationship let us consider a sailplane which, by circling a thermal, has risen to the altitude h_* where the thermal begins to weaken or dissipate. The craft then leaves the thermal and sets out on a straight glide at an airspeed corresponding to some particular value of L/D, not necessarily the speed for maximum L/D. If the craft continues the glide without encountering a thermal, it will, of course, ultimately reach an altitude below which it is unlikely that any thermals will be found in a sufficiently developed form to provide "lift", and if the sailplane sinks below this level, the necessity of a landing is almost certain. Let us define this lower altitude limit as h_o. The obvious requirement which must be satisfied then, if the sailplane is to remain airborne and continue soaring, is that it intercept at least *one usable* thermal while gliding down from h_* to h_o. By "usable" we mean that the thermal must be of sufficient size and strength that the sailplane can circle within it and gain altitude, that is, that equilibrium flight can be accomplished. It is thus not the total number of thermals intercepted which is of importance, but only the number of usable ones.

Referring to figure 9, the sailplane will traverse a horizontal *air distance* G while descending the vertical distance h_*-h_o where G is given by

$$G = (h_* - h_o)\,\mathrm{ctn}\,\theta \tag{12}$$

Here θ is the gliding angle and since

$$\mathrm{ctn}\,\theta = \frac{L}{D} \tag{13}$$

the glide distance can be expressed as

$$G = (h_* - h_o)\cdot\frac{L}{D} \tag{14}$$

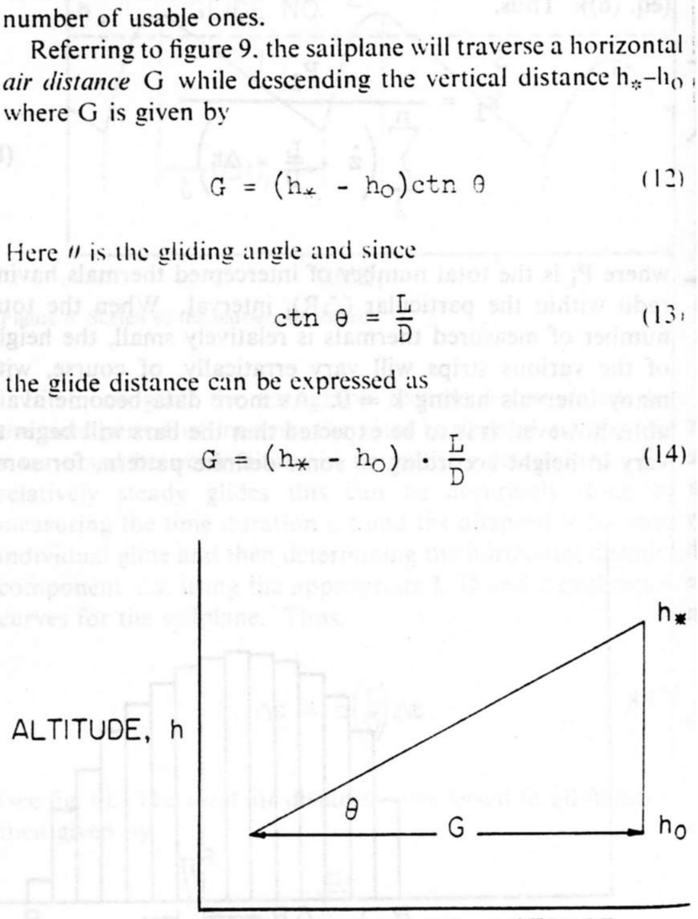


Figure 9. The glide relations

Now from the definition of N as previously given, it follows that the product NG is equal to the total number of thermals of usable size which will be intercepted, on the average, in the course of the glide. We shall call the product NG the soaring reliability index and denote it by the symbol γ. The soaring reliability index is thus given by

$$\gamma = (h_* - h_o) \cdot \frac{L}{D} \cdot \int_{R_m}^{R'} \sigma \, dR \qquad (15)$$

using equations (11) and (14). This index implicitly connects all the primary meteorological and aerodynamic factors which affect the soaring reliability of a given sailplane operating over a given geographical area. It can be specialized for studying any specific meteorological effects desired through the use of the corresponding selective $\sigma(R)$ function for that particular meteorological condition.

