PERFORMANCE TESTING OF SAILPLANES *)

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SUMMARY: After a survey of the basic formulae for the relation between the aerodynamic properties and the performance of a sailplane, some test methods for steady flight and their instrumentation are reviewed.

A method is given for the calibration of the angle of attack indicator in towed flight, which may stimulate the application of this instrument by which performance testing can be accelerated considerably.

It seems, however, possible to save testing time to a much greater degree by the application of non-steady flight techniques.

A method of this nature, based upon the authors experience with powered aircraft, which requires relatively simple instrumentation, is proposed at the end of the report.

I. INTRODUCTION.

The present-day high performance sailplane has reached such a degree of perfection that further improvements can be realized only at a slow rate. As a result of this only minor increases in performance can be expected for the successive designs, which implies that also the performance measuring techniques have to meet ever growing demands, as they are the means which enable us to ascertain whether the results, contemplated by the designer, actually have been reached.

The performance testing of the Slingsby "Sky", as recently reported (ref. 1), is a typical example of the great care which has to be taken in the execution and evaluation of the performance measurements in order to achieve this purpose.

On the other hand this report also shows clearly that a good deal of time has to be spent on the execution of the flight tests and therefore the question arises, as to how far an improvement could be obtained in this respect, without derogation from the accuracy of the test results.

In investigating this problem it might be useful also to pay attention to recent methods and instrumentation for performance testing of powered aircraft.

In the Netherlands some experience has been gained during the postwar years by the National Aeronautical Research Institute (N.L.L.) in flight tests with glider and powered aircraft which are put forward in this respect, hoping it may be of use to the development of sailplane performance testing procedures.

II. BASIC FORMULAE

In general the performance of a sailplane is expressed by the curve showing the relation between the rate of sink (corrected to standard sea level conditions) and the equivalent airspeed. In "glider pilots' terminology" this curve is called the **polar curve**; the aerodynamicist, however, defines the polar curve as the relation between the lift- and drag coefficients for different angles of attack.

Both polar curves are closely related and can easily be derived from one another, using the following basic formulae **) (see section 4, Symbols

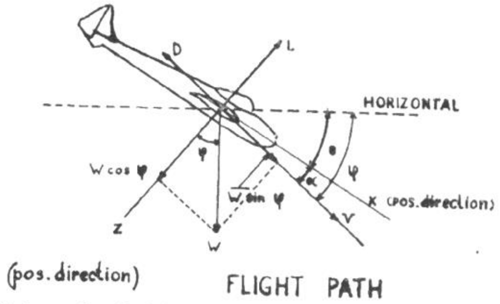

Figure 1. Sailplane in steady flight

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*) *Report MP 107 of the N.L.L., Amsterdam; C.C.L. Class.: **E 200**.*

**) *Strictly speaking the formulae (1a), (1b) and (1c) are only valuable when the sailplane* and figure 1):

$$L = C_L \frac{\rho V^2}{2} S = W \cos \varphi \qquad (1a)$$

$$D = C_D \frac{\rho V^2}{2} S = W \sin \varphi \qquad (1b)$$

$$\frac{D}{L} = \frac{C_D}{C_L} = \tan \varphi \text{ (glide ratio)} \qquad (1c)$$

and

$$v_s = V \sin \varphi \text{ (true rate of sink)} \qquad (2)$$

<u>If C_L and C_D are known</u>, the related V and v_s can be calculated, using (1a) or (1b), (1c) and (2) from

$$\boxed{V} = \sqrt{\frac{2W}{\rho S}} \sqrt{\frac{1}{\sqrt{C_L^2 + C_D^2}}} \boxed{\approx \sqrt{\frac{2W}{\rho C_L S}}} \qquad (3)$$

and

$$\boxed{v_s} = V \sqrt{\frac{C_D^2}{C_L^2 + C_D^2}} \boxed{\approx \frac{C_D}{C_L} V \approx \sqrt{\frac{2WC_D^2}{\rho S C_L^3}}} \qquad (4)$$

