Computerized Glider Analysis

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Nomenclature

a	– slope of lift versus incidence
A	– Fourier's Series coefficient
b	– wing span
C_d	– drag coefficient
C_{dj}	– induced drag coefficient
C_{dp}	– aerofoil section drag coeff.
C_L	– lift coefficient
C_{Lo}	– local lift coefficient for wing $C_L = 0$
$C_{L_{N=1}}$	– local lift coefficient for wing $C_L = 1$
C_{LR}	– resultant lift coefficient
C	– wing chord
W	– all-up weight
Re	– Reynolds number
V	– speed of flight
w	– rate of sinking
Y	– station along wingspan
α	– aerofil incidence
α_i	– induced incidence
α_o	– incidence for zero lift
γ	– local circulation coefficient
ϑ	– angular station of "y" section
$\varkappa$	– auxiliary angle for drag calculation
μ	– slope of lift versus incidence for local chord
φ	– resultant incidence

1. Introduction

In design practice it is necessary to examine the influence of particular parameters on glider properties and to find on this basis the optimum values of performance. The problem is solved by designers more or less strictly according to possibilities of computing forms or methods applied.

The progress and popularization of digital computers permits them to be used in daily practice. The high degree of complication and labour involved in the computing process as well as the demands for increased performance call for the application of the digital computer.

The digital computer can be used in each stage of the design process, that is to say aerodynamics, performance, loadings, structural properties and aeroelasticity.

In the current practice at SZD, for each of programmes the above stages have been prepared, to facilitate the analysis of the various design steps. The results of one step become the starting data for the next. The further evolution of computing leads to one complete programme giving the optimum synthesis of the glider. It consists of a separate modulus for each step. Each step can also be separated according to the needs of the problem under consideration.

The aim of the present paper is to drow attention to some of the problems concerned with programming, and using the digital computer, in establishing the optimum values of the parameters of the glider.

2. Aerodynamic Characteristics of Aerofoils

The choice of aerofoil and wing geometry is the basic problem in the preliminary design project. Since the aerofoil development is not part of the designer's work (belonging rather to the field of aerodynamic scientists activity, and so calling for special study) we can base our work on wind tunnel results for the limited Re numbers. The published data usually range to Re greater than $0.7 \cdot 10^6$ and most of the NACA sections greater than $3 \cdot 10^6$, whereas for glider purpose the necessary range is for Re smaller than $0.4 \cdot 10^6$.

The characteristics for interesting Re numbers appropriate to the chosen chords have to be found. The shapes of these curves can be obtained by suitable modifications of the curves given by wind-tunnel results.

For example the curve $C_L(\alpha)$ for $Re_x < Re_1 < Re_2 < Re_3$ can be found as follows:

1) find by extrapolation $C_{Lmax\,x}$ on base of known values of C_{Lmax} (see figs. 1 and 2);

2) Modify the curve for the nearest value of Re:

$$C_{Lx}(\alpha) = C_{L1}(\alpha_1)\,\frac{C_{L\,max\,x}}{C_{L\,max\,1}} \qquad (1)$$

where:

$$\alpha = (\alpha - \alpha_0)\,\frac{C_{L\,max\,1}}{C_{L\,max\,x}} + \alpha_0 \qquad (2)$$

When $Re_1 < Re_x < Re_2$ the curves C_{L1} and C_{L2} are to be modified in the same way as above. Then the intermediate curve is to be found by linear interpolation:

$$C_{Lx} = C_{Lx1}\,\frac{Re - Re_2}{Re_1 - Re_2} + C_{Lx2}\,\frac{Re - Re_1}{Re_2 - Re_1} \qquad (3)$$

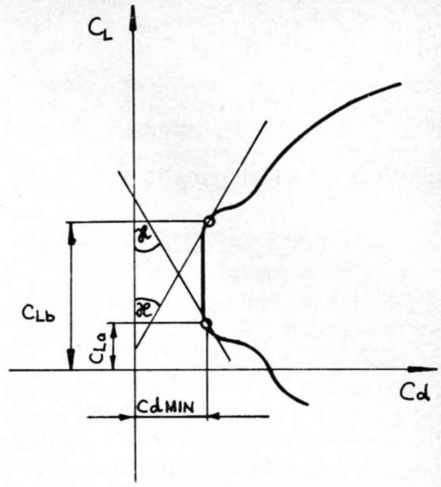

FIG. 3

If the change of Re is followed by the change of α it is necessary to allow for this fact.