In equation (15), the integral limit R' corresponds physically to the minimum thermal size within which the particular sailplane design under consideration can circle in equilibrium flight, and R_m is a constant which corresponds either to the actual maximum thermal size measured, or to the *practical* upper radius limit of the $\sigma(R)$ curves where $\sigma \rightarrow 0$ (thus excluding some few isolated thermals which may have $R > R_m$). The value of the integral is therefore a function only of R', the minimum *usable* thermal size, and R' in turn is a function primarily of the aerodynamic characteristics of the sailplane in circling flight (as will be discussed shortly). Thus the aerodynamic properties of the sailplane determine the value of the integral and hence the value of the reliability index γ. The L/D ratio is purely a function of the aerodynamic efficiency of the craft, and h_*-h_o depends upon how high the thermals rise, on an average basis.

In general, it would of course be desirable to have R' as small as possible and σ, L/D, and h_*-h_o as large as possible in order to obtain the maximum value of the reliability index γ. However, σ and h_*-h_o are set by the meteorological conditions of the particular area and may be of rather restricted magnitude. Hence for high soaring reliability, the craft must possess a proper balance between R' and L/D. As discussed in reference 2 the simultaneous requirements of a small R' value and a large L/D value for a fixed geometry sailplane are incompatible so that we may expect some one particular combination of these properties (i. e., some particular aircraft configuration) to possess a maximum value for γ, for given soaring conditions.

Design of reliable soaring planes

This brings us therefore to the need for explicitly relating the aerodynamic characteristics of sailplanes with the soaring reliability index γ. This is accomplished by finding the integrated effect of the span length, aspect ratio, parasite drag, and wing loading of the craft on γ. In general, whether a given thermal can be used by a specific sailplane for gaining altitude depends not only on the thermal size, but also upon the thermal strength. Hence, the effects of both of these factors must be considered in any meaningful analysis of soaring reliability. In order to include the simultaneous effects of thermal strength and size, we proceed as follows.. First, all thermal data records are examined and the value of v_c for the very weakest measured thermal is determined Here v_c is the relative vertical velocity ν_c–V' at the center of the thermal shell ($r = 0, \sigma = 0$), and is given in terms of the thermal properties by the relation

$$v_c = \frac{\Gamma}{R}\left[\frac{1}{2} - \frac{1}{4\pi}\left(\ln\frac{8R}{a} - \frac{1}{4}\right)\right] \qquad (16)$$

using equation (1). It may reasonably be expected then that of all the thermals which may be intercepted in future flights, none which are of a usable size will have a value of v_c less than this minimum. Using this minimum value $(v_c)_{min}$ and an average value of R/a as determined from the thermal measurements, a corresponding value of Γ/R can be determined, using equation (16). Then a series of curves of v(r) can be plotted for various thermal sizes R'_i as shown in figure 10(a), where v(r) is the variation of v with r in the plane $\eta = 0$ (ref. 1), and hence corresponds to the maximum relative velocity in the (weakest) thermal for each value of R'_i. Each curve corresponds to a different thermal size R'_i, as noted. All these minimum strength thermals have the same value of $v_c = (v_c)_{min}$ and of Γ/R and r/a. Thus, since it is highly unlikely that any usable size thermals will be encountered in flight which have a weaker v(r) variation in the core plane, these curves may be used to determine the minimum usable thermal size R' for any given sailplane whose circling performance curve $\dot{z}(r)$ is known.

