TOTAL ENERGY VARIOMETERS

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It has been known for a considerable time that if the "static" side of a glider variometer is connected to a device which supplies a pressure $(p-\frac{1}{2}\rho V^2)$, the variometer readings are proportional to the rate of change of total energy (kinetic plus potential) of the glider. The present paper explains the advantages of this arrangement, discusses the theory of variometers and indicates the present means adopted in this country to supply the variometer with the required pressure.

Given a variometer which indicates rate of change of total energy, it is useful to consider its precise advantages to the glider pilot, who naturally wishes to use any available lift to the best advantage. For example, in thermal soaring, he wishes to locate and circle in the strongest part of the thermal. This process is rendered unnecessarily difficult if an ordinary variometer is used, because its readings do not necessarily show where the best lift occurs. Thermals are frequently quite rough and even with careful flying it is difficult for the pilot to prevent the air speed altering quite appreciably from time to time, particularly in cloud. These speed variations lead to so-called "stick thermals"; thus, if the speed reaches 45 m.p.h., and the pilot sharply pulls up the nose to reduce speed to, say, 40 m.p.h., the glider will climb momentarily and the variometer will show the added effects of the thermal and the zoom. Hence, when the airspeed is decreasing in a thermal, the variometer will show too high a rate of climb, and conversely, if the airspeed is increasing its indications will be too small. The pilot, trying to estimate where the best part of the thermal lies, therefore has mentally to disentangle the "real" and "stick" thermals, since the variometer indications only provide accurate information about the real thermal if the airspeed is exactly steady.

The Total Energy Variometer eliminates this confusion entirely, because it removes the effects due to the varying airspeed. The indications of the instrument mean what they say; if it indicates that the western side of a thermal is better than the eastern side, it really is, regardless of the changes of airspeed. It does not, of course, eliminate the slight lag inherent in all variometers, nor can it be expected to ignore an incipient spin or stall whilst circling.

Suppose that a glider, fitted with a Total Energy Variometer, flies at a steady airspeed in still air. Since the airspeed is steady, the "dynamic head" remains constant (since it is proportional to the square of the airspeed) but since the glider is sinking at a uniform rate, the atmospheric pressure is increasing. The constant "dynamic head" suction has no effect on the instrument, but the increasing atmospheric pressure causes air to flow into the capacity via the variometer which indicates the appropriate rate of sink. Under these steady conditions, the suction is obviously doing nothing at all and we might just as well have connected the "static" side of the variometer to the airspeed static tube or left it open to the cockpit in the old-fashioned manner.

However, let us now suppose that the glider is again flying in still air, but with the airspeed varying between, say, 40 and 50 m.p.h. At some particular instant, suppose the airspeed is 45 m.p.h. and increasing (shortly to reach 50 m.p.h.). Under these conditions the rate of sink is a little greater than it would be if the airspeed were steady at 45 m.p.h., because the glider is performing a gentle dive and is more nose-down than usual at this speed. The atmospheric pressure is therefore increasing, at a rate somewhat greater than if the speed had been steady at 45 m.p.h. However the "dynamic head" suction is also increasing, so we have:

Pressure at variometer "static" connection equal to

a. **Atmospheric pressure** increasing at the rate corresponding to a steady airspeed of 45 m.p.h.

plus

b. an additional rate of increase of **atmospheric pressure** because the glider is diving a little,

plus

c. a **suction** increasing because the airspeed is increasing.

Now, since (b) is an increasing **pressure** and (c) is an increasing **suction**, these cancel out, and we are left with (a), so that the variometer instrument does not know that the airspeed is altering, only that at that moment the airspeed is 45 m.p.h. It therefore indicates the rate of sink corresponding to a steady airspeed of 45 m.p.h.

By arguing in this fashion, it will be seen that at any instant, the variometer will ignore the effect of the dive or zoom and will merely indicate the rate of sink corresponding to whatever the airspeed may be at that instant. For the changes of speed considered, its reading might vary between 2½ and 3 ft/sec sink, which would not be very noticeable, although just at the instant considered above, the actual rate of sink might well be as much as 7 or 8 ft/sec.

In practice, it is the experience of pilots that quite violent dives and climbs produce very little noticeable change in the variometer reading.

If the glider is flying at, say, 40 m.p.h. and the airspeed is gradually increased to say, 60 m.p.h., the reading of the variometer will of course gradually increase until it shows the new rate of sink corresponding to 60 m.p.h. A pilot accustomed to an ordinary variometer, with its rapid response to movements of the elevator, may feel at first that the Total Energy Venturi introduces a large lag, although this is not in fact so.