If on the other hand **<u>V and v_s are known</u>**, (1b) and (2) give

$$\boxed{C_D = \frac{2W}{\rho S} \frac{v_s}{V^3}} \qquad (5)$$

and combining (1a) and (2)

$$\boxed{C_L} = \frac{2W}{\rho S} \frac{\sqrt{V^2 - v_s^2}}{V^3} \boxed{\approx \frac{2W}{\rho S V^2}} \qquad (6)$$

To facilitate the comparison of performance data, the rate of sink is usually reduced to standard sea level conditions, the so called equivalent rate of sink, and this quantity is plotted against the equivalent airspeed, which is the airspeed indicator reading, corrected for instrument and position errors *).

The relation between equivalent and true airspeed is

$$\boxed{v_o = V \sqrt{\frac{\rho}{\rho_o}}} \qquad (7)$$

From (7) it follows that the true rate of sink v_s is related to the equivalent rate of sink $v_{s_o} = V_o \sin \varphi$ through

$$\boxed{v_{s_o} = v_s \sqrt{\frac{\rho}{\rho_o}}} \qquad (8)$$

The relation between the rate of sink as derived from the altimeter and the true rate of sink is

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is not accelerated in any direction. This condition could not be realized unless the atmosphere had a constant density.

From ref. 2 it will be seen, however, that these relations may be applied to sailplanes without measurable errors when the indicated airspeed is kept constant. The relations for accelerated flight are given in section 3, sub-section d.

*) *Since compressibility effects are negligible for the low speeds considered, calibrated and equivalent airspeeds are identical.*

$$v_{s_{alt}} = v_s \frac{T_{stand}}{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Combining (3) and (9)

$$v_{s_0} = v_{s_{alt}} \frac{T}{T_{stand}} \sqrt{\frac{\rho}{\rho_0}}$$

which formula, in accordance with App. D of ref. 1, also can be written as

$$\boxed{v_{s_0} = v_{s_{alt}} \sqrt{\frac{T}{T_{stand}}} \sqrt{\frac{\rho_{stand}}{\rho_0}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

III. METHODS OF PERFORMANCE TESTING

Four methods will be considered in succession, which according to the underlying principle will be referred to as 'rate of sink'-, 'angle of attack'-, 'towed flight'- and 'acceleration'-method.

a. 'RATE OF SINK' METHOD

Evidently, the most obvious method for determining sailplane performance is the direct measurement of the rate of sink.

The rate of sink indicator (variometer) has shown to be a less suitable instrument for accurate quantitative measurements. It is, therefore, preferable to derive the rate of sink from altimeter readings.

The method thus only requires a precision altimeter and airspeed indicator (which can be easily installed by removing the normal dashboard instruments) and a clock. The position error of the airspeed system has to be accurately determined which required separate flights with a suspended static bomb.

The atmospheric temperature, which according to formula (10) also has to be known, can be measured conveniently in the towing aircraft during the climb preceding the free flight if an extension of the sailplane instrumentation by an air thermometer is undesirable. Ref. 1 gives a detailed description of this method and its evaluation as applied to the Slingsby 'Sky'.

The application of photographic recording of the instrument readings increases the accuracy considerably for several reasons, the most important of which is that the pilot can devote his attention entirely to accurate flying.

During the performance tests on the 'Sky', mentioned in ref. 1, a photo-camera has been used, taking pictures of the dashboard of the sailplanes.

In sailplanes where sufficient space is available, as for instance in two-seaters, a small automatic observer may have advantages over this method.

Figure 2 shows an automatic observer which was developed by the N.L.L. for this purpose.

