A DIRECT TECHNIQUE FOR MEASURING SAILPLANE PERFORMANCES

by

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INTRODUCTION

The need for a performance testing technique which is less time consuming and less dependent on perfect weather is already rather well known (Ref. 1).

This paper gives a brief discussion of the working principle, and refers to the first test results of a measuring probe making use of two servo accelerometers and incorporating automatic upwash compensation.

Practically it is an angle of glide measuring system capable of working both in steady straight and in circling flight.

LIST OF SYMBOLS

A	apparent acceleration
C_L	lift coefficient
C_D	drag coefficient
c_p	probe reference chord
C_m	probe hinge moment-angle of attack slope
D	drag
E	L/D
L	lift
M	mass of the glider
Q	weight of the glider
Q_p	weight of the probe
S	wing surface of the glider
S_p	wing surface of the probe
q	$1/2\ \rho\ V^2$, dynamic pressure
ρ	air density
V	glider velocity

PRINCIPLE OF OPERATION

Let us write the equation of motion of the center of mass of a glider in free flight in the following vector form:

$$\vec{F}_a + M\ (\vec{g} - \vec{a}) = 0, \qquad (1)$$

where $\vec{F}_a$ is the resultant aerodynamic force; $M\ (\vec{g} - \vec{a})$ is the resultant "effective force" (Ref. 2) acting on the mass M, and is the sum of the gravity force $M\vec{g}$ and the inertia force $-M\vec{a}$ where $\vec{a}$ is the acceleration of the center of the mass.

Equation 1 can be rewritten in the form:

$$\vec{F}_a = M\ \vec{A} \qquad (2)$$

where $\vec{A} = \vec{a} - \vec{g}$. We shall call $\vec{A}$ the apparent acceleration of the center of mass; in fact $\vec{A}$

would be measured as an acceleration by accelerometers, or experienced as an acceleration by a human body.

Let us consider a flight condition in which both the force $\vec{F}_a$ and the velocity $\vec{V}$ of the center of mass lay in the aircraft plane of symmetry; in this case we can resolve the force $\vec{F}_a$, in the plane of symmetry, into its usual wind components -- lift, L, and drag D (Fig. 1). If accordingly we also resolve $\vec{A}$ into the components A_n and A_t, from equation 2 we have

$$L = M\,A_n \qquad D = M\,A_t \tag{3}$$

and then

$$L/D = A_n/A_t. \tag{4}$$

It follows that, in principle, if we had a platform placed in the center of mass of the glider, capable of keeping accurately two accelerometers in the direction of L and D, we could have accurate measurements of A_n and A_t, and then from (4), an accurate measurement of the L/D ratio.

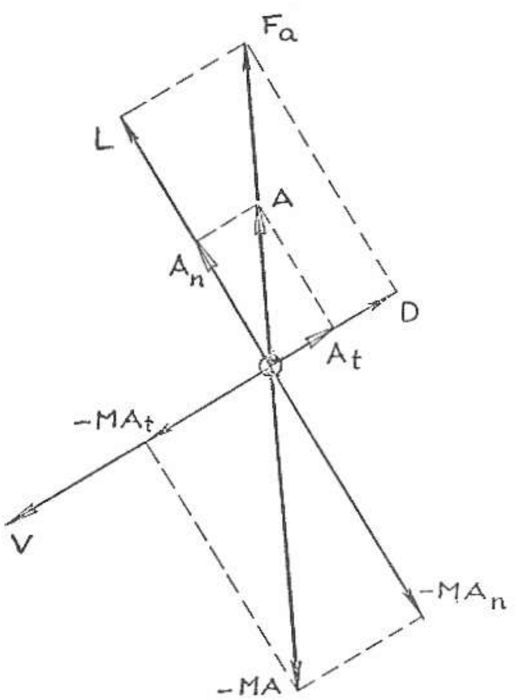

Figure 1.

It is worth noting that such measurements will not be affected by the movements of the air in which the glider is flying, nor by the acceleration of the glider itself*.

Obviously, to obtain good accuracy in the measurement of L/D the following requirements have to be fulfilled:

a) the accuracy of the two accelerometers must be high enough and the cross sensitivity, specially for the one measuring A_t, must be low enough;

b) the accuracy in the orientation of the two accelerometers must be adequate.

c) the two accelerometers must be placed in the center of mass or in a place having the same acceleration.

Requirement a) can be easily fulfilled by servo accelerometers, which may have an accuracy of about .01% and a cross sensitivity lower than 10^{-4}.

Requirement b) seems to be the most difficult to meet, particularly for high values of L/D.

For example, we fix the goal of obtaining a maximum error of ±3% in L/D, which means an error of ±1.2 if L/D = 40.

Let A_n' and A_t' be the values of the components of the acceleration $\vec{A}$ measured by two accelerometers, aligned respectively with the angular errors ε_n and ε_t. If A_n and A_t are the true values, and no other error is present, we have (Fig. 2):

$$\begin{aligned} A_n' &= A_n \cos \varepsilon_n - A_t \sin \varepsilon_n \\ A_t' &= A_n \sin \varepsilon_t + A_t \cos \varepsilon_t \end{aligned} \tag{4}$$

If we put $\cos \varepsilon = 1$ and $\sin \varepsilon = \varepsilon$ (which gives an error lower than 1% if $\varepsilon \leq 8^o$), the relative error in $E = L/D$ results:

$$\begin{aligned} \frac{E' - E}{E} &= \frac{E'}{E} - 1 = \frac{1 - \varepsilon_n/E}{1 + \varepsilon_t\, E} - 1 \\ &\simeq - \varepsilon_n/E - \varepsilon_t\, E. \end{aligned} \tag{5}$$

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* In accelerated flight this system will measure the instant value of L/D, which is well known to be different from the corresponding steady value (Ref. 3).

