Main Static Aeroelastic Effects on Sailplane Longitudinal Stability and Control

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1. Introduction

It has been remarked on several occasions that the aeroelastic deformation of the sailplane structure may considerably modify the longitudinal stability and control characteristics with respect to those predicted by the usual calculations based on the assumption of a «rigid» sailplane.

Several papers in the past dealt with this problem and presented experimental data compared with theoretical results (ref. 1, 2, 3).

The problem has become, and is becoming, more and more important owing to the increasing flight operational airspeeds and to the adoption of structural materials with low modulus of elasticity (plastic composites, for instance).

Theoretical calculations which are normally carried out in the design stage assuming a «rigid» sailplane may as a result be inadequate. A need may exist, therefore, to take into account some static aeroelastic effects in the equilibrium equation and/or in the stability condition.

In the present paper the effects of the wing torsional deformation and of the fuselage bending deformation are considered, as being probably the most important ones, as other authors (ref. 2 and 3) have already pointed out. The classical theoretical expressions for equilibrium and stability are therefore modified, in order to take into account these aeroelastic effects, and discussed. A comparison with experimental data registered in flight on a two-seater wooden sailplane allows an appreciation of the better approximation obtained.

2. Theoretical Expressions

Under current simplifying assumptions the equation for the sailplane equilibrium about the pitching axis is written as follows:

$$
(1)\quad
\left.
\begin{aligned}
&C_{M_o} + \frac{x_o - x'_a}{c} \cdot C_L \\
&+\left[C_{D_w} - C_{L_w}\left(\frac{C_{L_w}}{a_w} - i_w\right)\right]\frac{z_G}{c} \quad \text{Wing drag term}
\end{aligned}
\right\}\ \text{Sailplane less tail}
$$
$$
\left.
-\frac{\bar{V}'}{1+F}\left[\begin{aligned}&\frac{a_t}{a_w}\left(1-\frac{d\varepsilon}{d\alpha}\right)C_L - a_t(i_w - i_t)\\ &+ a_t\tau\delta + a_t\tau_{tab}\delta_{tab}\end{aligned}\right]
\right\}\ \text{Tail}
$$

(see list of symbols at the end).

Several terms in eq. 1 are affected by the elastic deformation of the sailplane under flight loads. The wing bending, for instance, modifies z_G. The wing torsion affects i_w, $(1 - d\varepsilon/d\alpha)$ and C_{Dw} (this latter effect has been explained and evaluated in ref. 6). i_t is affected by fuselage bending and tailplane/elevator torsion. $i_w - i_t$ may also be affected by deformations of the wing/fuselage attachments under load (ref. 2).

It is believed that the most important effects are due to wing torsion and fuselage bending, as several authors have outlined. The other effects mentioned above may be not negligible in particular cases.

The wing drag term is included in eq. 1. It has been remarked (ref. 4) and demonstrated in detail (ref. 5) that this term cannot be disregarded «a priori»: it often occurs on sailplanes that the vertical shift (z_G) of the SLT a.c. with respect to the sailplane C.G. is so large that the drag term becomes important.

In order to avoid too lengthy expressions, the effect of the drag term will not be included in the following equations. When accounting for it, it should be noted that the main aeroelastic effects which may affect the drag term are: the variation of C_{Dw} dure to the elastic wing twist (considerable at high speed, see ref. 6); the variation of i_w; the variation of z_G/c due to the wing elastic bending. In the calculations presented in par. 3, the wing drag terms has been included, but only accounting for the second of the three above listed effects, i.e. that due to i_w, estimated as the more powerful.

The description 'wing drag term' has been used here, following the usual practice. Strictly, it comprises two components (1) due to $C_{D_W} \cos\alpha$ and (2) due to $C_{L_W} \sin\alpha$, where α is the angle of incidence of longitudinal reference line. In the equation appears as $(C_{L_W}/a_w - i_w)$ and $\cos\alpha$ is assumed to be equal to unity and $\sin\alpha$ to equal α. In practice, term (2) may be even larger than term (1); the description 'drag term' is thus something of a mis-nomer. Even more strictly there is yet another component due to $C_{D_W} \sin\alpha$. However this is small and has been ignored.