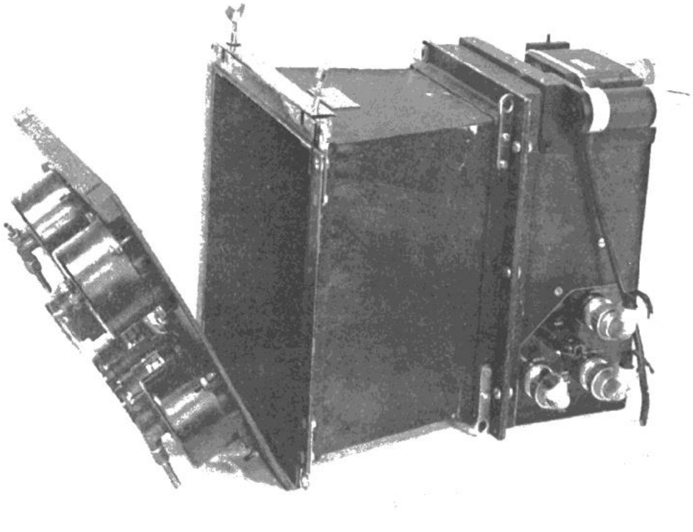

Figure 2. Automatic observer for sailplanes

The observer is equipped

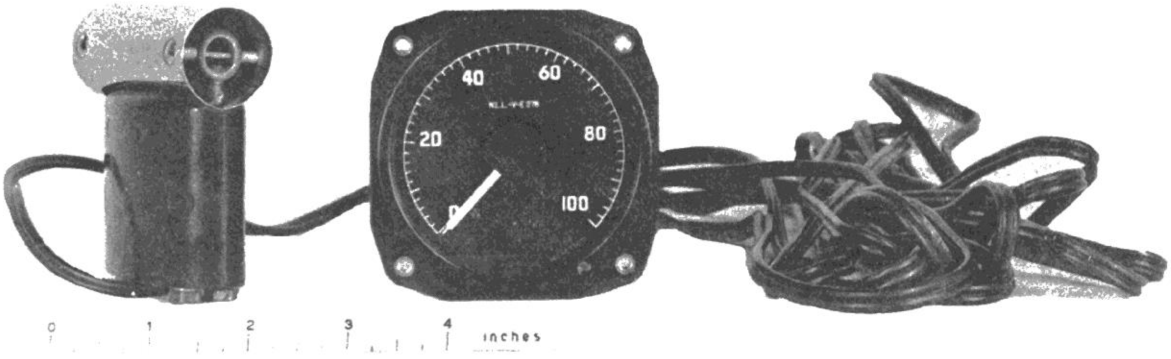

Figure 3. Electrical resistance thermometer

with a remote-controlled automatic camera (Robot) with a frame size of 24 x 24 mm^2.

In order to reduce the overall-dimensions as far as possible a mirror has been built in.

The illumination consists of several small incandescent lamps energized by an 8 Volt dry battery.

A retarded action relay prevents a picture being taken before the lamps have reached their maximum light intensity.

As an example of an ambient air thermometer figure 3 shows an electrical resistance thermometer which was developed by the N.L.L. for the medium speed range. The measuring element consists of a resistance wire, wound on a small anodized aluminium tube, which is lightened by slits to keep its heat capacity as low as possible. A coat of enamel protects the resistance wire and keeps it in place. The coil, which is in direct contact with the airstream is surrounded by a polished sun shade. The indicator is a ratiometer, having a scale in 100 divisions. The instrument has a very low time constant (15 sec at 7 knots and 7.5 sec at 20 knots airspeed) and can be energized by a 24 Volts dry battery.

For stagnation and friction of the air a correction $- .0065 \frac{\rho_0}{\rho} q$ (Centrigrade, q in kg/m^2) has to be applied.

The overall accuracy is ± .25 Centrigrade for a measuring range of 100 Centrigrades.

For aerodynamic purposes the knowledge of the angle of attack belonging to the C_L- and C_D-values (to be calculated by the formulae (5) and (6)) is often required.

This quantity is determined (see figure 1) by the difference of the flight path angle φ and the longitudinal inclination θ, which therefore, has to be measured by a suitable inclinometer. Since, as stated in the note on page 11, acceleration effects are negligible in flights with constant indicated airspeed, a pendulum inclinometer (for instance as shown in figure 4) can conveniently be used for this purpose.

The accuracy obtained in this way, however, is poor and for small angles of attack the method fails entirely.

Another disadvantage involved in the 'rate of sink' method is the detrimental influence of vertical air movements.