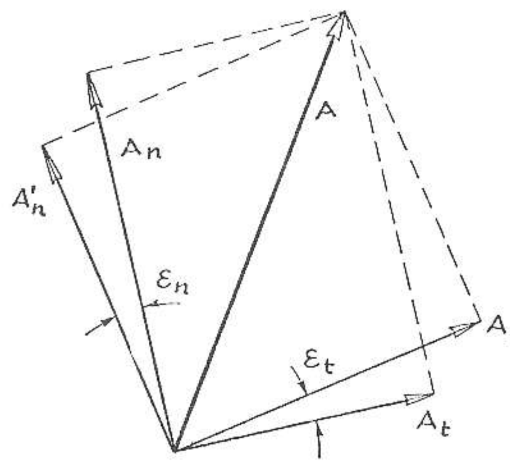


Figure 2.

If E is rather high, the error ε_t may have a strong effect, while ε_n has practically none; if we want to have an error in L/D lower than 3%, with L/D = 40, the error in the alignment of the accelerometer measuring A_t must be:

$$\varepsilon_t < \frac{.03}{40} \simeq .043^\circ \simeq 2.5' \qquad (6)$$

This result may be rather difficult to achieve.

Requirement c) could be fulfilled more easily in steady flight conditions, as steady straight flight and steady circling, which seem to be the most interesting flight conditions for performance measurements.

STRAIGHT FLIGHT

In steady straight flight all the points of the glider have the same speed and the same apparent acceleration.

The two accelerometers* could be mounted in a trailing bomb towed on a long rope away from the influence of the sailplane. This will have two main disadvantages:

a) the trailing bomb will have the same speed and acceleration of the glider only if the flight condition is absolutely steady for a rather long time (at least the time required to travel the distance between the glider and the trailing bomb, plus the time required to damp oscillations). Such long steady flights could be difficult to achieve, especially if the air is not completely smooth.

b) the deployment and retraction of the probe would be time consuming and rather delicate, also considering the fragility of the instruments being towed.

Another possibility seems to be that of placing the accelerometers in a self-aligning probe, mounted somewhere near the glider, for instance ahead of the wing leading edge.

In this position the direction of the relative wind is changed, due to the influence of the wing itself, by an upwash angle δ_u, whose magnitude depends mainly on the distance from the wing, and on the local value of the lift coefficient.

For a high aspect ratio glider at a distance of 1.5 - 2 m from the leading edge, the upwash angle δ_u would be of the order of 2°, at maximum L/D, which is a very high figure, compared to the maximum alignment error (Eq. 6), which is allowed.

But this may be compensated by an adequate offset of the probe center of mass with respect to the hinge.

UPWASH COMPENSATION

If the probe is placed ahead of the wing, in a position where the aerodynamic influence of the wing is predominant, the upwash angle can be considered to be proportional to the local lift coefficient c_L, which in turn can be considered proportional to the global lift coefficient C_L*; then

$$\delta_u = HC_L \qquad (7)$$

where H depends on the glider and on the position of the probe.

In a steady straight glide we may assume:

$C_L = Q/qS$, and hence:

$$\delta_u = HQ/qS = K/q \qquad (8)$$

* Actually in this case only the accelerometer A_t is needed, since A_n has a constant known value (the acceleration of gravity).

* This could be achieved by a proper selection of the probe position along the wing span.

If Q_p is the weight of the probe, and d the distance of the probe center of mass from the hinge (Fig. 3), the probe will assume with respect to the local wind V', the angle of attack δ_p, which gives equilibrium between the aerodynamic hinge moment $q\ S_p\ c_p\ C_{m\delta}\delta_p$ and the moment of the weight, which, for small angles, is $Q_p d$. Then

$$\delta_p = Q_p d/qS_p c_p C_{m\delta} = K_p/q \qquad (9)$$

From Figure 3, the error in the alignment of the probe with respect to the asymptotic wind is

$$\delta_u - \delta_p = (K - K_p)/q \qquad (10)$$

If the distance d is so adjusted that $K_p = K$ the alignment error is compensated.

The value of d which gives exact compensation for a given glider and a given position of the probe depends on the weight of the glider, but does not depend on the speed. That means that if the upwash is compensated for a certain speed it will be compensated for all flight speeds.

The compensation can be actually done (a) by properly adjusting the offset d of the probe center of mass, or (b) it can be "computed," correcting the measurements taken with a probe not exactly compensated. In both cases one of the following techniques may be used:

I - At a certain equivalent flight speed $\overline{V}$ the value of the L/D ratio $\overline{E}$ is accurately known, for instance from the measurement taken with another method, as partial glide or comparison flight. In this case the offset d is adjusted (a), or the correction is computed (b), to have the figure $\overline{E}$ at the equivalent air speed $\overline{V}$.

II - The glider flies, for a certain time during towing, at a constant equivalent speed V, at constant height, in a completely still air. In this case the angle of glide with respect to the air is nil and the offset d can be adjusted, or the correction can be computed to have the measure $A_t = 0$.

STEADY CIRCLING

In steady circling all the points of the glider move along helices having the same pitch and the same vertical axis.

In one of such points the apparent acceleration has a vertical component which is proportional to the radius of the helix.

The velocity relative to the air of the same point has a vertical component equal to the glider sink speed (relative to the air) and a tangent component which is proportional to the radius of the helix.

Then, if the probe has the same distance from the axis as the glider center of mass, the angle between velocity and apparent acceleration is the same in the probe position and in the center of mass; and if upwash compensation is still working the probe will measure the true L/D ratio.

If the probe is placed on one wing the measure will be affected by errors which tend to be equal in magnitude and opposite in sign for right and left circling, in the same conditions.