The curve $C_d(C_L)$ is to be found in a similar way, provided that the modification is based on the function of $C_{d\,min}$ (Re).

For laminar sections it is necessary to take into account the function of Re concerned with the shape of the laminar "bucket".

The angles $\varkappa$ (see fig. 3) are to be given in the programme in the form of data ranging $15° \leqslant \varkappa \leqslant 30°$ (4) when the results are in practice independent of their value.

3. Lift Distributions along the Span

Lift distribution calculations are very time consuming. In the range of a straight line function of lift versus incidence, the "zero" distribution and unit distribution enable the total lift when the lift coefficient is C_{LR} to be found:

$$C_L(y) = C_{Lo}(y) + C_{LR} \cdot C_{LN=1}(y) \qquad (5)$$

In the region of C_{Lmax} the calculation is to be performed by means of approximations, including corrections for lift slope "a". It is convenient to use the matrix method [3].

Noting the circulation in Fourier Series for each wing section there is (see fig. 4):

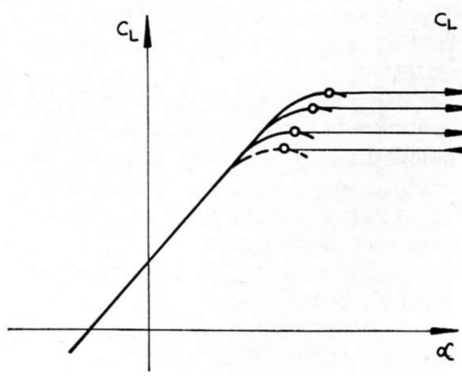

FIG. 1

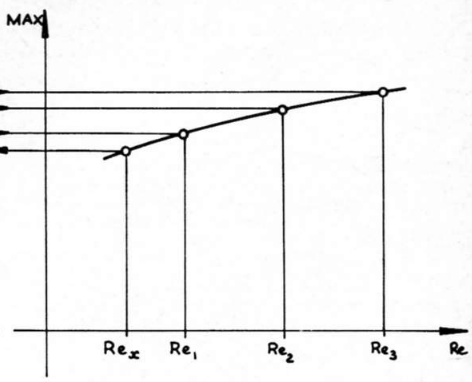

FIG. 2

$$\gamma = \sum_{n=1}^{n=m} A_n \sin n\vartheta \qquad (6)$$

where m is number of wing spanwise stations.

Therefore for all wing stations:

$$\{\gamma\} = [S]\{A\} \qquad (7)$$

where:

$\{\gamma\} = \begin{Bmatrix} \gamma_1 \\ \gamma_2 \\ \vdots \\ \gamma_m \end{Bmatrix}$ is the column matrix of circulation

$\{A\} = \begin{Bmatrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{Bmatrix}$ is the column matrix of circulation Fourier Series.

[s] is the matrix of sine functions.

$$[S] = \begin{bmatrix} \sin\vartheta_1, & \sin 2\vartheta_1, & \sin 3\vartheta_1 & \ldots & \sin m\vartheta_1 \\ \sin\vartheta_2, & \sin 2\vartheta_2 & \ldots & & \\ \ldots & & & & \\ \sin\vartheta_m & \sin 2\vartheta_m & \ldots & & \sin m\vartheta_m \end{bmatrix} \qquad (10)$$