Finally the 'rate of sink' method required principally the execution of partial glides over rather large height intervals in order to ensure sufficient accuracy in the determination of the rate of sink from the height-time graph. Consequently, considerable flying time is required.

b. *ANGLE OF ATTACK* METHOD

The disadvantages of the *rate of sink* method, mentioned above, can be eliminated by application of an angle of attack indicator. As seen from figure 1, the angle of attack α together with the longitudinal inclination θ gives the flight path angle φ *). The rate of sink then can be calculated by formula (2).

Although this method seems to be ideal, it should be stressed that in order to obtain sufficient accurate results, both angle of attack indicator and inclinometer must possess a high standard of precision; an accuracy of .1 degree is required.

Figure 4 shows a longitudinal pendulum inclinometer, developed by the N.L.L., which is adapted for this purpose. As stated before no corrections due to acceleration effects need be applied for flights with constant indicated airspeed.

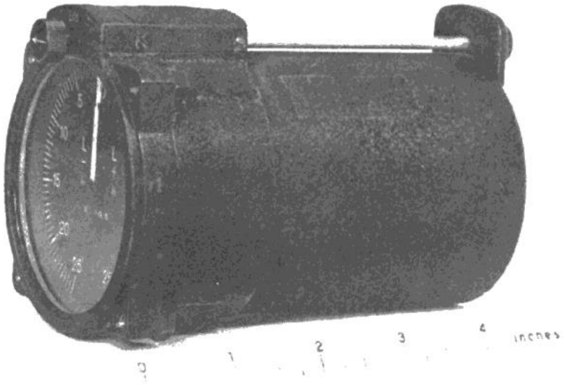

Figure 4. Pendulum inclinometer

The instrument is provided with a permanent magnet which causes eddy current damping of the pendulum motion; the damping amounts to about .7 of the critical damping.

The pendulum is connected to the pointer axis by phosphor bronze strips and has a measuring range of ± 25 degrees.

The accuracy is ± .1 degree and the natural frequency amounts to 3,2 cps.

Figure 5 illustrates an angle of attack indicator which was developed by the N.L.L. as a first step to gain some experience in the application of such instruments to sailplanes.

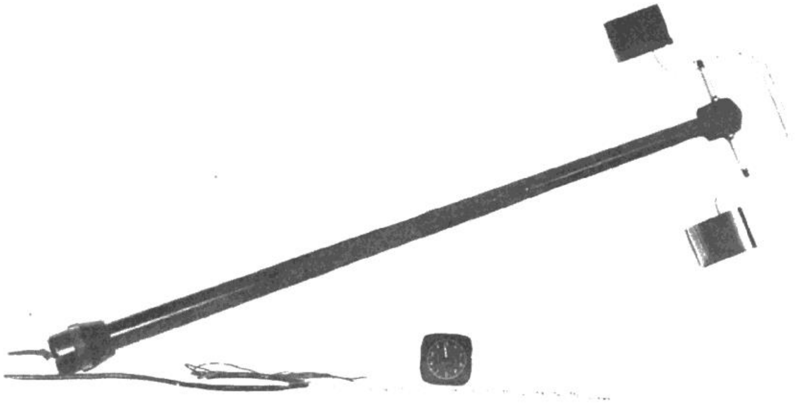

Figure 5. Angle of attack indicator for sailplanes

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*) *In Great Britain as well as in the Netherlands attempts have been made in the past to measure the flight path angle directly by means of an inclinometer with remote indication, mounted in a suspended streamline body with stabilizing tailplanes, similar to the suspended static bomb. Since not very promising results were obtained with respect to accuracy, these devices have not been developed any further.*

The instrument has a double vane mounted on an axis, the rotation of which is transferred by steel wires to a microdesynn transmitter mounted at the other end of the boom. Its measuring range is 27 degrees and the accuracy is ± .1 degree.

With this instrument mounted in front of the wing of a Govier-trainer, some tests were made. This arrangement has the advantage that only small deviations of the undisturbed airstream direction may be expected, which moreover can be approximated fairly well by calculation. So it was thought that calibration in flight would not be strictly necessary. It appeared, however, that the torsion of the wing introduced errors which cannot be calculated or measured with sufficient accuracy.