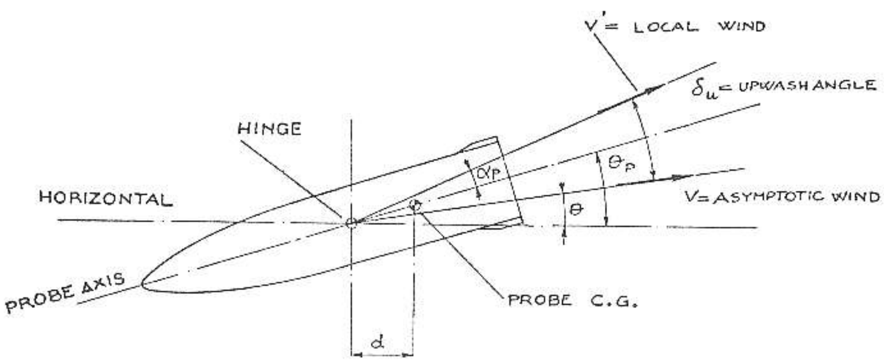


Figure 3.

REQUIREMENTS OF DIFFERENT COMPENSATION TECHNIQUES		
METHOD / COMPENSATION	METHOD I: KNOWN $\bar{E}$ AT SPEED $\bar{V}$	METHOD II: LEVEL TOW FLIGHT
ADJUSTING OF THE OFFSET d	SMOOTH AIR MECHANISM FOR ADJUSTING d ACCURACY IN E	STILL AIR MECHANISM FOR ADJUSTING d
COMPENSATION BY COMPUTING	ACCURACY IN $\bar{E}$	STILL AIR

Thus a suggested technique could be the one of making the same measurements in right and left circling, and then to average the measurements.

The measure of the normal acceleration A_n may also be used to evaluate the angle of bank ϕ, by the relation

$$n = A_n/g = 1/\cos\phi \tag{11}$$

which is valid if the glide angle respect to the air is not too large.

In steady circling the effective resultant mass force is:

$$nQ = L \tag{12}$$

If the probe is placed in a position where the apparent acceleration is the same as in the glider center of the mass, the moment of the effective mass force of the probe with respect to the hinge is nQ_pd.

In this case Eqs. 8, 9 and 10 become

$$\delta_u = nK/q \tag{13}$$

$$\delta_p = nK_p/q \tag{14}$$

$$\delta_u - \delta_p = (K - K_p)\, n/q \tag{15}$$

Thus the same compensation which is valid in straight flight will also hold in circling.

UNSTEADY FLIGHT

In a generally accelerated flight this measuring method will not work. Among other things the upwash compensation will not be valid because the instant relation between the upwash angle and the lift coefficient will be strongly affected by unsteady aerodynamic effects.

EFFECT OF AIR TURBULENCE

The measurements will not be affected by the movements of the atmosphere, provided that such movements are sufficiently smooth. If the air is even moderately rough, it may not be easy to obtain true steady flight conditions, and to avoid significant prove oscillations. This will cause significant oscillations of the measurements, that could be filtered in different ways, and a certain scatter in the filtered figures, the latter being due mainly to aerodynamic unsteadiness.

This may require the recording of a large number of measurements and application of a suitable smoothing technique, but the method is so fast that the measurements necessary for a complete polar can be taken in a very limited number of flights.

ERROR ANALYSIS

Let us suppose that the compensation has been done for the equivalent air speed $\bar{V}$, at which the value $\bar{E}$ is accurately known (method I) or at which the glider has been towed at constant speed and constant height (method II).

We now evaluate the order of magnitude of the error in the measured value E_i, in different flight conditions, due to the following sources:

a) The relation between the probe aerodynamic hinge moment and the angle of attack δ_p is not linear and homogeneous.

b) The relation between δ_u and C_L is not the simple Eq. 7 but

$$\delta_u = HC_L\,(1 + \varepsilon_L) \tag{16}$$

where ε_L is a function of C_L which is nil when $C_L = \bar{C}_L$, i.e. at compensation speed. For instance, if the relation between δ_u and C_L is linear but non-homogeneous, of the type

$$\delta_u = H'C_L + \delta_o$$

from Eq. 16 it is easily found that

$$\varepsilon_L = \frac{\delta o}{\bar{\delta}_u} (\bar{C}_L/C_L - 1) \quad (16a)$$

c) The presence of the probe and of the probe support increases the sailplane drag coefficient by an amount $C_d^* = \varepsilon^* \bar{C}_d$, where $\bar{C}_d$ is the drag coefficient at compensation speed.

d) The weight of the glider Q is different from the weight Q by the amount $\varepsilon_q \bar{Q}$.

The error due to (a) may be kept reasonably small by a proper design of the probe, allowing very good geometrical symmetry of the probe itself, very small interference from the probe support, and constant $C_{m\alpha}$ for small angles of attack.

Besides, the accuracy of mechanical alignment of the accelerometers in the probe and of the related electronic equipment may be accurately checked by ground calibration, i.e., checking the measures when the probe is oriented at predetermined angles with respect to the horizontal on the ground.

If the nondimensional quantities ε_L and ε_q are small compared to unity, from Eqs. 7, 8, 13 and 16 we have, for straight and circling flight*:

$$\delta_u \simeq \frac{n}{q} K (1 + \varepsilon_L + \varepsilon_q) \quad (17)$$

From Figure 3:

$$\Theta_p = \Theta + \delta_u - \alpha_p \quad (18)$$

where

$$\Theta \simeq \frac{1}{E*} = \frac{C_d + C_d^*}{C_L} = \frac{1}{E} (1 + \frac{\bar{C}_d}{C_d} \varepsilon^*) \quad (19)$$

and

$$\Theta_p \simeq \frac{1}{E_i} \quad (20)$$

E* being the actual L/D of the glider with the probe, and E_i the corresponding indicated value.

