GLIDER INDUCED ERRORS IN TOTAL ENERGY VARIOMETRY
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1. INTRODUCTION
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Although turbulence, which is not being dealt with here, is the ultimate limiting factor in total energy variometry, aircraft induced perturbations are sufficiently strong to make interpretation of the total energy variometer's response rather difficult for the soaring pilot, or expressed otherwise: the signal may be treacherous. Even in the absence of strong turbulence, disturbances may reach the magnitude of thermals encountered, or the polar sink rate. This unfortunate state of affairs is due to fact that it is the TE-variometer's transitional response - when entering a thermal for instance - from which the pilot draws his conclusions on movement of the surrounding air, whereas the steady state output is of little importance. This is aggravated by the glider normally being in a more or less unsteady state of flight at the very critical moment, in pull up for instance, thereby reinforcing or producing additional disturbances in TE-response. Nota bene, these are not at all errors to be attributed to the variometer, but perturbations induced by the aircraft itself, in various ways.

The sheer impossibility to explain the TE-vario's response on board his Standard Cirrus with the knowledge commonly available then, has induced the author in 1980 to commence the work, part of which is being reported here. During the study one effect was investigated after the other, using simple theoretical analysis, experimental work on the ground, and in flight measurements. Every theoretical result was proved in flight. Results have allowed to do away with some of the nuisances. Against others, there is no remedy.

According to the investigation, and also based on the results of talks with pilot customers - the author produces variometers and probes - the various effects as encountered in practice are listed below, in descending order of importance:

1) Changes in probe pressure induced by the tail fin, by elevator deflection, by wing and fuselage.
2) Accelerated motion of the glider.
3) Influence of air columns in the plane.
4) Side slip induced by control action or turbulence.
5) Errors produced by the probes themselves.
6) All other errors.

Unfortunately the first group of errors is the most difficult to predict, if not unpredictable. These errors are amenable to measurement in flight nearly only. Groups 2) and 3) are relatively simple deal with analytically. Group 4) is even more difficult to treat than group 1), whereas probes can be investigated experimentally on the ground.

This report does follow a logical order different from the one above.

2. INFLUENCE OF NORMAL ACCELERATION ON POLAR SINK RATE

In a pull-up the wing has to produce increased lift to carry the acceleration force on top of the weight of the plane. Increased lift means also increased drag, and increased drag means increased energy loss rate: the plane will sink faster than at a load factor of 1. How much faster?

There is a formal difficulty: In a pull up the sink rate is due to 2 things, energy loss of the plane, and the vertical component of the plane's velocity as it proceeds on its generally inclined trajectory. Fortunately, here, a total energy variometer - of the ideal kind - will only indicate the energy loss rate, but will not be influenced by the vertical component of velocity itself, which may be considerable indeed, 15 m/s easily, in a pull-up. We shall therefore limit ourselves to the enrgy loss rate, directly indicated by an ideal te-variometer (the altitude variometer of the old times would respond rather more to the vertical component of the plane's velocity).

For clarity we recall the total energy equation:

$$E = 1/2\ m\ vv + m\ g\ H \qquad (a)$$

rearranging a bit, introducing air density, and differentiating with respect to time, as does the te-variometer, we find the output of the latter:

$$1/mg\ dE/dt = 1/rho\ g\ \times dq/dt + dH/dt \qquad (b)$$

where E = total energy of the plane
m = mass of the plane
g = earth's gravitational constant
rho = air density
q = dynamic pressure = 1/2 rho vv
H = altitude of the plane

We see that it is the rate of energy loss per unit of weight of the plane, that the te-variometer indicates.

We also see that its output can be interpreted as a vertical speed in the strict sense only, and only then, when the rate of change of dynamic pressure is zero, implying stationary circular or straight flight. In the first case the te-vario will indicate sink rate according to the "circular polar", and in the second according to the normal polar.

Even if it is not a real vertical speed, it being masked by the "trajectory" component, as a means to more easily interpret the term "energy loss rate per unit of weight", it can be taken as an equivalent sink rate: its time integral will give the altitude lost during a particular manoeuvre after return to the initial state.

However in all cases, and at any time, the te-vario will indicate the energy loss rate of the plane.

As concerns the aircraft:

$$L = q \times A \times Cl \qquad (1)$$

$$q = 1/2\ rho\ vv \qquad (2)$$

where L = Lift
A = wing area
Cl = Lift coefficient of the plane
v = velocity of plane

Now lift must be equal to the sum of the mass forces acting on the plane: weight plus acceleration forces, for simplicity expressed by the load factor indicated by the g-meter.

$$L = m \times g \times n \qquad (3)$$

where n = load factor

Drag of the plane is:

$$D = q \times A \times Cd \qquad (4)$$

where Cd = drag coefficient

It is to be taken into account that drag coefficient is a function of the lift coefficient. It can be deduced from the drag polar of the plane.

Drag, in combination with the plane's velocity will dissipate power according to:

$$Nl = v \times D \qquad (5)$$

where Nl = Power loss generated by aerodynamic friction

This power must be equal to the energy loss rate of the plane expressed in equation (a):

$$Nl = dE/dt \qquad (6)$$

Substituting the weight specific energy loss rate in the te-vario equation (b) above:

$$wt = 1/m\,g \times dE/dt \qquad (6)$$

and rearranging equations (a) to (6) we obtain easily:

$$* \quad Cl = 2\,m\,g/\rho A \times 1/v^2 \times n \quad * \qquad (8)$$

$$* \quad wt = \rho A/2mg \times v^3 \times Cd(Cl) \quad * \qquad (9)$$

This system can be simplified by introducing the lift-, and drag coefficients of n=1:

$$* \quad Cln = n \times Cl0 \quad * \qquad (10)$$

$$* \quad wtn = Cdn/Cd0 \times wt0 \quad * \qquad (11)$$

where: index 0 stands for stationary straight flight,
index n for accelerated flight.
v = constant

With this system of equations interpretation becomes very simple indeed:

* To find the accelerated lift coefficient multiply the one measured in stationary flight (at veolocity v) by the load factor.
* To find the accelerated "total" sink rate, multiply the stationary one with the ratio: drag coefficient belonging to the lift coefficient of accelerated flight, divided by the drag coefficient of stationary straight flight.