A better solution is to place the instrument on a rigid mounting in front of the nose of the fuselage. Since now a calibration in flight is necessary anyway, the instrument can be placed at a relatively small distance from the fuselage nose. This calibration which in fact is the main problem when applying the *angle of attack* method, has to be made in horizontal towed flight and is discussed in the next sub-section.

c. *TOWED FLIGHT* METHOD

When the sailplane is equipped with an instrument which permits the measurement of the cable tension and its direction relative to the sailplane, a direct measurement of the drag and lift is possible in **horizontal** towed flight.

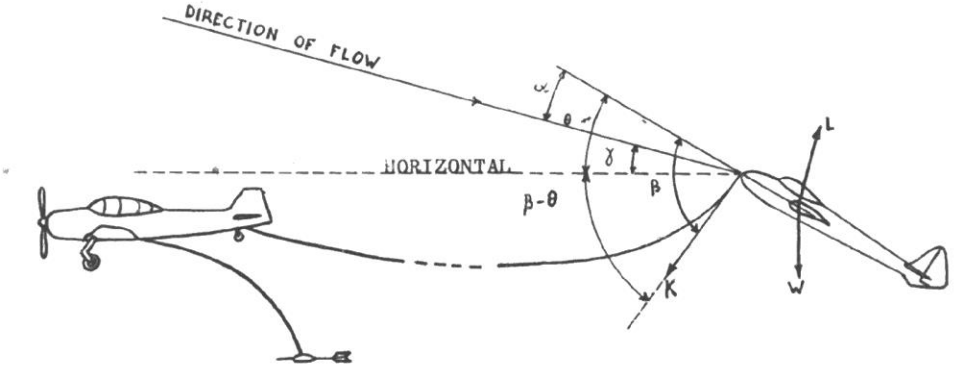

Figure 6. Horizontal towed flight

In this condition (see figure 6)

$$L = W \cos \gamma + K \sin (\gamma + \beta - \theta) \text{ and}$$

$$D = -W \sin \gamma + K \cos (\gamma + \beta - \theta).$$

Now W is about 10 times K, so when the downwash angle γ is small, these equations can be simplified to

$$L = W + K \sin (\beta - \theta) \qquad (11)$$

and

$$D = -W \sin \gamma + K \cos (\beta - \theta) \qquad (12)$$

For the purpose of lift-drag measurements it is possible, as shown later on, to estimate γ with sufficient accuracy, when the sailplane is flown at a sufficient height, say a wing span, above the towing aircraft.
Furthermore, the static position error of the sailplane airspeed system can be determined simultaneously by means of a static bomb suspended below the towing aircraft.

The method, however, puts a limit on the speed range, so that the polar curve can be measured only partially. Furthermore, it has proved to be extremely difficult, even in very quiet air, to maintain steady flight conditions of both coupled aircraft with sufficient precision.

Therefore, this method is not recommendable for performance testing.

As stated in sub-section b the calibration of the angle of attack indicator has to be made in horizontal towed flight. The limited speed range which can be realized in towed flight, requires an extrapolation of this calibration to an extent which depends on the performance characteristics of the towing aircraft and the sailplane relative to one another.

According to figure 6 the angle of attack is determined by the difference of the longitudinal inclination θ (to be measured with the inclinometer of figure 4) and the downwash angle γ.

In ref. 3 the value of γ near the wing of the sailplane is calculated along the following lines.

Assuming the sailplane is flying sufficiently high above the towing aircraft to allow the influence of the propeller slipstream and the wake of the wing to be neglected, the downwash only results from the circulation of the free and bound vortices of the wing of the towing aircraft.

The downwash angle γ_1 resulting from the free vortices can be determined by taking the mean value of the local downwash angles γ_1 at a number of points of the wing located at different distances from the plane of symmetry of the sailplane (for instance with mutual distances of .1 of the towing aircraft's wing span), attaching a "weight" to the local γ_1-values according to the local chord of the wing.