If the glider is now climbing in a thermal, the Total Energy Variometer behaves in exactly the same way as in the "still-air" case considered previously. It ignores the effects due to changing airspeed and for all practical purposes it may be assumed to indicate the actual vertical velocity of the thermal less the rate of sink which the glider would have if it were flying steadily at the **average** airspeed which the pilot maintains, since he will be flying near the speed for minimum rate of sink. The information which it gives the pilot is therefore free from confusion due to the changing airspeed of the glider and hence gives much clearer indications of the behaviour of the thermal itself.

Whilst the foregoing has been written as applying to thermal soaring, the Total Energy Variometer is obviously equally essential under all soaring conditions, for almost invariably the glider is likely to encounter turbulent conditions which will cause variations in the airspeed.

To summarise, therefore, the Total Energy Variometer is a device which performs the following functions:

a. It eliminates the effects of fluctuating airspeed, provided of course that the variations are not too great.
b. If the airspeed is steady it has no effect, and the variometer shows the appropriate reading.
c. The pilot therefore treats it just like an ordinary variometer, but no longer has to make allowance for "stick" thermals. It is therefore a particularly valuable aid to

pupils on their early soaring flights.

The practical development of a suitable source of suction has occurred largely in this country. In 1947, Mr H. KENDALL conducted some experiments (Ref. 1) in which a small curved plate was fitted to each side of the front fuselage of the Surrey Gliding Club's Weihe, the curvature of the plate being adjusted until the appropriate local pressure drop was obtained. This was measured by connecting the vents on the curved plates to the 'static' side of an airspeed indicator and the 'pitot' side of the instrument to the static head. When the readings of this A.S.I. agreed with those of the normal glider instrument, the correct suction had been attained. A similar device if fitted to Mr WILLS' 'Sky'. This arrangement is aerodynamically clean, does not tend to ice up, and is fairly insensitive to yaw due to the use of a pair of vents on opposite sides of the fuselage. However, it suffers from the disadvantage that it has to be 'tailor-made' for each particular installation. In 1948, the author fitted an Olympia, entered for the World Gliding Championships in Switzerland, with a Venturi which had been adjusted in a wind tunnel to give the required suction. This was quite useless, for it was extremely sensitive to small changes of yaw which therefore produced large changes of variometer reading. The matter was then allowed to rest for some time, until, stimulated by Mr WELCH's demand for a satisfactory venturi, a prototype was made up for the 'Sky' which he flew at the 1952 Championships in Spain. This Venturi has an external circular plate at its downstream end, which produces a large wake and renders the conditions at the exit insensitive to yaw. The intake is not greatly affected by yaw, and hence the suction remains virtually constant up to quite large angles. Wind tunnel tests have shown that the pressure coefficient changes from (-1.0) at zero yaw to (-1.05) at 40° yaw. The pressure coefficient changes slightly with REYNOLDS number: with a venturi 2¼" long, it is (-0.96) at 40 ft/sec., (-1.0) at 60 ft/sec. and (-1.05) at 120 ft/sec. In practice, these variations are entirely masked by position error and the fact that the variometer cannot be read to such a degree of accuracy. Since small venturis cannot be designed by a simple application of BERNOULLI's equation, and in this case the suction is influenced by the external plate, the proportions of this device were obtained by trial-and-error wind tunnel tests in the 5 ft x 4 ft tunnel at the Imperial College of Science & Technology.

This venturi has proved very satisfactory in practice, and is being manufactured by the COBB-SLATER Instrument Company. Compared with Mr KENDALL's blisters, it has the advantage that it can be obtained 'off the shelf' and quickly fixed to any glider. The same care should be taken in its location as for a pitot/static head. Small venturis suffer from the disadvantage that they ice-up easily, but the simplest solution is to fit a water trap, so that when the ice melts, water is not drawn into the variometer. A venting device may also be incorporated, so that if the venturi ices up, the 'static' side of the instrument may be vented to the cockpit, and one reverts to the conventional state. COBB-SLATER supply a suitable vent-drain device. The ideal arrangement would be to incorporate an electric heater in the venturi, similar to Mr BLANCHARD's pitot-heater (Ref. 2).