From this, Eq. 9 and Eq. 14 it follows

$$\frac{1}{E_i} = \frac{1}{E} (1 + \varepsilon^* \bar{C}_d/C_d) + \frac{n}{q} K (1 + \varepsilon_L + \varepsilon_q - K_p/K) \quad (21)$$

The compensation may be done adjusting the value of K_p in such a way that the corrected L/D is $E_c = E_i$, or may be computed with the relation

$$\frac{1}{E_c} = \frac{1}{E_i} - \frac{n}{q} \Delta K \quad (22)$$

Obviously, at the compensation speed $\bar{V}$,

$$n = 1; \; C_d = \bar{C}_d; \; q = \bar{q}; \; \varepsilon_L = \varepsilon_q = 0.$$

Then, if method I is used, the value of K_p is so adjusted that:

$$\frac{1}{\bar{E}} = \frac{1}{\bar{E}} (1 + \varepsilon^*) + \bar{\delta}_u (1 - K_p/K), \quad (23)$$

or the value of ΔK is so fixed that:

$$\frac{1}{\bar{E}} = \frac{1}{\bar{E}} (1 + \varepsilon^*) + \bar{\delta}_u (1 - K_p/K) - \frac{\Delta K}{\bar{q}} \quad (24)$$

where:

$$\bar{\delta}_u = K/\bar{q} \quad (25)$$

In both cases we have:

$$\frac{1}{E_c} = \frac{1}{E} [1 + \varepsilon^* (\bar{C}_d/C_d - \xi) + \bar{E}\bar{\delta}_u \xi (\varepsilon_L + \varepsilon_q)] \quad (26)$$

where:

$$\xi = \frac{C_L}{\bar{C}_L} \frac{E}{\bar{E}} \quad (27)$$

To simplify the evaluation of the order of magnitude of the measuring error we make the assumption that $\bar{E}\bar{\delta}_u \simeq 1$, which is exact if $\bar{E} = 40$ and $\bar{\delta}_u = .025$ rad $= 1.5^o$, and that the relative error $(E_c - E)/E$ is small compared to unity.

We then have:

$$(E_c - E)/E = - \varepsilon^* (\bar{C}_d/C_d - \xi) - (\varepsilon_L + \varepsilon_q) \xi \quad (28)$$

* All the quantities related to circling flight may be considered averaged between the values corresponding to right and left turning.

If method II is used, at speed $\bar{V}$, $\theta = 0$, and the value of Kp is so adjusted that:

$$\theta_p = \frac{1}{\bar{E}_i} = \bar{\delta}_u (1 - K_p/K) = 0 \qquad (29)$$

i.e. it is adjusted to the value

$$K_p = K; \qquad (30)$$

or the value of ΔK is fixed so that:

$$\frac{1}{\bar{E}_c} = \bar{\delta}_u (1 - K_p/K) - \Delta K/q = 0 \qquad (31)$$

In both cases, with the assumptions made above, we have:

$$(E_c - E)/E = -\varepsilon^* \bar{C}_d/C_d - (\varepsilon_L + \varepsilon_q)\xi \qquad (32)$$

If the equivalent speed of compensation $\bar{V}$ is near to the maximum L/D, ξ, which obviously has the value 1 at $\bar{V}$, may be expected to remain near unity at speeds lower than $\bar{V}$, where C_L increases and E decreases, and to be much lower at higher speeds, where both C_L and E decrease.

We may then make the following comments about the effect of the parameters ε_L, ε_q and ε^* on the relative errors in L/D measurements:

— ε_L, by definition, is nill at speed $\bar{V}$ and may significantly increase at higher speeds (e.g., according to Eq. 16a, but its effect is reduced at higher speeds by the fact that the coefficient ξ becomes much smaller. For instance, if Eq. 16a is valid, the effect of ε_L would be:

$$- \bar{E}\bar{\delta}_u \xi \varepsilon_L = E\delta_o(C_L/\bar{C}_L - 1),$$

which may be large only if δ_o has a significant value.

—ε_p must be kept lower than the maximum allowable relative error, being mutltiplied by a factor of the order of unity in Eqs. 28 and 32.

—ε^*, i.e. the relative increase in drag due to the probe and to the probe support must be as low as possible; in any case larger errors must be expected at higher speeds. The way to reduce this error seems to be the one of having a probe and a support as small and as clean as possible.

It is worth observing that the same error will be encountered using a trailing bomb, where the increase in drag may be rather high due to the length of the rope.

CONSTRUCTION OF THE PROBE

Following the principles discussed above we have designed a first probe which is now being flight tested on a *Caproni A21* glider.

In designing the probe we have tried to

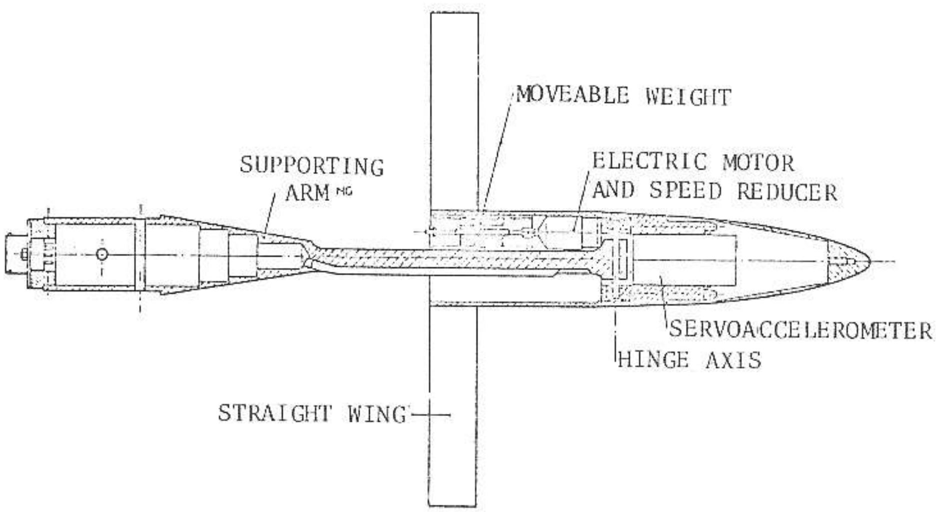


Figure 4. Probe

achieve the following results:

- minimum weight and dimensions of probe and support
- minimum aerodynamic interference on the probe from the support
- optimum geometrical accuracy with available technology.