Neglecting the viscosity of the air, γ_1 is given by (see section 4 Symbols).

$$\tan \gamma_1 = \frac{W_t}{4\pi\rho V^2 b} \left[\frac{b - y}{(b - y)^2 + z^2} - \frac{b + y}{(b + y)^2 + z^2} \right] \qquad (13)$$

The downwash angle γ_2, resulting from the bound vortex at a horizontal distance x behind the wing of the towing aeroplane, is determined by

$$\tan \gamma_2 = \frac{W_t}{3\pi\rho \frac{V^2}{2} x^2} \qquad (14)$$

It appears that in practice $\gamma_1 \gg \gamma_2$ and, therefore, in the calibration of the angle of attack indicator the downwash angle γ can be taken to equal γ_1.

Figure 7 gives a comparison of polar curves as measured in free flight and in towed flight, in the latter case allowing for and disallowing the downwash angle γ. The results confirm that (13) may be applied to the calibration of an angle of attack indicator in towed flight.

Taking $z = 10$ m, γ_1 varied from .1 to .2 degree along the span of the sailplane. So it seems possible to neglect γ completely when somewhat greater height differences are applied. It should be investigated in practice how far this presumption is right.

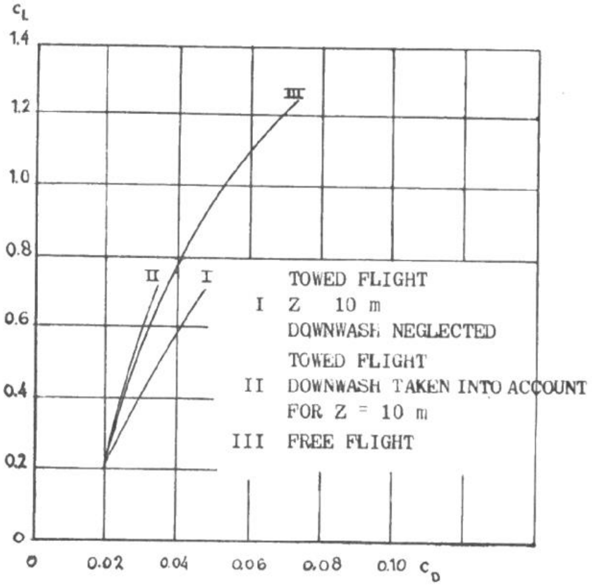

Figure 7. Comparison of polar curves as measured in free flight and towed flight

6. 'ACCELERATION' METHOD

To conclude this review of performance test methods, the application of a 'non-steady flight-technique' is suggested which, as far as known, hitherto never has been reported for application with sailplanes, although it might offer great advantages over the methods described before.

During the last years some experience has been gained in drag measurements of powered aircraft in accelerated flight by using precision-accelerometers. Recent work on this subject in the Netherlands, aimed at the simplification of the instrumentation needed for this purpose, shows that it might be attractive to introduce unsteady flight techniques also for the performance testing of sailplanes.
In section 2 it has been shown that the measurement of the lift-drag curve may be considered as an indirect method to determine the performance of a sailplane.

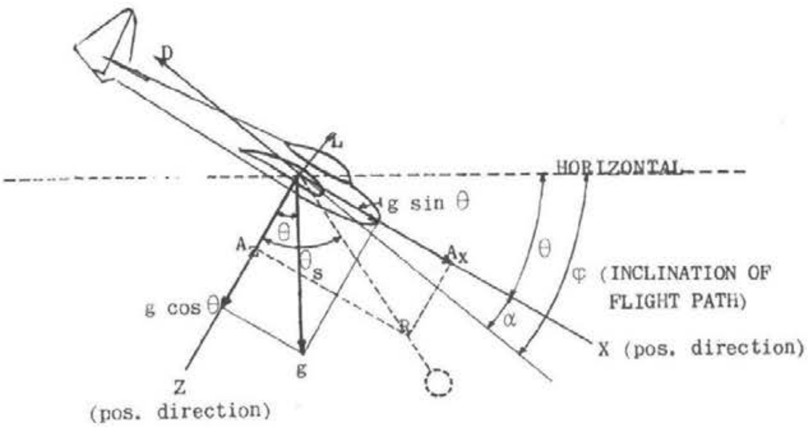

Figure 8. Sailplane in accelerated flight

The principle of the 'acceleration' method, which actually is such an indirect method, is illustrated in figure 8, where in order to get a clear picture, the sailplane is shown in a fictive, exaggeratedly retarded flight.