The induced angle of attack of the chosen wing section is given by the formula:

$$\alpha_i = \sum_{n=1}^{n=m} \frac{n A_n \sin\vartheta}{4 \sin\vartheta} \qquad (11)$$

and for all wing stations:

$$\{\alpha_i\} = [P]\{A\} \qquad (12)$$

where the matrix

$$[P] = \begin{bmatrix} 1/4 & \frac{2\sin 2\vartheta_1}{4\sin\vartheta_1} & \frac{3\sin 3\vartheta_1}{4\sin\vartheta_1} & \ldots & \frac{m\sin m\vartheta_1}{4\sin\vartheta_1} \\ 1/4 & \frac{2\sin 2\vartheta_2}{4\sin\vartheta_2} & \ldots & \ldots & \ldots \\ 1/4 & \frac{2\sin 2\vartheta_m}{4\sin\vartheta_m} & \ldots & & \frac{m\sin m\vartheta_m}{4\sin\vartheta_m} \end{bmatrix} \qquad (13)$$

Computing from eq. (7)

$$\{A\} = [S]^{-1}\{\gamma\} \qquad (14)$$

and substituting this result in eq. (12) we obtain:

$$\{\alpha_i\} [P][S]^{-1}\{\gamma\} \qquad (15)$$

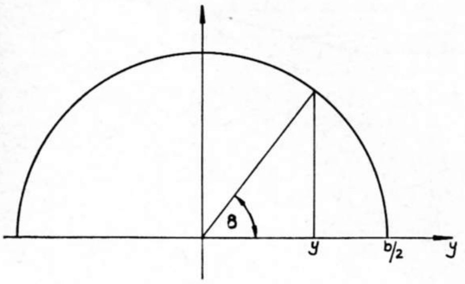

FIG. 4

The actual angle of attack at each wing station is the difference between the geometric and induced angles of attack:

$$\varphi = \alpha - \alpha_i \qquad (16)$$

and depends on the circulation by the formula:

$$\varphi = \mu\gamma \qquad (17)$$

where: $$\mu = \frac{b}{a \cdot c} \qquad (18)$$

The angles of attack at all wing stations result in the formula:

$$\{\varphi\} = [\mu]\{\gamma\}. \qquad (19)$$

where $[\mu]$ is the diagonal matrix:

$$[\mu] = \begin{bmatrix} \mu_1 & 0 & 0 & \ldots & 0 \\ 0 & \mu_2 & 0 & \ldots & 0 \\ \ldots & & & & \\ 0 & \ldots & & & \mu_m \end{bmatrix} \qquad (20)$$

The geometric angle of attack results from eqs. (16) and (19) in the form:

$$\{\alpha\} = [PS^{-1} + \mu]\{\gamma\} \qquad (21)$$

Therefore the circulation distribution can be obtained direct from the equation:

$$\{\gamma\} = [PS^{-1} + \mu]^{-1}\{\alpha\} \qquad (22)$$

and for each wing section the lift coefficient is:

$$C_L = \frac{b}{c}\gamma \qquad (23)$$

On the basis of eq. (22) we obtain directly the circulation distribution on the wing for angle of attack of interest and for the chosen μ.
In the case of a nonlinear function of $C_L(\alpha)$ the calculation is to be carried on by means of iteration, making a correction for μ after each iteration according to the value of circulation obtained, as follows (see fig. 5):

$$\{{}^i\gamma\} = [PS^{-1} + {}^i\mu]^{-1}\{\alpha\} \qquad (a)$$

$${}^i\varphi = {}^i\mu\, {}^i\gamma \qquad (b)$$

$${}^i\gamma' = \frac{c}{b} C_L({}^i\varphi) \qquad (c)$$

$${}^{i+1}\mu = \frac{{}^i\varphi}{{}^i\gamma'} \qquad (d)$$

The value for μ obtained from eg. (d) is to be once more substituted into eq. (a).
For many aerofoils the function $C_L(\alpha)$ is nonlinear for angles of attack well below the critical (approximately from 0.5 C_{Lmax} onwards). This fact calls for using iteration even in the range of maximum gliding ratio.
On the basis of lift distribution calculations it is possible to find the necessary aerodynamic twist of wing enabling the correct character of stalling, as well as the minimum stalling speed, to be obtained.