2.1. Wing torsion:

The main effect of the wing torsion is on the wing setting i_w. If i_{wo} is the angle of the zero lift direction of the rigid wing with respect to the sailplane longitudinal reference line (depending also on the design washout of the rigid wing, if any) and ε is the elastic twist of the wing tip section with respect to the wing root section, the resultant i_w can be expressed as

$$(2)\qquad i_w = i_{wc} + J.\varepsilon\,.$$

Note that ε is negative for washout, which is the usual case.

ε can be considered as being directly proportional to the torsional moment, assuming that the deformations are within the elastic range:

$$(3)\qquad \varepsilon = k_1 \cdot M_t,$$

k_1 depending on both span-wise distributions of torsional stiffness and torsional moment.

The torsional moment on a sailplane wing can be expressed as the sum of three components:

a) the moment due to the local aerodynamic moments about the sections' aerodynamic centres (whose coefficient is invariant with angle of attack, by definition of aerodynamic centre);
b) the moment due to the local lift acting at the a.c., with respect to the wing twisting axis;
c) the moment due to the distributed wing mass force with respect to the wing twisting axis.

If the sailplane is considered as performing steady quasi-Horizontal glides in the whole allowed speed range, the resultant wing lift L_w is practically equal and opposite to the sailplane weight W ($L_w \cong W$), and the resultant wing mass force is the wing weight W_w. In these conditions, the components "b" and "c" of the torsional moment are practically independent of the airspeed.

This is not exactly true for the component "b" if the wing angle of sweep is not zero or negligible, as the wing elastic torsion interacts with the lift distribution.

If the wing angle of sweep is zero or negligible both constant components "b" and "c" are small with respect to "a". This has been verified by means of calculations on different types of wing structures representing extreme cases. For instance, in the case of a leading edge torsion box structure the section shear centres are very near to the section aerodynamic centres: the component "b" is very small, while "c" is larger but always small compared with "a", even at low airspeed. In the case of a torsion box structure (with two or more cells occuping the whole wing section, the section shear centres result he to the local mass centres: the component "c" is very small, while "b" is larger but always small compared with "a", even at low airspeed.

In all these cases, therefore, only a small error is made if the torsional moment is considered as due to the component "a" only. Since the component "a" is directly proportional to the airspeed V_i squared, it follows that:

$$M_t = k_2 \cdot V_i^2 \quad (k_2 = C_{Mo}(S/2)c(\varrho\sigma/2)),$$

and, therefore, from (3) and (2):

$$\varepsilon = k_1 \cdot k_2 \cdot V_i^2,$$

(4) $$i_w = i_{wo} + J k_1 k_2 V_i^2 = i_{wo} + k_3 V_i^2 = i_{wo} + k'/C_L$$

$$(k_3 = J k_1 k_2 \quad \text{and} \quad k' = k_3 (2 W/S)/\varrho_o)$$

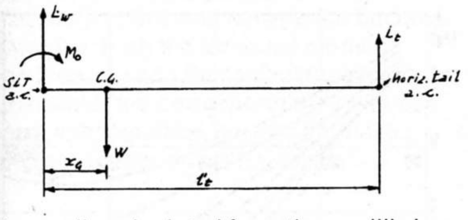
as $J = di_w/d\varepsilon$ is practically constant for a given wing and should be determined by the well known methods of theoretical aerodynamics.

2.2 Fuselage bending:

The effective value of the tail setting i_t is changed by the bending of the fuselage under aerodynamic and mass loads.

In the assumption of steady quasi-horizontal glides, the mass loads are simply the distributed weight of the rear part of the fuselage and of the tail surfaces; the aerodynamic load is the balance horizontal tail load L_t.

With the simple, but here sufficiently approximate, loading scheme of the following sketch, in which the moment contribution of the wing drag term is disregarded, the tail balance load can



be easily calculated from the equilibrium condition:

$$\begin{cases} L_w + L_t = W \\ L_w \cdot x_G + M_o - L_t (l'_t - x_G) = 0. \end{cases}$$

It follows that:

(5) $$L_t = \frac{W \cdot x_G + M_o}{l'_t}$$

where the component $W x_G / l'_t = L_{to}$ for a given sailplane weight and C. G. location, is independent of airspeed V_i, whereas the component M_o/l'_t is directly proportional to V_i squared:

$$L_t = L_{to} + k_4 \cdot V_i^2.$$

The effect of the mass loads on the fuselage bending is also independent of the airspeed V_i and, moreover, independent of W and x_G, as the variable weight (useful load) of a sailplane is located in the fuselage fore part and in the wings (ballast). This effect on i_t is usually small: it can often be neglected. In any case, it can be included in the design tail setting i_{to}, relating to the rigid sailplane. If data from static loading tests are not available, as will be the case in the design stage, theoretical calculations should be carried out. The rear part of the fuselage can be considered as a beam restrained at the wing/fuselage attachments and subject to the load L_t, concentrated at the section approximately corresponding to the horizontal tail a.c.

