VARIOMETER COMPENSATION DURING ACCELERATED FLIGHT

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Presented at the XXI OSTIV Congress, Wiener-Neustadt, Austria (1989)

THE POLAR SINK

Improvements in the performance of total-energy probes (11, 12, 16, 17) and variometer systems (18, 19, 20) have greatly reduced the errors from these sources and the effects of changes in acceleration now need to be considered. During accelerated flight, changes in the normal acceleration g' experienced by the glider result in changes in the polar sink. Since the calibrations of netto and speed-to-fly systems are based on $g = 9.81$ m/s/s, they will show errors during accelerated flight. To obtain an estimate of the size of errors that can be expected, the approximate incremental changes in polar sink on an ASW-15 for accelerations between 0 and 3 g are listed in Figure 1. They are quoted as knots error rather than as percentage changes, since this is what the pilot observes (1 knot = 0.515 m/s.)

Reducing g' to near zero has only a relatively small effect on the variometer indication over the normal cruising speed range, although the percentage change may be quite large. The indication changes between 0g and 1.5g are not very large. Increasing g′ to 3 produces a significant increase in the sink rate, even at 120 kt. These indications are, however, much smaller than those often observed in a high performance glider during a pull up. The effect of the changing acceleration on the air in the instrument tubes, flexing of the tubes, inbalance in the meter movement and errors in the total energy compensation can all contribute to the different.

Speed Kt	Sink Kt	Incremental Values of Sink for Different g Loads Kt	Kt				
40	-1.1	0.7	0.6	:	Region of high		
50	-1.3	0.6	0.4	: -0.7	lift coefficients		
60	-1.7	0.5	0.4	-0.6	: -1.5	-2.6	
70	-2.4	0.4	0.3	-0.5	-1.3	: -2.2	-3.4
80	-3.3	0.4	0.3	-0.5	-1.1	-2.0	: -3.0
90	-4.5	0.3	0.3	-0.4	-1.0	-1.7	-2.6
100	-6.1	0.3	0.2	-0.4	-0.9	-1.6	-2.4
110	-8.0	0.3	0.2	-0.3	-0.8	-1.4	-2.2
120	-10.2	0.3	0.2	-0.3	-0.7	-1.3	-2.0
g'Load	1	0	0.5	1.5	2.0	2.5	3.0

Figure 1. Polar sink and the approximate changes for different g′ loads and speeds for an ASW-15 glider compared to 1g values.

The figures were obtained by fitting a cubic polar of the form $Vs = A.V^3 + B.N^2/V$ to the experimental polar, where A and B are constants and n is the g′/g ratio. The cubic polar gives a reasonably good approximation to the experimental data except at high values of Cl near the stall. The coefficients do not take into account the smaller changes in drag due to changes in Reynolds number.

Approximate n.g polars can be generated from experimental 1g polars by scaling the foreward speed by $\sqrt{n}$ and the sink speed by $n.\sqrt{n}$ (1). This transform takes account of most of the changes in drag with Cl except near zero g, but not the changes with Reynolds number.

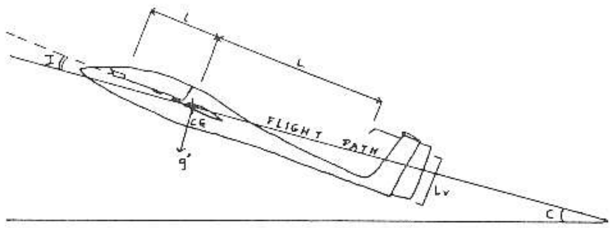
ACCELERATION EFFECTS ON THE INSTRUMENT TUBING

The acceleration forces also act on the air in the instrument connecting tubes (5) and can give significant errors. When a glider flies into a thermal it experiences vertical and axial accelerations. There may also be gust effects and changes in pitch. The pilot has only about 3 seconds to decide whether to fly through the thermal, pull up, or pull up and circle. A reasonably accurate indication of the thermal strength is difficult to achieve in these conditions and the indications of some current systems are nearly meaningless. Similar problems arise during 'S' maneuvers under a thermal street and when climbing in narrow thermals and straw fires.

Vertical tubes.

When initiating a pull-up, the tailplane is accelerated downwards and then decelerated to its equilibrium position. With a total energy probe mounted near the top of the fin, the vertical tube may be a meter long. A rate of change of acceleration of 1g per second is easily achieved and the variometer experiences a lift error followed by a sink error.

Figure 2.



The pressure produced by a column of air of length Lv (Figure 2), density p under an acceleration of g′ is p.Lv.g′. The change in pressure per unit height is p.g. As a variometer senses the rate of change of pressure,

Indication error = $1/p.g \bullet d/dt(p.Lv.g')$
$= Lv/g \bullet dg'/dt$

For a 1 meter column of air subjected to a rate of change of acceleration of 1g per second, a fast variometer will indicate a 1 m/s error - about 2 knots.