In this way, the effect of the variation in thermal strength for a constant thermal size can be taken into account. More detailed analyses are of course possible by using the v(r) curve for each R'_i corresponding to the v_c and R/a values of the weakest thermal in each $\triangle R_i$ interval. When sufficient thermal data become available for analysis, it may

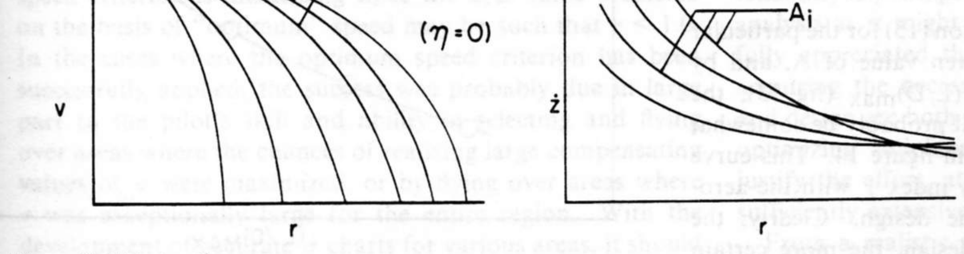


Figure 10. Velocity diagrams
(a) The minimum velocity diagram
(b) The sailplane performance diagram

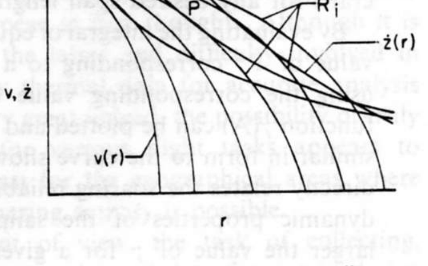


Figure 11. The minimum usable radius diagram

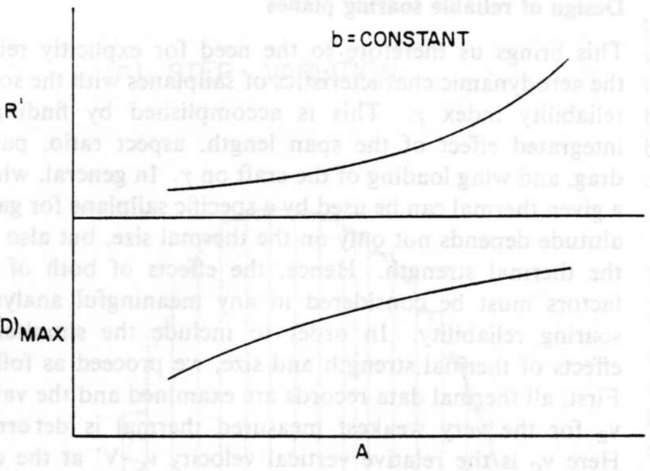


Figure 12. The R'(A) and $(L/D)_{max}$ (A) functions

be found possible to define quite definite correlations between thermal size and thermal strength (i. e., between R. Γ. and R/a).

Next a series of sailplane design charts is prepared according to the procedure of reference 2. The curves on these charts, the general form of which is sketched in figure 10(b). give the variation of ε with r for various aspect ratio and span length values, for the structural weight parameters and drag properties of the aircraft design configuration being considered. The minimum thermal velocity diagram (fig. 10(a)) is then superposed on the sailplane design chart for a given span length to yield a graph of the type shown in figure 11. The point of tangency P of a given ε(r) curve (corresponding to a particular A value) with a v(r) curve establishes the value of R' for that particular sailplane, since this R' gives the smallest thermal size in which the craft could circle in equilibrium and thus continuously gain altitude. Actually, this value of R' is the absolute lower limit, and a more practical limit might be somewhat larger in value, in order to allow for a suitably large region over which equilibrium can be attained in the minimum sized thermal. The method for establishing the minimum thermal strength, however, makes some allowance for this need for a sufficient equilibrium region. From such a graph as shown in figure 11, the variation of R' with aspect ratio A can be determined and plotted as shown in figure 12.

From the design procedure of reference 2 the variation of $(L/D)_{max}$ with A can also be determined and plotted as shown in figure 12. Using A as a parameter, the variation of R' with $(L/D)_{max}$ can finally be plotted as shown in figure 13. This curve gives the required functional relationship between $(L/D)_{max}$ and the minimum usable thermal radius R', allowing us to evaluate equation (15) and thus determine the soaring reliability index for the particular sailplane design as a function of the aspect ratio (and other properties of the craft) for any desired span length.