The deflection line of the fuselage rear part should then be calculated: i_t is measured by the rotation of the section where L_t is applied. It is perhaps worth remarking that the shear deformation of that part of the fuselage which corresponds to the wing/fuselage attachments may give an important contribution to Δi_t.

In any case, it can be written:

$$\Delta i_t = \Delta i_{to} + k_5 \cdot V_i^2,$$

(6) $$i_t = i_{to} + \Delta i_{to} + k_4 V_i^2 = i'_{to} + k_5 V_i^2$$
$$= i'_{to} + k''/C_L \text{ where}$$

where $i'_{to} = i_{to} + \Delta i_{to}$, $k'' = k_5 (2 W/S)/\varrho_o$ and

Δi_{to} = increment of tail setting due to L_{to},

$k_5 \cdot V_i^2$ = increment of tail setting due to $L_t - L_{to}$.

2.3 Elevator angle for trimming:

Expressions (4) and (6) of i_w and i_t, respectively, introduced in eq. 1 (in which the wing drag term is disregarded) allow the determination of δ_{trim}, i.e. of the elevator angle required for trimming the sailplane at a given C_L, or steady airspeed

$$V_i = \sqrt{(2W/S)/\varrho\sigma C_L},$$

taking into account the two aeroelastic effects considered:

(7) $$\delta_{trim} = \frac{1+F}{\bar{V}'} \frac{1}{\tau} \frac{1}{a_t} \left(C_{Mo} + \frac{x_G - x'_a}{c} \cdot C_L \right)$$
$$- \frac{1}{\tau} \left[\frac{1}{a_w} \left(1 - \frac{d\varepsilon}{d\alpha}\right) C_L - (i_{wo} - i_{to}) - \underbrace{(k' - k'') \frac{1}{C_L}}_{\text{Elastic term}} + \tau_{tab} \delta_{tab} \right]$$

2.4 Stick-fixed neutral point (N):

For the "rigid" sailplane (eq. 47 in ref. 4), not including the wing drag term:

$$\frac{x_{N'}}{c} = \frac{x'_a}{c} + \frac{f \cdot \bar{V}'}{1 + fF} \cdot \frac{a_t}{a_w} \cdot \left(1 - \frac{d\varepsilon}{d\alpha}\right)$$

For the "elastic" sailplane, by differentiating with respect to C_L eq.1 in which the "elastic" i_w and i_t are introduced:

(8) $$\frac{x_N}{c} = \frac{x'_a}{c} - \frac{\bar{V}'}{1+F} \left[\frac{a_t}{a_w} \left(1 - \frac{d\varepsilon}{d\alpha}\right) - a_t \frac{2 W/S}{\varrho_o} (k'' - k') \frac{1}{C_L^2} \right]$$

2.5 Stick-free neutral point (N′):

For the "rigid" sailplane (eq. 83 in ref. 4), not including the wing drag term:

$$\frac{x_N}{c} = \frac{x_a}{c} + \frac{\bar{V}'}{1+F} \cdot \frac{a_t}{a_w} \left(1 - \frac{d\varepsilon}{d\alpha}\right)$$

For the "elastic" sailplane:

(9) $$\frac{x_{N'}}{c} = \frac{x'_a}{c} - \frac{f \bar{V}'}{1+fF} \left[\frac{a_t}{a_w} \left(1 - \frac{d\varepsilon}{d\alpha}\right) - a_t \frac{2 W/S}{\varrho_o} (k'' - k') \frac{1}{C_L^2} \right]$$

2.6 Stick force to trim (P):

From ref. 4 (eq. 106):

(10) $$P = -G S_e c_e \frac{1}{2} \varrho_o V_i^2 (b_1 \alpha_s + b_2 \delta_{trim} + b_3 \delta_{tab}) + P_f + P_m$$

The aeroelastic effects are contained in δ_{trim} and α_s. δ_{trim} is given by eq. 7.