4. Wing and Glider Polars

On the basis of local values of C_L (obtained from the lift distribution) it is possible to find the local induced and section drag coefficients. Integrating them over the whole span we obtain the total drag of the wing. In this way the need of calculation of Lilienthal's polar for the wing mean aerodynamic chord is eliminated. At the same time the risk of missing the influence of low Re number on the wing tip is avoided. On wing tip there exists the more rapid decrement of lift when compared with the increment on wing root.
On fig. 6 there is shown the scheme of wing polar calculation according to Re

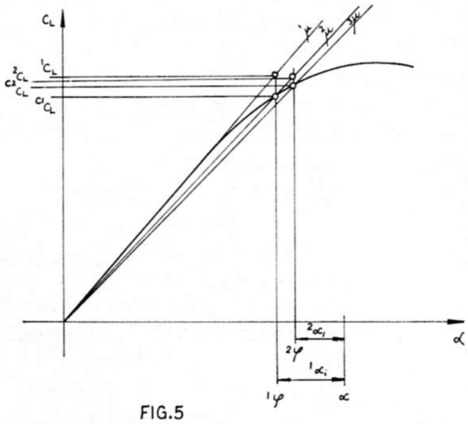

FIG.5

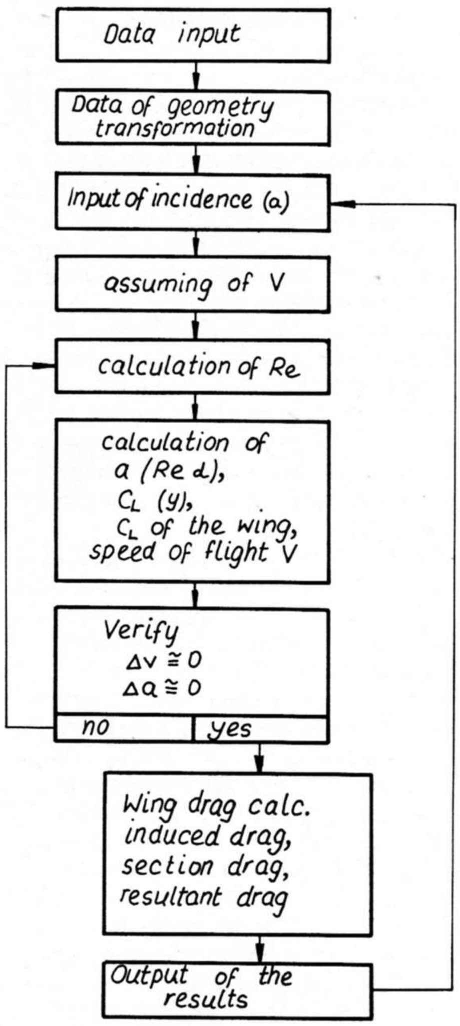

FIG. 6

number changes depending on actual flight speed. This scheme has been employed in SZD-B2 programme for digital computer. In this programme the values of flight speed and local lift slope are compared with values from iteration the last but one. These values are corrected according to actual value of C_L of wing for interesting value of angle of attack.
The calculations performed due to SZD-B2-programme give the basic wing characteristics of known geometry, aerofoils and all up weight of gliders in form of the functions:

$$C_L(\alpha);\ C_{di}(\alpha);\ C_{dp}(\alpha) \text{ and } V(\alpha)$$

The analysis of parasite drag of the glider is a vast separate problem. It can be solved on the basis of wind-tunnel results, of flight tests.
Assuming this problem to be solved namely, that we have the parasite drag versus fuselage incidence, the resultant characteristics for the whole glider may now be determined.
By combining in various ways wing and parasite drags we obtain a new parameter, that means the wing to fuselage wedge angle. Choice of this angle enables one to obtain either the highest possible value of best gliding ratio, or the best cruising characteristic with smaller best gliding ratio. The last way is recommended for high performance gliders of standard class having no flap.
The glider characteristic enables the speed polar to be calculated in the usual way. The speed polar is the popular characteristic of the glider enables the comparison with other gliders to be made and the cross-country flight properties to be defined.
Furthermore the glider in flight is subjected also to the action of pitching moments which are balanced by the tail load. The tail load in most cases acts downwards giving a decrease of total lift which results in a decrease of gliding ratio, sometimes by more than 10 percent.
Correcting the speed polar in respect of tail load we obtain the so-called «equilibrium polar». This polar can be compared with flights test results, and used to define the cross-country flight properties. Calculations with tail load included take account of basic glider parameters like aerofoil section, fuselage length, and c. g. position, on which the tail load depends.
The commonly accepted method of calculating the speed polar with tail load neglected, and usually not verified by flight test results, which we find in many publications, does not allow a true comparision of gliders of the same class or of the same standard to be made.