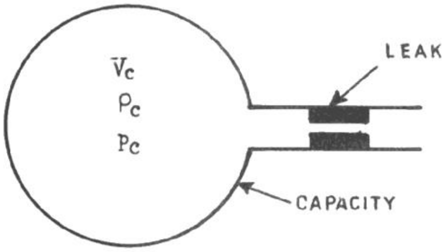
Most total-energy devices produce a slight oscillation in the variometer reading, partly because they are sensitive to small scale atmospheric turbulence, and partly because the pressure they supply may not be quite steady (e.g. the external plate on the author's venturi will produce some turbulence). In practice, one soon becomes accustomed to this effect, and it ceases to be a source of annoyance. It has been suggested that these small fluctuations could be damped out by inserting a suitable length of small-bore tube between the venturi and the instrument, but this will tend to increase the lag in the response of the instrument.

In this country, a Total Energy Variometer is now considered virtually indispensable, and most British sailplanes are to be seen carrying some device to supply the required suction.

THEORY OF THE TOTAL ENERGY VARIOMETER *)

Before dealing with the total energy variometer, it is convenient to consider the ordinary type of instrument in order to investigate its errors and limitations.

Consider a vessel connected to atmosphere via a small leak. Then the mass of air in the vessel, M_c, is given by:



$$M_c = \rho_c V_c \qquad (1)$$

Let us suppose that the initial capacity pressure was p_o and that subsequent changes and pressure and density, although not necessarily adiabatic, follow a law of the type:

$$p_c = \text{const.} \times \rho_c^n \qquad (2)$$

Then from equations (1) and (2)

$$M_c = V_{c\rho o} \left(\frac{p_c}{p_o}\right)^{\frac{1}{n}} \qquad (3)$$

Now if the leak consists of a capilliary of radius r and length l, the rate of discharge of air through the leak is given by:

$$\frac{dM_c}{dt} = \frac{\pi r^4}{8\mu l} \cdot \rho_c (p_c - p) \qquad (4)$$

For the present purposes we will neglect the changes in viscosity, and suppose that, for laminar flow through the leak, the rate of mass flow is given by:

$$\frac{dM_c}{dt} = K \rho_o (p_c - p) \qquad (4a)$$

where K is a function of the characteristic dimensions of the leak.

On the assumption that the instrument is calibrated to read true rate of climb or descent at sea level, we wish to determine what true rate of climb or descent corresponds to given indication at altitude.

Fundamentally, there are two types of variometer:

a. *Constant geometry leak* Here the indicator is a sensitive pressure gauge which measures $(p_c - p)$, which is therefore fixed at a given indication. Since "K" is always the same, at a given indication $\left(\frac{1}{p_c} \frac{dM_c}{dt}\right)$ is fixed at all altitudes.

b. *Constant pressure difference type.* Here the instrument is arranged so that the size of the leak adjusts itself so as to keep $(p_c - p)$ constant. The indicator is, in effect, the leak itself. (E.g. the leak may be the annulus between a pellet and the walls of a tapered vertical tube. The position of the pellet is observed against a scale.) Hence a given indication corresponds to a certain geometry and hence a given value of "K".

Hence again, at a given indication $\left(\frac{1}{p_c} \frac{dM_c}{dt}\right)$ will be fixed at all altitudes.

*). *Revised version of theorygiven in Ref. 3*

The ordinary aircraft rate of climb indicator corresponds to type (a), the *Cosim* glider variometer to type (b) and the German *Horn* glider variometer combines both principles of operation. In all cases, however, the instrument reading will be a function of $\left(\frac{1}{\rho_c} \quad \frac{dM_c}{dt}\right)$.

From equation (3)

$$\frac{1}{\rho c} \quad \frac{dM_c}{dt} = V_c \quad \frac{\rho_0}{\rho_c}\left[\frac{1}{n}\left(\frac{p_c}{p_0}\right)^{\frac{1}{n}-1}\right]\frac{d}{dt}\left(\frac{p_c}{p_0}\right) = \frac{V_c}{n} \cdot \frac{p_0}{p_c} \quad \frac{d}{dt}\left(\frac{p_c}{p_0}\right)$$