The response rate of the variometer limits the errors actually indicated. A 2 second filter will damp out most of the effect, but a fast instrument with an audio system may react significantly. This is more likely to be an annoying distraction than a serious nuisance.

Axial tubes - rotational acceleration.

As the climb angle changes, an axial tubes rotate about the center of mass and experience a centripetal acceleration. If the length of tube in front of the center of mass is l, the length behind it is L and the angular velocity is w, the pressure error at the variometer is:

$$= {}_0\int^{L} p.r.w^2.dr - {}_0\int^{l} p.r.w^2.dr$$
$$= p/2.(L^2 - l^2).w$$

Indication error = $1/p.g \bullet d/dt\,(L^2-l^2).p.w^2$
$= (L^2-l^2).w/g.dw/dt$

This will be zero if l = L, for a probe mounted on the fuselage just behind the wing. For a fin mounted probe, putting in reasonable values for the length, angular velocity and acceleration suggests that the magnitude of this effect may be up to about half that due to the acceleration on a 1 meter vertical tube, although the timing will be different. The effect is transient and should be damped out by a gust filter.

Axial tube - axial acceleration.

Since the dynamic forces act through and about the center of gravity, the instrument signals have to be measured in this frame of reference. A glider experiences an axial acceleration of - g.sin(C) while climbing, where C is the climb angle. If the angle of incidence is I, the air in a tube of length (L+l) lying along the fuselage axis exerts an acceleration pressure of p.g.(L+l).sin(C).cos(I) at the variometer. The vertical pressure difference between the variometer in the instrument panel and the center of gravity is p.l.g.sin(C+I). When the climb angle is changing:

Indication error =
-1/p.g•d/dt.p.g.((L+l).sin(C).cos(I)-l.sin(C+I))=
-d/dt.(L.sin(C).cos(I)-l.cos(C).sin(I))=
-(L.cos(C).cos(I)+l.sin(C).sin(I)).dC/dt+(L.sin(C).sin(I)+l.cos(C).cos(I)).dI/dt
approx. value=-L.cos(C).dC/dt

Putting in reasonable values for L, l and dI/dt for the second term, typically gives errors of less than 1 kt. Maximum values are experienced during large changes in g load at intermediate speeds. The effect is transient and should be removed by the gust filter.

The second factor in dC/dt typically contributes less than 10% of the total. The first factor generates significant errors and it is effective all the time the climb angle is changing - which may be several seconds. It will not be damped out by the gust filter. The contributions due to the forward tube l nearly balance out and the system behaves almost as if the instrument was actually located at the probe position.

The rate of change of inclination of the flight path can be calculated from the normal acceleration g', measured at center of gravity and the speed V. The centripedal acceleration is V^2/R where R is the radius of curvature of the flight path. The angular velocity dC/dt = V/R.

Indication error = L.cosC.(g'-g.cosC)/V

With a tail mounted total energy probe, the tube may be more than 3 meters long. Typical errors are shown in Figure 3.

Speed Knots	Variometer indication error-sink is negative Knots					
40	1.7	0.8				
50	1.3	0.7	-0.7	-1.3		
60	1.1	0.6	-0.6	-1.1	-1.7	-2.2
70	1.0	0.5	-0.5	-1.0	-1.4	-1.9
80	0.8	0.4	-0.4	-0.8	-1.3	-1.7
90	0.8	0.4	-0.4	-0.7	-1.1	-1.5
100	0.7	0.4	-0.4	-0.7	-1.0	-1.3

Figure 3. Variometer errors due to acceleration effects on a 3 meter connecting tube in near horizontal flight.

Together with the changes in polar sink, these effects are large enough to mask indications of lift and to give serious errors in Netto variometer readings. They are likely to be serious errors in netto variometer readings. They are likely to be serious during dolphin style soaring and on entry into a thermal. The acceleration effects may have been previously confused with indications of polar sink or with errors in total energy compensation.

Reducing the g' loading from 0.5 to 0 produces significant changes in the indication, in contrast to the effect on the polar sink. It has been assumed that the rate of change of acceleration due to the change of drag with speed, is small. If an accelerometer is used to sense the normal acceleration g' and cos C is set constant at 0.95, the calculated values will have maximum error of about +/- 10% for glide angles between + and - 26 degrees to the horizontal, which should allow adequate compensation.

PROBE MOUNTING POSITIONS

While there are a number of possible positions, there is no location which is free of problems (1, 2, 3, 8). Possible locations are on the fin, on top of the fuselage behind the wing, underneath the fuselage, in front of the nose, on the front of the nose and on the wing tip. High performance sailplanes are generally much more sensitive to total energy errors than low performance sailplanes, due to the wider operating speed range.