If A_x and A_z be the components of the acceleration as measured by accelerometers (thus including gravity 'acceleration') along the X- and Z axes in an arbitrary flight condition, the lift and drag are determined by

$$L = \frac{W}{g} A_z \cos\alpha - \frac{W}{g} A_x \sin\alpha \quad \text{......} \quad (14)$$

$$D = \frac{W}{g} A_z \sin\alpha + \frac{W}{g} A_x \cos\alpha \quad \text{......} \quad (15)$$

So it is possible to determine the lift-drag curve within the whole speed range in only **one** flight by accelerating the sailplane from stalling to maximum diving speed and recording the indications of a normal and a longitudinal accelerometer, together with the angle of attack.

In order to determine the coefficients C_L and C_D as well as the equivalent rate of sink (see formulae (4) and (8)), the airspeed and the free air temperature should also be measured.

For the direct measurement of A_x a very sensitive accelerometer is required. However, this instrument can be replaced by the pendulum inclinometer illustrated in figure 4, as this instrument indicates (see figure 8) the direction θ_s of the resultant of A_x and A_z.

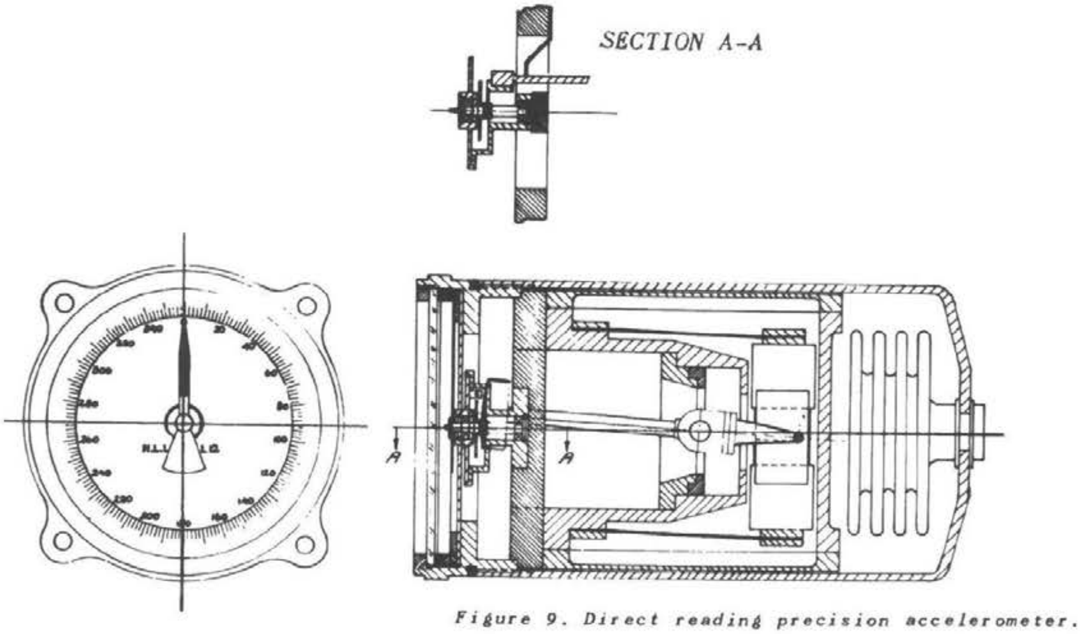

Figure 9. Direct reading precision accelerometer.

Now $A_x = A_z \tan \theta_s$ and thus, only a normal accelerometer will suffice.

To this end, the N.L.L. developed a direct reading accelerometer with high accuracy, taking the pre-war D.V.L. as a basis.