α_s, by introducing the aeroelastic terms in eq. (110) of ref. 4, is given by:

(11) $$\alpha_s = \frac{1}{1+F} \left[\frac{2 W/S}{\varrho_o} \left(1 - \frac{d\varepsilon}{d\alpha}\right) \frac{1}{V_i^2} - (i_{wo} - i_{to}) - (k_3 - k_5) V_i^2 - F (\tau \delta_{trim} - \tau_{tab} \delta_{tab}) \right]$$

P_f is the stick force required to balance the control friction force. Of course, P_f can be determined by tests on an existing sailplane, and only estimated or disregarded in the design stage.

P_m is the stick force required to balance the control mass force in the static condition. It can be measured or calculated.

3. Application to a particular sailplane and comparison with experimental results

The availability of experimental results for a particular sailplane suggested the application of the theoretical expressions presented in the preceding paragraph, in order to verify their validity through a direct comparison.

The sailplane considered is the M-200 two-seater with a wooden structure.

A three-view drawing of this sailplane is presented in fig. 1. The experimental data were carefully obtained through flight tests by Paolo Piantella (ref. 9), who also investigated theoretically the main aeroelastic effects.

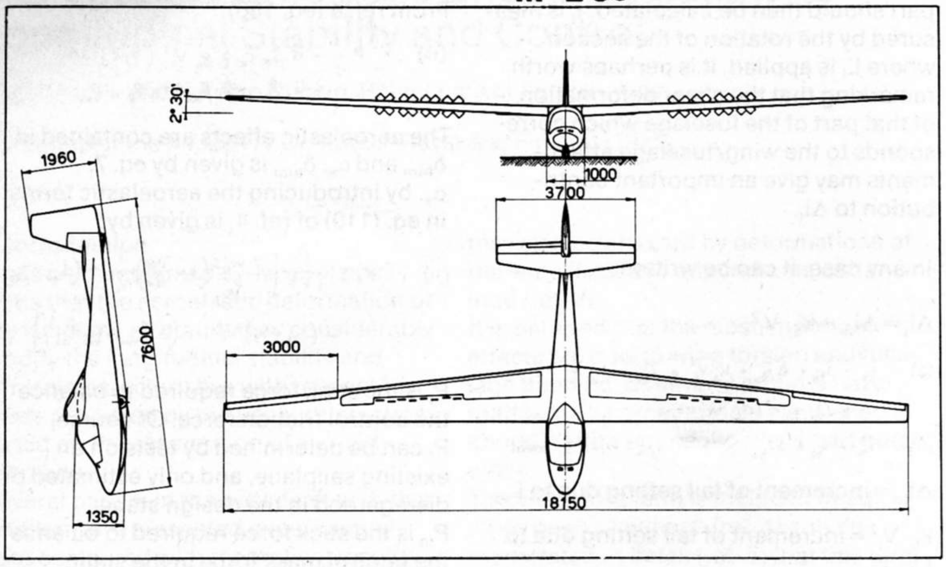
Fig. 2 and 3 show the elevator angle for trimming (δ_{trim}) as a function of the airspeed. The theoretical curves relate to the "rigid" and to the "elastic" sailplane (eq. 7). The latter are calculated both disregarding and including the wing drag term.

The "elastic" theoretical curves show, obviously, an increasing divergence with increasing airspeed with respect to the "rigid" curve. The interesting fact is that a maximun value of δ_{trim} is reached at airspeeds in the range 140–170 km/h ($d\delta/dV_i = O$). Unfortunately, experimental points are not available at higher speed in order to allow a more complete verification of the theoretical behaviour. However, the experimental data relating to other sailplanes and reported in ref. 1 and 2, do confirm that a maximum value of δ_{trim} may be definitely reached.

In fig. 4 the same curves as in fig. 2 appear, but the separate effects of wing torsion and fuselage bending are shown in order to allow an evaluation of their relative importance on the particular sailplane considered.

Fig. 5 and 6 illustrate the function "stick force to trim" vs. airspeed (eq. 10). It should be remarked that the gradient dP/dV_i for the "elastic" sailplane