Hence the instrument reading will be a function of $\frac{1}{p_c} \quad \frac{dp_c}{dt}$, and if the pressure difference across the orifice is very small compared with p_c (as is usually the case), this becomes very nearly $\frac{1}{p} \quad \frac{dp}{dt}$

$$\text{Now} \quad \frac{1}{p} \quad \frac{dp}{dt} = \frac{1}{p} \quad \frac{dp}{dh} \cdot \frac{dh}{dt} = -g \, \frac{\rho}{p} \cdot \frac{dh}{dt} = -\frac{g}{RT} \cdot \frac{dh}{dt} \quad \ldots\ldots\ldots\ldots (5)$$

Hence the relationship between the actual rate of climb or sink and the indicated figure at a height *h* feet in the ICAN troposphere is given by:

$$\frac{\left(\frac{dh}{dt}\right)_h}{\left(\frac{dh}{dt}\right)_o} = \frac{T}{T_0} = \frac{288 - 0.00198\,h}{288} = 1 - 0.00688\left(\frac{h}{1000}\right) \quad \ldots\ldots\ldots\ldots (6)$$

It will be observed that the instrument reading is greater than the true quantity by about 0.7 per cent per 1,000 ft. For most purposes in gliders it may therefore be assumed to give the true figure.

The *TOTAL ENERGY* VARIOMETER

It has been shown (equation (5)) that the variometer reading is a function of $\left(\frac{1}{p} \quad \frac{dp}{dt}\right)$ i.e. $\left(\frac{1}{T} \quad \frac{dh}{dt}\right)$. Since $\frac{Wdh}{dt}$ is the rate of change of potential energy of the aircraft, the readings of the variometer are a direct measure of this quantity, subject to the previous corrections.

Suppose now that the instrument is connected to a venturi supplying a pressure $p - \frac{1}{2}\rho V^2$. The variometer reading will now be a function of $\left(\frac{1}{p - \frac{1}{2}\rho V^2}\right) \frac{d}{dt} \left(p - \frac{1}{2}\rho V^2\right)$ and if $\frac{1}{2}\rho V^2$ is small compared with p, this may be written

$$= \left(\frac{g\rho}{p}\right) \quad \left(\frac{dh}{dt} + \frac{d}{dt} \cdot \frac{V^2}{2g} + \frac{V^2}{2g} \cdot \frac{1}{\rho} \cdot \frac{d\rho}{dt}\right)$$

i.e. $= \left(\frac{g}{RT}\right)\left[\frac{d}{dt}\left(h + \frac{V^2}{2g}\right) + \frac{V^2}{2g} \cdot \frac{1}{\rho} \cdot \frac{dp}{dt}\right]$

Consider the order of magnitude of the last term.

Now $\frac{1}{\rho} \quad \frac{dp}{dt} = - g \frac{d\rho}{dp} \cdot \frac{dh}{dt}$ and it may be shown that in the ICAN troposphere $\frac{d\rho}{dp} =$ $= \frac{1.134}{a^2}$, where *a* is the local speed of sound.

So the last term becomes $\frac{-1.134}{2} M^2 \frac{dh}{dt}$ where M is the Mach number of the aircraft.

Now in supposing that the venturi always supplies $(p - \frac{1}{4}\rho V^2)$ it is implied that the flow may be regarded as incompressible, i.e. that the Mach number is very small, so that this term is negligible compared with $\frac{dh}{dt}$. (For a glider it will be about 0.5 per cent of $\frac{dh}{dt}$).

The variometer reading, under these circumstances may be regarded as a measure of $W \frac{d}{dt}\left(h + \frac{V^2}{2g}\right)$, the rate of change of *total energy* of the aircraft. The variometer reading now becomes *rate of change of energy height*, using the phraseology of R. & M. 2557. This reading is, of course, subject to the same altitude errors as the ordinary variometer.

SYMBOLS

p : pressure
ρ : density
T : temperature
V_c : volume of capacity
M : mass of air
R : constant in equation of state, $p = R\rho T$
n : index of expansion
a : speed of sound
μ : coefficient of viscosity
g : gravitational constant
M : Mach number, V/a
v : aircraft true forward speed
h : height, feet
W : aircraft weight
t : time

SUFFICES

0 : refers to I.C.A.N. sea-level conditions
c : refers to conditions in the capacity

Symbols without suffix refer to local atmospheric conditions.

REFERENCES

1. H. KENDALL, **The Total Energy Variometer*, *Gliding*, Vol. 3, No. 1.
2. P. BLANCHARD, *A Pitot head for Gliders*, *Gliding*, Vol. 3, No. 2.
3. F.G. IRVING, *The Total Energy Variometer*, *Gliding*, Vol. 3, No. 2.