Fin mountings may be affected by elevator and rudder movements and require a long connecting tube. The probe should be mounted close to the top of the fin, both for conventional and t-tails. With t-tails, probe lengths of at least 1/2 m and 1 m should be used with all flying and conventional elevators, respectively.

Mountings on top of the fuselage may be affected by suction and turbulence from the wing and by changes in the airflow around the fuselage. A probe length about equal to the fuselage diameter at that point is required and it should be mounted about a chord behind the wing. This position is fairly free of suction effects from the upper surface of the wing and is clear of the wing wake. The aerodynamic drag may be reduced by fitting the probe stem with an aerofoil sleeve. A probe mounted level with the trailing edge of the wing gives very deceptive variometer indications, due to the large pressure changes on the upper surface of the wing.

Although there is often a position of near-zero static error underneath the aft part of the wing, a probe mounted under the fuselage would be more sensitive to slip, since the directional change in the airflow near the fuselage is much greater than the changes in slip angle. It would need to be hinged or retractable, although it could be coupled to the undercarriage mechanism. A slightly reduced suction coefficient would be needed to allow for the difference between the air velocity in the free-stream and that near the fuselage.

A probe can be mounted in front of the nose on some glass gliders, but, depending on the shape of the nose, it may need to be more than a meter long to be reasonably free of the influence of the fuselage. The inner section may have to be increased in diameter to keep the assembly sufficiently rigid. The overall tube length could not be less than about 2 meters, but this position does have the advantage that the acceleration effects from the polar and from the tubing partially tend to compensate each other. The nose affects the static pressure and the flow velocity at surprisingly large distances in front of it (1, 6) and the influence changes with slip angle. To prevent large airspeed indicator errors, the wash from the probe must be kept clear of a nose pitot head under all flight conditions.

Probes have been successfully mounted on top of the nose at right angles to the airflow, near the position of zero static error (13). Although this position is quite sensitive to slip, it is worth considering for lower performance gliders.

The wing tip can provide a very satisfactory mounting position during straight flight, but the large differences in tip velocity cause problems during circling flight (1).

GUSTS, GUST FILTERS AND YAW ERRORS

A total-energy system subtracts a signal from the sink rate which is proportional to the increase in airspeed. Sudden changes in airspeed occur when entering and leaving a horizontal gust. The total energy system feeds an 'error' proportional to the gust speed times the airspeed, into the variometer. A gust filter (4) reduces the variometer response to rapidly changing gust signals, while having only a small delaying effect on slower lift signals.

Since there is usually a speed change when entering a thermal, with higher cruise speeds and faster variometers, it has become progressively more difficult to distinguish between gusts and genuine lift. As a one-second system is likely to have about four times the gust problems of a two-second system, the readings from a slower variometer may actually be easier to interpret.

While all pressure transducer and some thermistor variometers have electronic gust filters built in, there is a limit to what can be achieved with conventional filter techniques without seriously reducing the response rate. 'Third order' filters, with a fairly sharp frequency cutoff, perform much better than simple first order filters. If the transit time through a gust is significantly less than the time constant of the filter system, the indication error is considerably reduced. If the transit time is appreciably longer, the effect of the error signal is reduced in amplitude but extended in time.

Considerable improvements in recognizing and removing gust effects are possible with micro-processor-controlled variometers (14). There is a maximum rate at which the glider can change speed under gravity, due to changes in the glide path. The rate of change of the airspeed signal can be monitored and any excess indications used to compensate for gust effects. Using a vertical accelerometer, accurate limits can be calculated for the axial velocity changes.

The true (uncompensated) climb rate can be derived from the total energy compensated variometer and airspeed signals. This signal should be comparable to the total energy signal in steady flight and will be larger during accelerated flight. However, it is only slightly affected by gusts, so any significantly larger total energy compensated signals are likely to be due to gusts (15). The airspeed signal may also be averaged or predicted separately over a much longer period than the uncompensated climb rate. A corrected total-energy signal largely free of gust effects may then be reconstructed.

Involuntary slip angles of 10-15 degrees may be experienced by a 15 m sailplane in normal soaring flight and open class sailplanes may suffer even larger errors. The pilot can experience a total instrument failure for several seconds. Open tube pitots are satisfactory up to about 20 degrees (8, 9, 10) and 'pot' pitots will work up to 30 degrees. Flush nose pitots can show significant errors at much smaller angles and it may be necessary to fit an extension tube. Two hole and twin slot total energy probes are likely to be satisfactory to more than 25 degrees. Providing nearly error-free static sources is more difficult. Combined pitot-static probes are satisfactory up to about 10 degrees and aft fuselage statics may work up to about 15 degrees. A static probe which works up to 25 degrees is available (7). In general, variometer systems which use only total-energy probe and pitot sources are likely to be more accurate and are easier to compensate than those which use pitot and static sources, with either electronic or mechanical compensation.

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