The probe assembly is shown in Figure 4. It accommodates only one servoaccelerometer, a *Kistler 305-A*, weighing about 100 gr. The second accelerometer, measuring A_n, has been placed in a fixed position, at the root of the support; that was possible due to the relative insensitivity of the L/D measurement to the alignment errors of the latter accelerometer.

The movable ballast in the probe has a weight of about 50 gr and a maximum displacement of about 30 mm.

The weight of the complete probe (without supporting rod) is about 500 gr.

At first the probe was equipped with a biplane straight wing with A/R = 10.

In this configuration the probe gave a good accuracy but suffered from probe-support flutter at about 150 km/h. This flutter was not very violent; it was experienced both in flight tests and in the wind tunnel (Fig. 5).

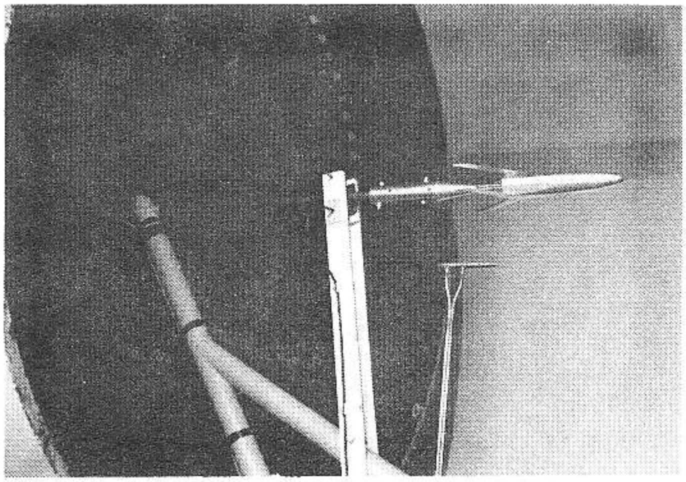


Figure 5.

To increase the flutter speed a new swept wing was developed which gave a flutter speed over 210 km/h (Fig. 6, 7).

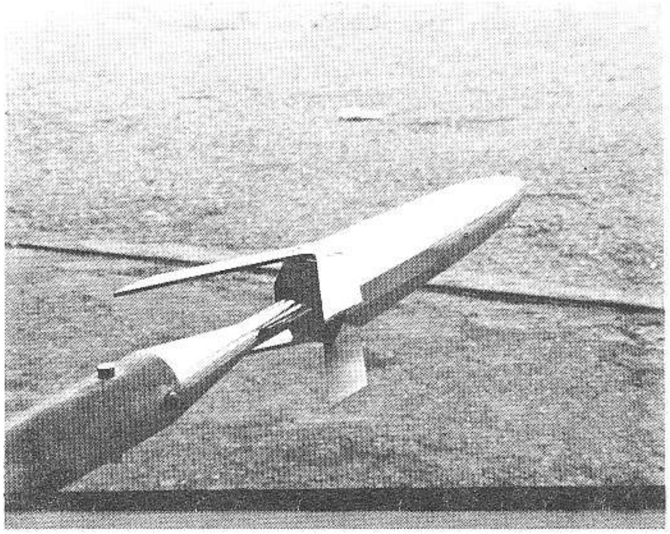


Figure 6.

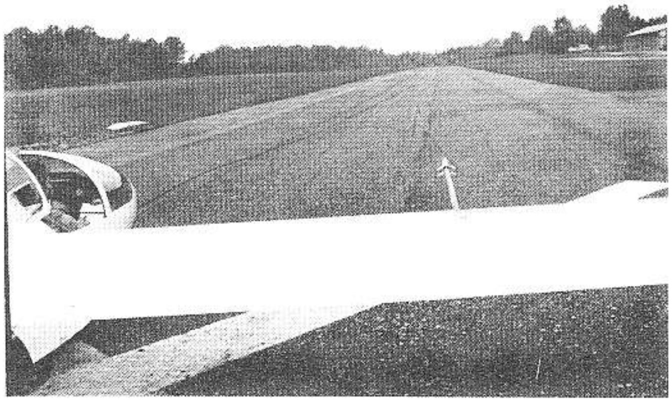


Figure 7.

The electronics is contained in a small box (Fig. 8), containing power supply (dry batteries), amplifiers, an analog divider (0.5% accuracy), filters, and an analog instrument for direct reading of L/D ratio and calibration.

Ground calibration can be done easily with a simple device bringing 3 levels mounted at predetermined angles (Fig. 9, 10).

FLIGHT MEASUREMENTS

Flight measurements have just started on a *Caproni A21 S* two-seater; some straight flight recordings are already available.