By evaluating the integral of equation (15) for the particular value of R' corresponding to a given value of A, and by using the corresponding value of $(L/D)_{max}$ (fig. 13), the function γ(A) can be plotted and will probably be somewhat similar in form to the curve shown in figure 14. This curve directly relates the soaring reliability index γ with the aerodynamic properties of the sailplane design. Clearly, the larger the value of γ for a given design, the more certain will be the ability of the craft to remain airborne, i. e., to perform reliable soaring. The minimum criterion for continuous soaring, however, is that the craft intercept at least *one* usable thermal in its glide and hence we may set the value $\gamma = 1.0$ as the lowest allowable limit for reliable soaring. This condition is denoted in figure 14 as a solid line at $\gamma = 1.0$.

The hypothetical reliability curve of figure 14 has several interesting features. For example, there may be two values of A for which $\gamma = 1.0$. At the lower value A_1, soaring reliability depends mainly upon the craft's ability to use a large range of thermal sizes, since its $(L/D)_{max}$ (i. e., its glide path) is relatively small. At the higher value A_2 reliability is due to the long glide path and consequent increase in thermal interceptions, although the plane cannot now use any but the larger thermals. Between A_1 and A_2 of course exists the aspect ratio A_* corresponding to the highest degree of soaring reliability $\gamma = \gamma_{max}$. For A values below A_1, the range of usable thermals may be large, but the glide path becomes so short that too few are intercepted. For A values above A_2 despite the long glide path, the size range of usuable thermals becomes so narrow that soaring ability drops off very rapidly as A increased.

In general, if γ_{max} is appreciably greather than 1.0, it would appear best to use an aspect ratio larger than A_* (but somewhat less than A_2) so as to take advantage of the higher $(L/D)_{max}$ value for efficient gliding and wind penetration. It must be appreciated, of course, that the relative shape and magnitude of the soaring reliability curve γ(A) will depend entirely upon the σ(R) variation for the area and will be implicitly affected by all the factors which influence the thermal conditions. In some areas, γ may never even approach 1.0 for any practical sailplane design at any time of the year; there just aren't enough usable thermals. In particular, γ(A) will be a relatively sensitive function of time (both of the day and of the year) for a given soaring area. Within a given time interval, γ(A) will vary with the general weather conditions (wind, lapse rate, etc.). When sufficient thermal data have become available, however, the average soaring reliability over a given area, under similar weather conditions, can in all probability be expressed with a reasonably high degree of confidence and a single sailplane design capable of reliable soaring over a wide range of conditions can be envolved.