M-200



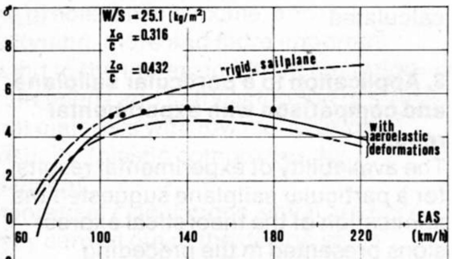


Fig. 2

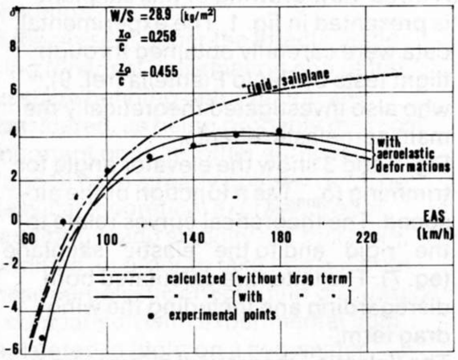


Fig. 3

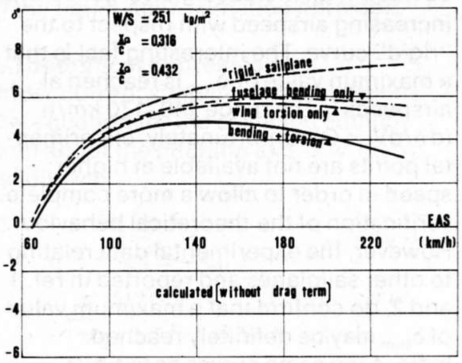


Fig. 4

decreases with increasing airspeed, whereas the opposite occurs on the "rigid" sailplane.
Again, the lack of experimental data at higher speeds does not allow a more extended comparison.
The M-200 elevator is fitted with a trim tab. The curves and the experimental points of fig. 5 and 6 relate to a fixed tab setting ($V_{trim} = 103$ km/h).
The effect of different tab settings (and corresponding different V_{trim}) on the P-V function is shown by the theoretical curves of fig. 7, relating to the "elastic" sailplane and including the effect of the wing drag term. It should be remarked that, at increasing V_{trim} (or decreasing δ_{tab}), the condition $dP/dV_i = 0$ is reached at lower airspeeds. This fact is entirely due to the aeroelastic effects as, for the "rigid" sailplane, dP/dV_i always increases with airspeed.
Fig. 8 compares the location of the "stick-fixed neutral point" (N) as a function of the airspeed for the "rigid" and "elastic" sailplane (eq. 8). The aeroelastic effect appears to be very strong: stick-fixed instability is reached at a relatively low airspeed (~150 km/h) in the particular case considered.
Fig. 9 compares the location of the "stick-free neutral point" (N') as a function of the airspeed for the "elastic" sailplane (eq. 9) with the location of the "stick-fixed neutral point" (N). It should be remarked that the two curves intersect at a given airspeed (170 km/h), i.e.

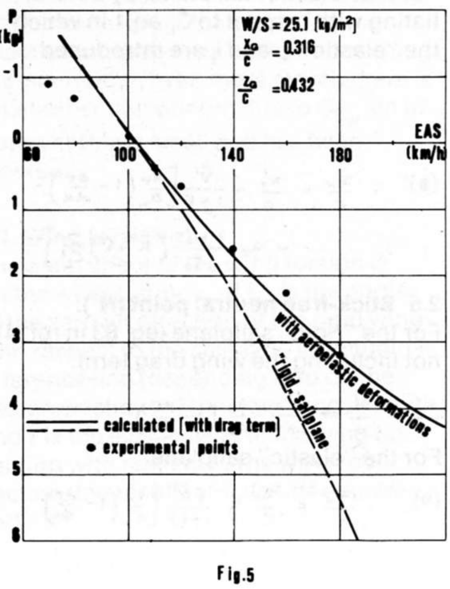


Fig. 5

the "stick-free margin" becomes higher than the "stick-fixed margin" above that airspeed: this is entirely due to the aeroelastic effects.