The measured points, in terms of equivalent sink speed V_z versus equivalent flight speed V, have been interpolated by a curve having the analytical expression

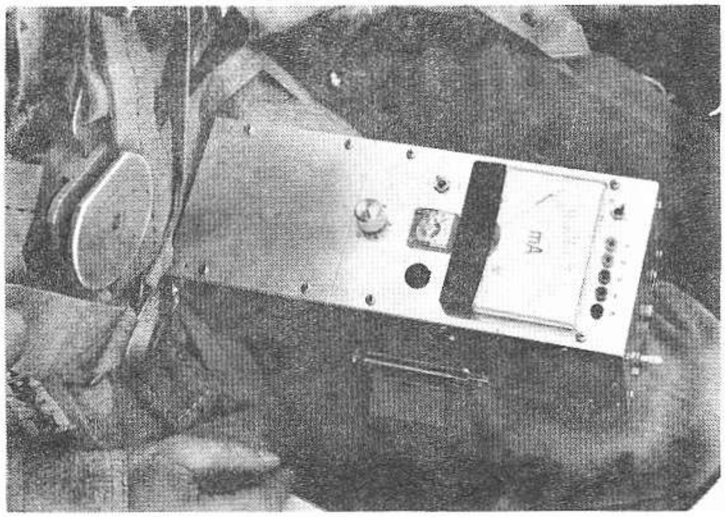


Figure 8.

$$V_z = A_1V^3 + A_2V^2 + A_3V + A_4 + A_5/V,$$

where the coefficients A_1, A_2, ..., A_5 have been computed, with the least squares technique, for the best fit with the measured points.

Then the upwash compensation has been computed, with method I, for E=40 and V= 100 km/h.

Figure 11 shows 62 measured points, recorded in 3 flights in the same day, with the straight wing probe, together with the fitted polar; the points and the polar shown are upwash compensated by computation.

The air was not particularly smooth, as it is in a hot late spring day in North Italy (Calcinate del Pesce, Varese). Figures 12 and 13 show the points taken in the first two flights, compared with the polar fitted to all measured points; they show a very limited scatter due to relatively low turbulence of the atmosphere.

In the third flight, which was done late in the morning, the air turbulence was higher, and consequently higher has been the scatter of measured points. In any case such scatter is limited, and the repeatability of the measurements seems to be very good.

Figure 14 shows 31 measured points (compensated by computation for E=40 at V = 100 km/h) taken with the swept wing probe in another hot day, and the fitted polar. The higher scatter may be explained by the fact that the air turbulence was a little higher in this day, and that the swept wing, having a smaller surface and aspect ratio, gives a less accurate alignment of the probe.

In Figure 15 the 2 fitted polars (straight wing and swept wing probe) are compared; there is a certain agreement between them, although the measurements taken with the straight wing probe are probably more accurate at low speeds.

As far was we can understand from our limited flight testing, the system seems to be able to work also in moderately rough air, requiring little time, with a limited scatter and a good repeatability.

Although accurate measurements of the *Caproni A21 S* performances are not yet available, it seems that the sink speeds figures we have obtained are too high at high speed.

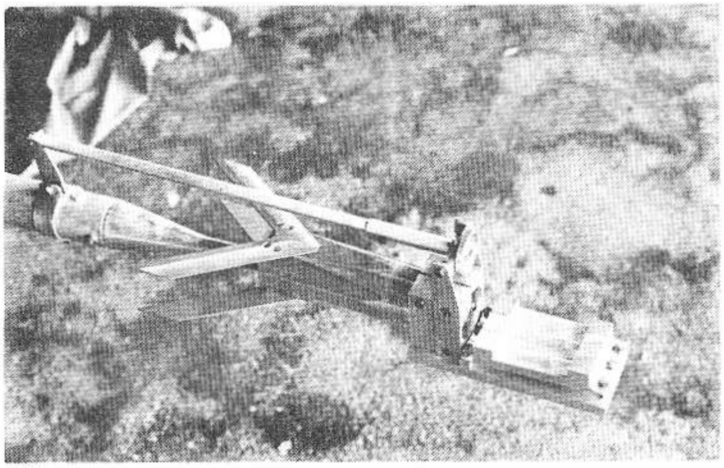


Figure 9.

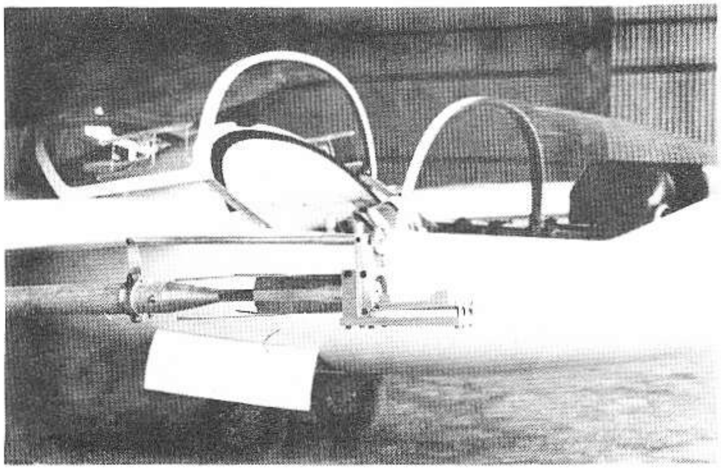


Figure 10.

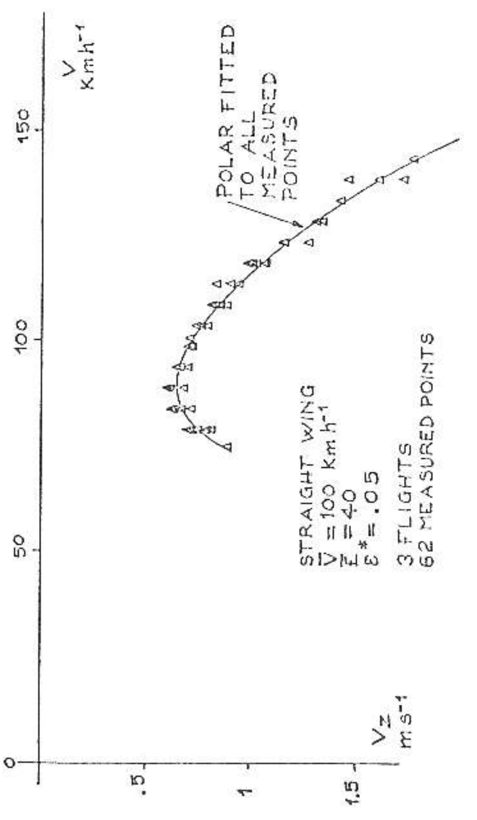


Figure 11.