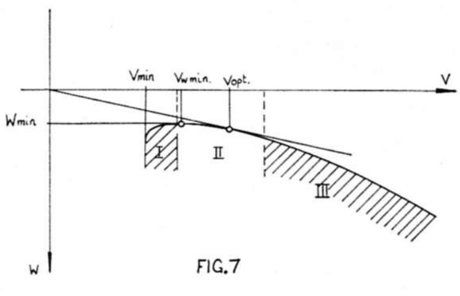

FIG.7

5. Cross-Country Flight Characteristics

For high performance gliders the most important feature is the function of cruising speed versus climbing speed of air in thermals. It synthesizes the properties of the glider in circling and cross-country flight. The problem is widely described in literature [1, 2, 4].
The appropriate analysis yields the conclusion that the speed polar can be divided into three regions (fig. 7):
I – region of circling speeds
II – region of max. range
III – region of cross-country speeds.
The second region is seldom exploited e. g. only in very weak meteorological conditions when the distance between thermals is very large, or when the thermals are weak.
When the cross-country flight characteristic is assumed to be the basis of glider optimization it is easier to do the calculation by means of a computer programme.
The stability and control properties of high performance gliders are not the subject of optimization, and are only one of the problems of interest to the designer.

6. Loadings and Strength Properties

For optimization of the glider parametres it is necessary to know the strength properties based on the loads on the main structure components.
On this basis it is possible to establish the all-up weight of the glider and to introduce appropriate corrections in the aerodynamic characteristics.
The most effective method of weight analysis is to base the calculation on the properties of an existing glider similar to the one being designed. Calculations based on statistical data or empirical formulas can be accepted as the first approximation, but for optimization purposes they fail. In most cases the prototype should be progressive and should include many novel structural conceptions outside the designer's experience.
The loading cases defined by design requirements are necessarily fragmented and do not form an entity which can be treated as to one complete design problem. For exemple the gust load on wing in based on one consideration whereas the tail load is on another.
Moreover the physical interpretation of loadings in design requirements is based on various approaches to the same problem. To prepare an universal programme for loading analysis on a computer it is necessary to employ many procedures, and to investigate all the national interpretations of loading cases. This, however, is a very complex task.
In programmes for the optimization of glider parameters there can be also included some phenomena of aeroelasticity, especially the wing distortion and control effectiveness. The flutter analysis is a very difficult computing problem and is usually replaced by defining only the stiffness criteria.
It is necessary to note the very important influence of wing twist on the aerodynamic characteristics of the glider. This fact is too often neglected in performance calculations.

7. Conclusions

The computerized glider analysis is a quick process enabling the examination of a great number of glider variants to be made. But this fact must not be allowed to lead to a surplusity of results which cannot be analyzed even by a large staff of designers. Therefore it is necessary to prepare a programme enabling the establishment of only the optimal variants of glider characteristics. In connection with this there is the necessity of establishing the optimization criteria.
If as a criterion we assume the best gliding ratio it is possible that two compared gliders will have the same value of gliding ratio but at different speeds. That exposes, however, the different cross-country flight properties which are the main feature of high performance glider. Moreover the best gliding ratio does not define the circling and cruising speed properties. In such a case other criteria are of interest, e. g. stalling speed, minimum sinking speed, and sinking speed at a selected cross-country flight speed.
There arises the problem of finding the multiplication factors for the final appreciation of such different criteria.
All the difficulties can be overcome when assuming the appropriate model of cross-country flight allowing for the analysis of only one parameter which is cruising speed versus thermal intensity. This criterion is valid for both the speed flights and distance flights.

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