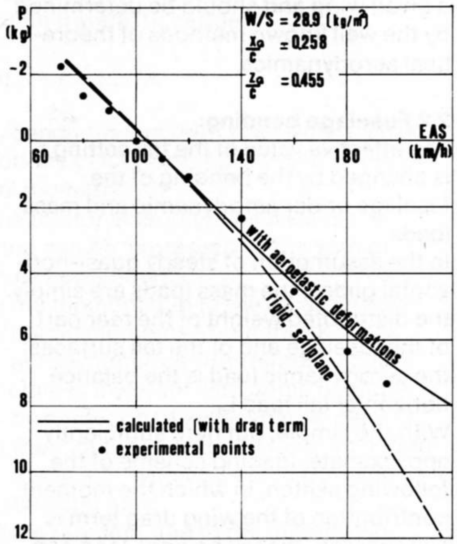


Fig. 6

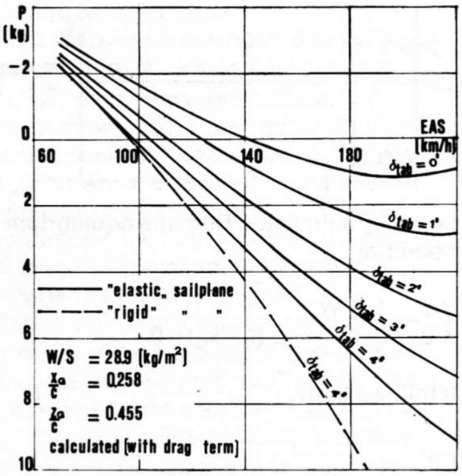


Fig. 7

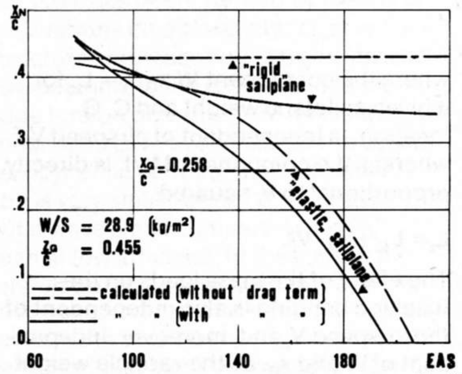


Fig. 8

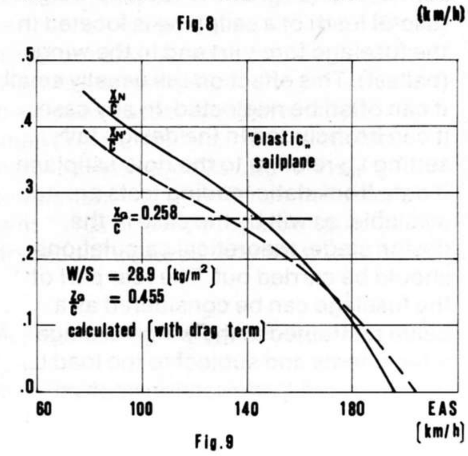


Fig. 9

4. Conclusions

It is confirmed that the static aeroelastic effects may have a considerable influence on the equilibrium and stability characteristics of a sailplane.

These effects are, in general, unfavourable: they can even produce stick-free and/or stick-fixed instability at high speeds, well within the range of operational airspeeds.

The comparison with experimental data, in the particular case considered, seems to confirm that, among the various static aeroelastic effects, those on i_w and on i_t are the most powerful.

From the designer's point of view, high wing torsional stiffness and fuselage bending stiffness should be regarded as imperative or highly desirable also under this respect.

The adoption of a high speed flap upwardly on a sailplane wing has certainly a strong favourable effect. In fact, the aerodynamic moment coefficient on the wing is numerically reduced for upward flap deflections and it may even become positive: both the torsional moment on the wing and the tail balance load, therefore, are correspondingly reduced. As a consequence, smaller aerolastic effects appear on both i_w and i_t.