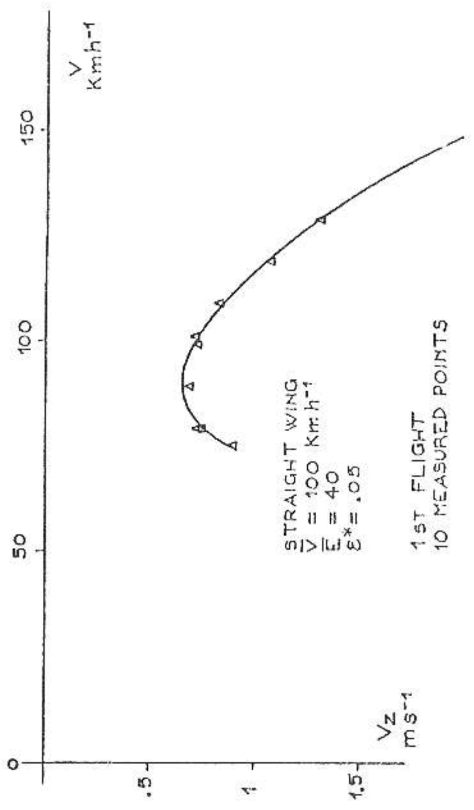


Figure 12.

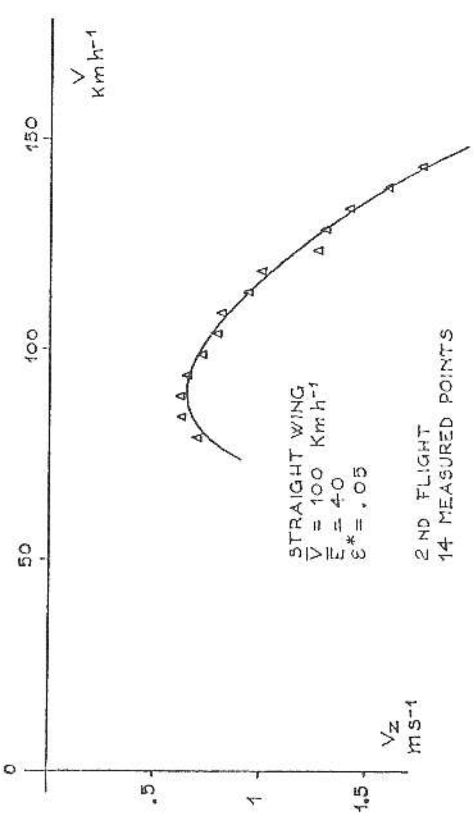
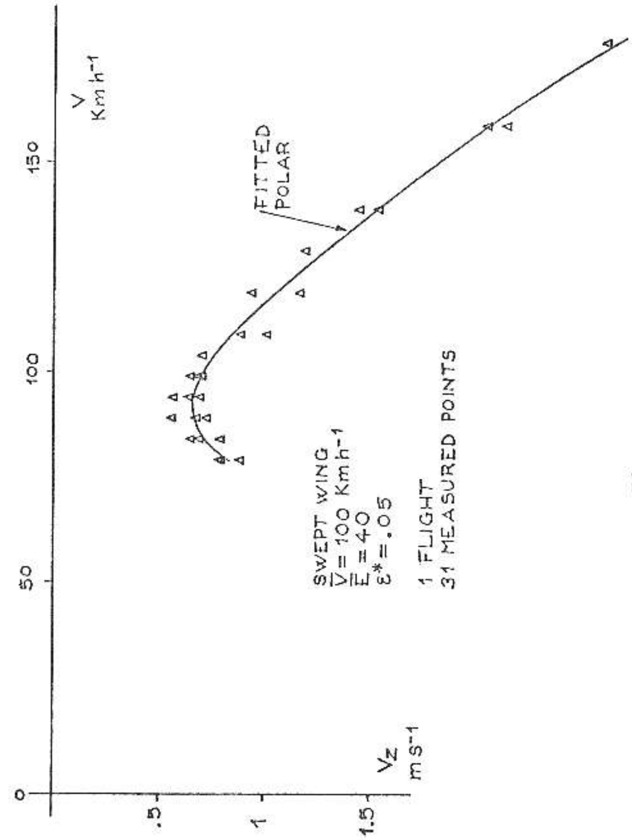


Figure 13.



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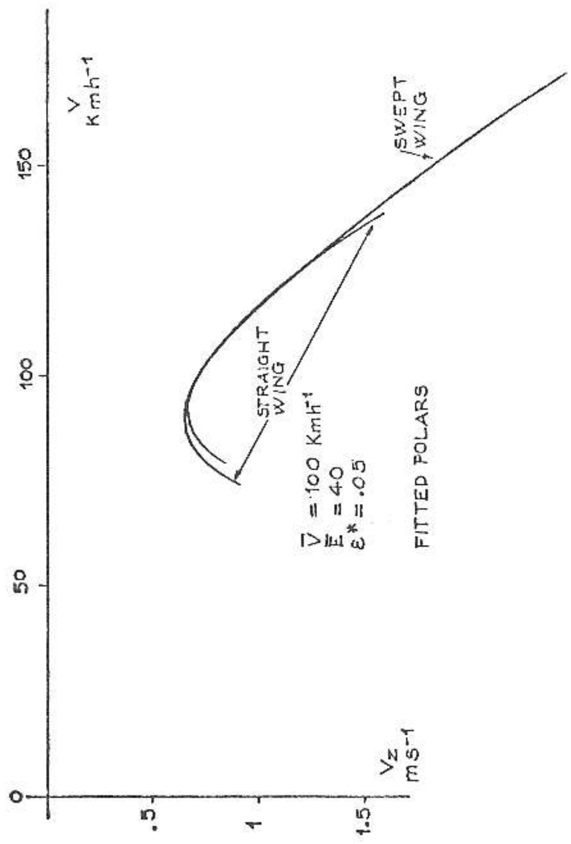

Figure 15.