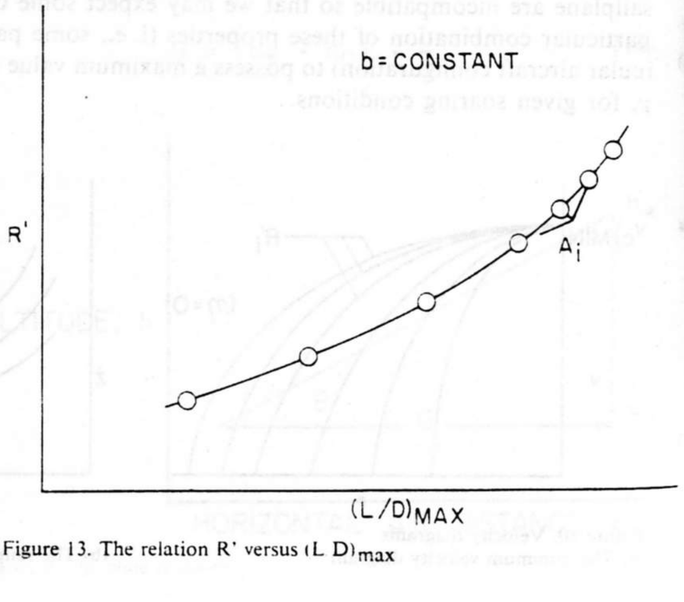


Figure 13. The relation R' versus $(L/D)_{max}$

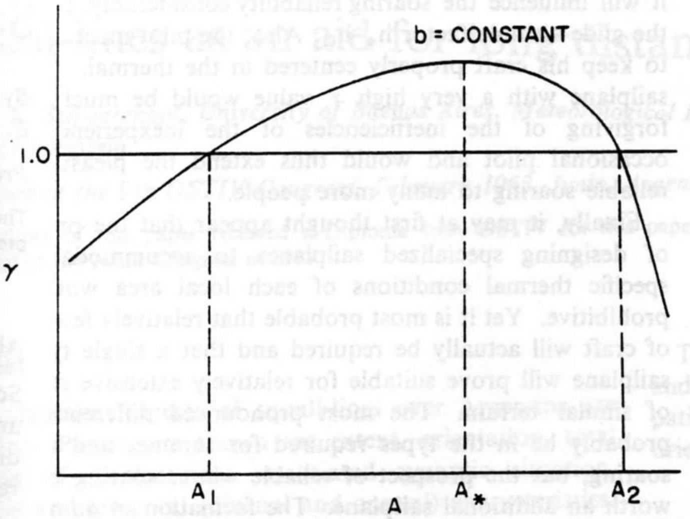


Figure 14. The soaring reliability diagram

A series of plots like that of figure 14 for various values of span length, when evaluated in light of the adverse characteristics of large spans in small thermals, will indicate the best combination of b and A for high soaring reliability while still meeting other performance goals (such as a high $(L/D)_{max}$ value). Thus the optimum sailplane configuration, corresponding to the particular structural weight functions and drag coefficient being used in the design analysis, can be arrived at. It is clear, however, that there may be definite limits set on both soaring and gliding efficiency by the existing thermal conditions; it is precisely the purpose of the soaring reliability index to provide a quantitative estimate of the extent of such limits. Knowing the $\sigma(R)$ curve for a particular area, sailplanes can be designed which will possess the best possible distances and penetration abilities while satisfying the more fundamental requirement of sufficient soaring ability.

Referring to equation (15), the principal factors influencing the success of cross-country distance flights become clear. For instance. is has long been the practice in distance flights to use a so-called "optimum" cruising speed and $(L/D)_{opt}$, where in many cases $(L/D)_{opt} < (L/D)_{max}$ if thermals are strong. By flying at the lower L/D value. the airspeed can be increased so that maximum ground distance can be covered during the hours of best thermal production. This procedure is successful, however, primarily in areas and at times where $\sigma(R)$ is so large that the L/D can be appreciably lowered while still maintaining the γ value above 1.0 for altitude-gaining ability. In developing the "optimum" cross-country speed criterion. account is taken only of the thermal strength (rate of climb) and it is assumed that a large enough (usable) thermal will be encountered in the course of each glide. It may happen, however, that in many cases the optimum speed criterion is misleading since the L/D value predicted on the basis of "optimum" speed may be such that $\gamma < 1.0$. In the cases where the optimum speed criterion has been successfully applied. the success was probably due in large part to the pilot's skill and ability in selecting and flying over areas where the chances of realizing large compensating values of σ were maximized, or by flying over areas where σ was exceptionally large for the entire region. With the development of accurate σ charts for various areas, it should become possible to determine a more truly "optimum" cross-country speed and L/D which will also account for the probability of intercepting a sufficient number of usable thermals.

The above considerations on soaring reliability are based on the rigid or fixed-geometry sailplane. If the sailplane can be provided with suitable means for varying its geometry (like the soaring bird possesses), it may become possible to attain very large values for both $\int_{R_m}^{R'} \sigma(R)\,dR$ and $(L/D)_{max}$.