List of symbols

a.c.	= aerodynamic centre;
a_t	= horiz. tail lift-curve slope;
a_w	= wing lift-curve slope;
b_1	= $ac\ /a\alpha$ (C_H = elevator hinge moment coefficient);
b_2	= $aC_H/a\delta$ (C_H = elevator hinge moment coefficient);
b_3	= $aC_H/d\alpha_s$ (C_H = elevator hinge moment coefficient);
c	= wing reference chord (m.a.c.);
c_e	= elevator reference chord;
C_{Dw}	= wing drag coefficient;
C.G.	= sailplane centre of gravity;
C_L	= sailplane lift coefficient = $C_{Lw}+C_{Lt}\,S_t/S$;
C_{Lt}	= horizontal tail lift coefficient;
C_{Lw}	= wing lift coefficient;
C_{Mo}	= pitching moment coefficient about the a.c. of the sailplane-less-tail (SLT);
f	= $1-\tau\, b_1/b_2$;
F	= $\frac{a_t S_t}{a_w S}\left(1-\frac{d\varepsilon}{d\alpha}\right)$;
G	= "elevator gearing" = $d\delta/ds$ (s = stick travel);
i_t	= horiz. tail setting (angle between the sailplane longitudinal reference line and the tailplane chord);
i_{to}	= design tail setting (for the "rigid" sailplane);
i'_{to}	= $i_{to}+\Delta i_{to}$;
i_w	= wing setting (angle between the sailplane longitudinal reference line and the wing zero lift direction);
i_{wo}	= wing setting (for the "rigid" sailplane);
J	= $di_w/d\varepsilon$ (see eq. 2 and 4);
$k_1,k_2,k_3,k_4,k_5,k',k''$	= aeroelastic coefficients;
l'_t	= tail arm (longitudinal distance between the sailplane-less-tail a.c. and the horiz. tail a.c.);
L	= sailplane lift;
L_t	= horizontal tail lift = tail balance load;
L_{to}	= $W\,x_G/l'_t$;
L_w	= wing (or, better, SLT) lift;
M_o	= putching moment about the a.c. of the SLT.
M_t	= resultant wing torsional moment;
N'	= stick-fixed neutral point;
N	= stick-free neutral point;
P	= stick force to trim;
P_f	= stick force required to balance the control friction;
P_m	= stick force required to balance the control mass force in the static condition (i.e. under the action of the acceleration of gravity only);
S	= wing surface;
S_e	= elevator surface;
S_t	= horiz. tail surface;
SLT	= sailplane-less-tail;
V'	= modified tail volume coefficient = $S_t l'_t\ /\ Sc$;
V_i	= equivalent airspeed (EAS);
V_{trim}	= equivalent airspeed in a quasi-horizontal steady glide;
W	= sailplane weight;
W_w	= wing weight;
x'_a	= longitudinal distance of SLT a.c. from leading edge of wing mean aerodynamic chord;
x_G	= longitudinal distance of C.G. from leading edge of wing mean aerodynamic chord (m.a.c.);
x_N	= longitudinal distance of N from leading edge of wing m.a.c.;
$x_{N'}$	= longitudinal distance of N' from leading edge of wing m.a.c.;
z_G	= vertical distance between the wing a.c. and the sailplane C.G., measured parallel to the sailplane vertical reference line;
α_s	= horizontal tail angle of attack measured between the sailplane chord and the direction of the local airflow at the tail;
δ	= elevator deflection angle;
δ_{tab}	= tab deflection angle;
δ_{trim}	= elevator angle required for the sailplane equilibrium in a quasi-horizontal steady glide;
Δi_t	= aeroelastic variation of the horiz. tail setting;
Δi_{to}	= aeroelastic variation of tail setting due to L_{to};
ε	= elastic twist of the wing tip section with respect to the wing root section;
P_o	= air density at sea level;
τ	= $d\alpha_s/d\delta$;
τ_{tab}	= $d\alpha_s/d\delta_{tab}$
$1-\frac{d\varepsilon}{d\alpha}$	= downwash factor. Here, α is the wing incidence and ε is the angle of downwash at the horizontal tail.

References

1. Jakubov, V. K.: «Influence of Elastic Wing-twisting on certain Characteristics of longitudinal Stability and Controllability of a Glider» – OSTIV Publication VIII, 1965.
2. Labuc, T. and Skrzydlewski, S.: «The effect of wing twist Distortion on Glider static longitudinal Stability with Stick fixed» – OSTIV Publication VIII, 1965.
3. Kacprzyk, J. and Nowak, M.: «The influence of Wing Flexibility on the Elevator Angle to Trim for a Sailplane in Steady Glide» – OSTIV Publication IX, 1968.
4. Morelli, P.: «Static Stability and Control of Sailplanes» – OSTIV, May 1976.
5. Duranti, P.: «Effetti di seconda approssimazione nella valutazione teorica delle caratteristiche di stabilità statica longitudinale dei velivoli» – Politecnico di Torino, Istituto di Progetto di Aeromobili, Publicazione n° 69, September 1974.
6. Stich, G.: «Einfluss der in Flugversuch vermessenen Tragflächendeformationen auf die Flugleistungen eines Kunststoffsegelflugzeuges» – OSTIV Publication XII, 1972.
7. Anderson, R. F.: NACA TR-572, «Determination of the Characteristics of Tapered Wings», 1936.
8. Abbott, I. H. and Von Doenhoff, A. E.: «Theory of Wing Sections» – Dover Publ. Inc., New York 1959, page 17.
9. Piantella P.: «Studio progettativo di aliante biposto con particolare riferimento alla stabilità longitudinale statica a comandi liberi e bloccati» – Politecnico di Torino, Tesi di Laurea, 1966.