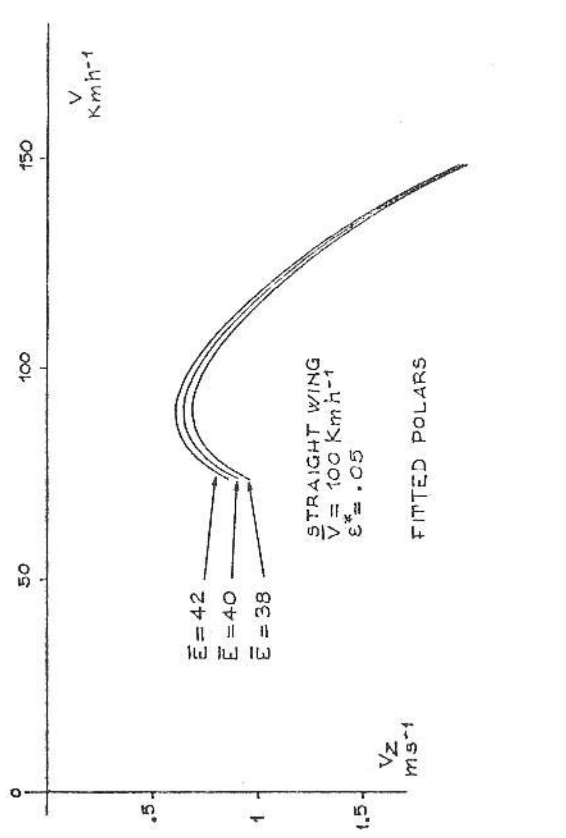

Figure 16.

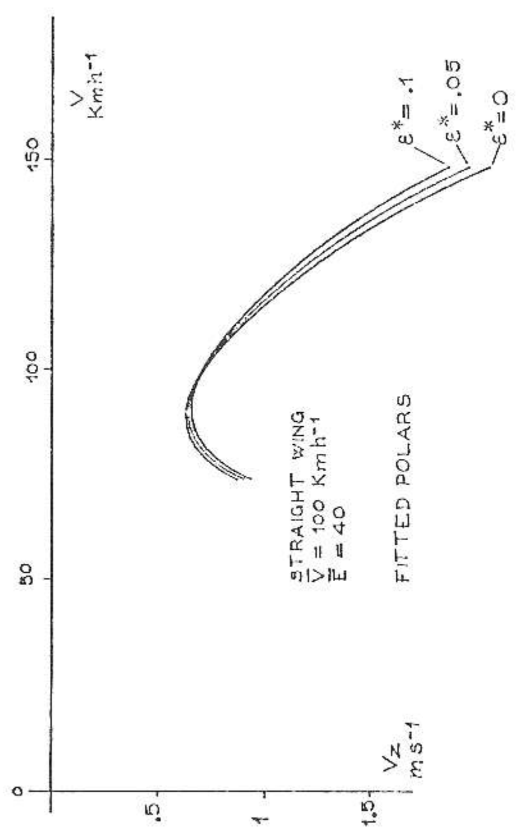

Figure 17.

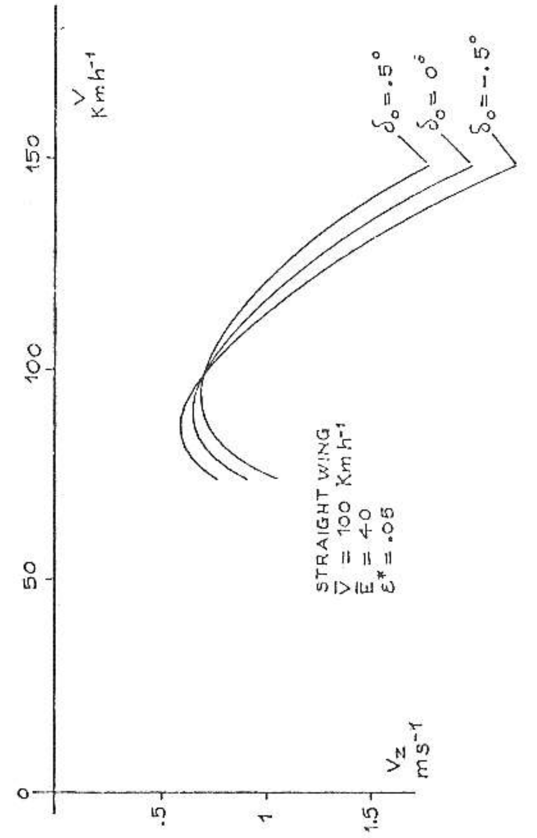

Figure 18.

As now we cannot explain this fact; ground calibration has been done very accurately and all electronic equipment is working with a high accuracy.

Figures 16, 17 and 18 show the polar obtained with the straight wing probe, corrected by computation for different values of $\overline{E}$, ε^* and δ_0. It seems that, although the effect of δ_0 (i.e. the upwash angle at zero lift) may be significant, it does not justify the difference between the measured and the expected performances at speed.

CONCLUDING REMARKS

The first test results seem to be encouraging us to continue the research; particularly favorable are the good repeatability and the short test flight time required.

We plan to develop the research in the near future along the following lines:

- upwash compensation with method II (level tow flight) at different speeds
- investigation on the effect of changing the position of the probe with respect to the glider wing
- design and construction of a new probe, much simpler, much smaller and much lighter.

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