Then the value of γ could be increased to a very high maximum. Considering that most soaring birds usually operate at a relatively low maximum altitude (equivalent to h_*), it becomes even more critical in their case that the σ integral and $(L/D)_{max}$ values both be large; hence the need for variable geometry. There is little doubt that the variable geometry characteristics of soaring bird wings play an important role in the bird's unexcelled soaring reliability. Since sailplanes usually climb to much higher altitudes in thermals than do soaring birds, it has been the opinion of some soaring enthusiasts that present-day sailplanes are superior in *soaring* ability to the birds. Such, however, is not the case. The bird, unlike the sailplane pilot, is not primarily engaged in soaring merely for pleasure, but in the quite serious business of searching for food. He therefore has no real need to climb to very high altitudes where his detailed observational abilities would be reduced, and when the bird leaves a sailplane in a thermal it is not because he cannot climb higher in the thermal but actually because he has no need to climb higher. In reality, it is an inspiring example of the bird's unexcelled soaring ability that he can risk leaving thermals at such low altitudes and still retain such a high degree of soaring reliability, considering how relatively seldom he resorts to flapping flight even at very low altitudes. The reader is invited to compare the conventional sailplane with the soaring bird in the light of equation (15).

Finally, since $\dot{z}(r)$ is known or can be measured for existing sailplanes, their soaring reliability index can be established for any and all areas for which sufficient thermal data exist. In fact, it may someday become possible to realistically predict which type of sailplane should be most successful in a particular national or international contest, knowing the contest location and prevailing weather conditions, and considering equal piloting abilities. The reliability index for existing sailplanes can of course be determined for any flight value of the L/D ratio, as well as for $(L/D)_{max}$, and hence the variation of γ with the gliding flight speed V can be established.

Concluding remarks

A primary objective of this paper has been to suggest that the problem of designing sailplanes with a predictable soaring reliability is perhaps not quite so invulnerable to quantitative analysis as it might appear at first thought. Although it is fully appreciated that the labor and difficulty involved in acquiring the necessary thermal data for accurate analysis and design are both very great indeed. the possibility of truly optimizing sailplanes for various flight tasks appears to justify the effort, at least for the geographical areas where sufficiently extensive soaring activity is possible.

From a realistic point of view, the task of collecting, classifying, and interpreting thermal data for use in design would, of course, involve a rather large, well organized, and coordinated effort. Yet, it is the very type of project which progressive soaring fraternities would find most interesting and enjoyable, and the results would be invaluable in improving the future "soarability" of the local areas. The knowledge gained would give pilots a much clearer picture and a better feel for the local thermal conditions. In regions where two "local" areas overlap, their combined data could perhaps be used to predict the reliability of very long distance flights. It is indeed hoped that some of the larger soaring organizations will undertake the data collection task, at least on an experimental or exploratory basis.

The importance of the thermal sailplane for collecting accurate data on thermal shell convections cannot be overemphasized. While conventional sailplanes can probably be used quite successfully to investigate the properties of the larger thermals, they are of little value for smaller thermals and for efficient design we must measure the entire range of practical thermal sizes. The value of the data which can be gathered by the thermal sailplane fully justifies the design and construction of several such craft for research purposes. The value of the meteorological data so obtained should prove of great value not only for soaring, but for aviation in general.

The considerations herein have been confined to the effect of the aircraft characteristics on soaring reliability. An efficient aircraft is the major factor in reliable soaring but the abilities of the pilot, of course, also play a most important role. Obviously, even the best sailplane will not perform satisfactorily unless the pilot is capable of making sufficient use of the thermals encountered. In this respect, the ability of the pilot to decide whether an intercepted thermal is "usable" or not before wasting much altitude in exploring it will influence the soaring reliability considerably, t the glide-altitude factor $h_* - h_0$. Also, the pilot must to keep his craft properly centered in the thermal. sailplane with a very high γ value would be mucl forgiving of the inefficiencies of the inexperienc occasional pilot and would thus extend the pleas reliable soaring to many more people.

Finally, it may at first thought appear that the pr of designing specialized sailplanes to accommoda specific thermal conditions of each local area wou prohibitive. Yet it is most probable that relatively few of craft will actually be required and that a single t sailplane will prove suitable for relatively extensive r of similar terrain. The most pronounced differenc probably be in the types required for summer and soaring, but the prospect of reliable winter soaring i worth an additional sailplane. The formation of num local technical groups capable of obtaining thermal dat of carrying out the design and construction of reliable planes for local soaring would be a most progressive st the advancement of practical soaring flight.

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