The construction of the instrument is shown in figure 9. The linear movement of a mass, suspended between two springs, is transmitted to the pinion of the pointer axis by a gear rack. The whole instrument is filled with damping oil.

The accuracy is ± .01 g at a range of -2 to +3 g. The damping is .5 of the critical damping which has proved to be sufficient for most flight tests.

From (14) and (15), using $A_x = A_z \tan \theta_s$, the glide ratio is found to be

$$\frac{D}{L} = \frac{C_D}{C_L} = \tan (\theta_s + \alpha) \dots\dots (16)$$

In order to avoid effects which might hamper the production of accurate results, such as errors in the measurement of the angle of attack and damping forces on the tail both due to pitching, or incalculable lag in the pitot system, and other instrumental response difficulties, it is recommended to approximate a rectilinear dive as closely as possible. Experience with powered aircraft has shown that good results are obtained when at minimum airspeed the longitudinal inclination is suddenly changed to the corresponding value at maximum diving speed after which the aeroplane gradually accelerates to this speed along a nearly rectilinear path.

When the maximum diving speed is reached, the measurement can immediately be repeated completely by pulling up to a longitudinal inclination corresponding to the minimum airspeed after which the aeroplane decelerates, again in nearly rectilinear flight.

The use of a horizon sight or lines on the cockpit hood may be very helpful to the pilot in keeping the attitude of the sailplane constant. Obviously, the measurements are not affected by large-scale air movements but local air movements will deteriorate the results. Therefore, a quiet atmosphere is desirable also for this method.

In the author's opinion, the very important time gain which can be achieved by the "acceleration" method, justifies a thorough investigation of its applicability to the performance testing of sailplanes.

IV. SYMBOLS

L	lift;
D	drag;
W	total weight of sailplane;
W_t	total weight of towing aeroplane;
K	tension of towing cable;
C_L	lift coefficient;
C_D	drag coefficient;
S	wing surface of sailplane;
V	true airspeed;
V_o	equivalent airspeed;
v_s	true rate of sink;
v_{s_o}	equivalent rate of sink;
$v_{s_{alt}}$	altimeter rate of sink;
T	free air temperature at test altitude;
T_{stand}	air temperature in standard atmosphere at pressure height (indicated by altimeter);
ρ	air density at test altitude;
ρ_o	air density at sea level in standard atmosphere;
$\rho stand$	air density in standard atmosphere at pressure height (indicated by altimeter);
g	acceleration of gravity;
q	dynamic pressure ($\frac{1}{2}\rho v^2$);
p	static (atmospheric) pressure;
φ	flight path angle;
θ	longitudinal inclination of sailplane;
θ_s	angle between pendulum axis and top axis of sailplane;
α	angle of attack;
β	angle between cable tension and longitudinal axis of sailplane;
γ	mean downwash angle near sailplane wing;
γ_1	ditto only due to free vortices of towing aeroplane;
γ_1	local downwash in a point of sailplane wing due to free vortices of towing aeroplane;
γ_2	downwash angle near sailplane wing due to bound vortex of towing aeroplane;
b	semispan of towing aeroplane;
x	horizontal distance of wings of towing aeroplane and sailplane;
z	vertical distance of ditto;
y	distance of a point of sailplane wing to plane of symmetry of towing aircraft;
A_x	longitudinal acceleration as measured by accelerometer;
A_z	normal acceleration as measured by accelerometer;
a_t	kinematical acceleration in flight direction;
t	time.

V. REFERENCES

1 *The performance Tests of the Slingsby *Sky** by K.E. MACHIN, M.A., Ph. D.;

2 *Die Flugpolarenmessung* by Rudolf SCHMIDT (Jahrbuch 1942 der deutschen Luftfahrtforschung);

3 *Preliminary Measurements of Lift and Drag of the Sailplane PH-111, type Govier in Towed and Free Flight*, N.L.L.-report V. 1426 (in Dutch);

4 *Measurement of Lift and Drag of the Sailplane PH-111, type Govier, in Towed and Free Flight*, N.L.L.-report V. 1433 (in Dutch).