Figure 2.1 below shows the relations for the ASW 19. for flight with a load factor of 2 for a flight speed of 170 km/h on the one hand, and about 90 km/h on the other: the difference is most striking. At the high speed the relative increase in energy loss rate is small, at the low speed end there is a dramatic increase in loss rate, obviously due to induced drag.

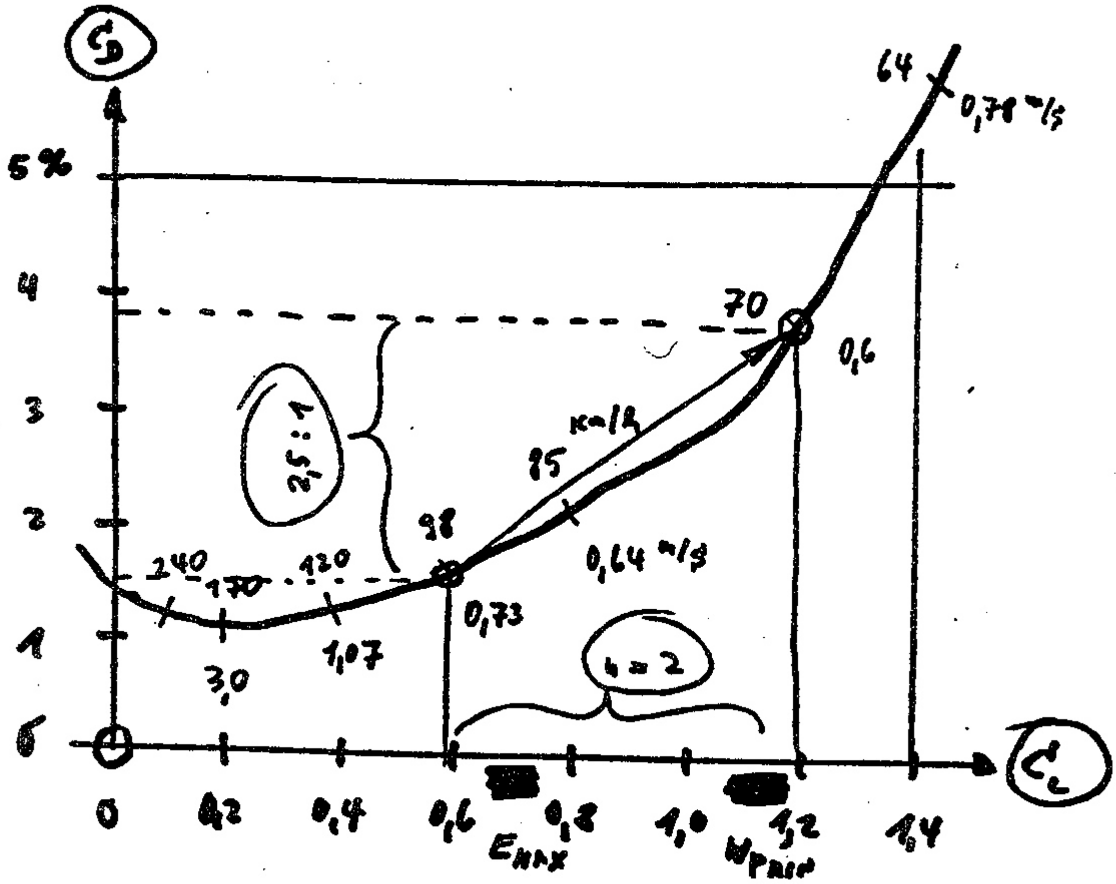

Figure 2.1: Changing load factor

By rearranging equations (8) and (9) one gets a set to transform the normal polar into a set of "accelerated" polars:

$$v = \sqrt{2g/rho \times m/A \times 1/Cl} \times \sqrt{n}$$

$$wt = \sqrt{2g/rho \times m/A \times Cd^2/Cl^3} \times \sqrt{n^3}$$

meaning: the set of "accelerated" polars is generated by multiplying velocity with the root of the load factor, and by multiplying sinkrate by the third power of that root. Figure 2 below shows the result, again for the ASW 19.

Taking the load factor of circular flight: n = 1 / cos phi , where phi = angle of bank, the accelerated polars apply also strictly to spiralling, n = 1,5 corresponding to an angle of bank of 48 degrees for instance. There is no reason to believe that for other types of gliders the fundamental behaviour found will be much different.

Discussion of the results obtained reveals:

* One should avoid large load factors at low speeds if one does not want to incur heavy energy losses, meaning losses in altitude, as a consequence.
* Large load factors, on the contrary are harmless at high speed.
* Load factors below 1 are even beneficial at low speeds.

Nota Bene: The accelerated polar is really different from the one generated by increasing wingloading by the factor n. This is very simply due to the plane's mass being different in both cases!

What is, now, the influence of normal acceleration, or the load factor on the response of an - ideal - total energy variometer?

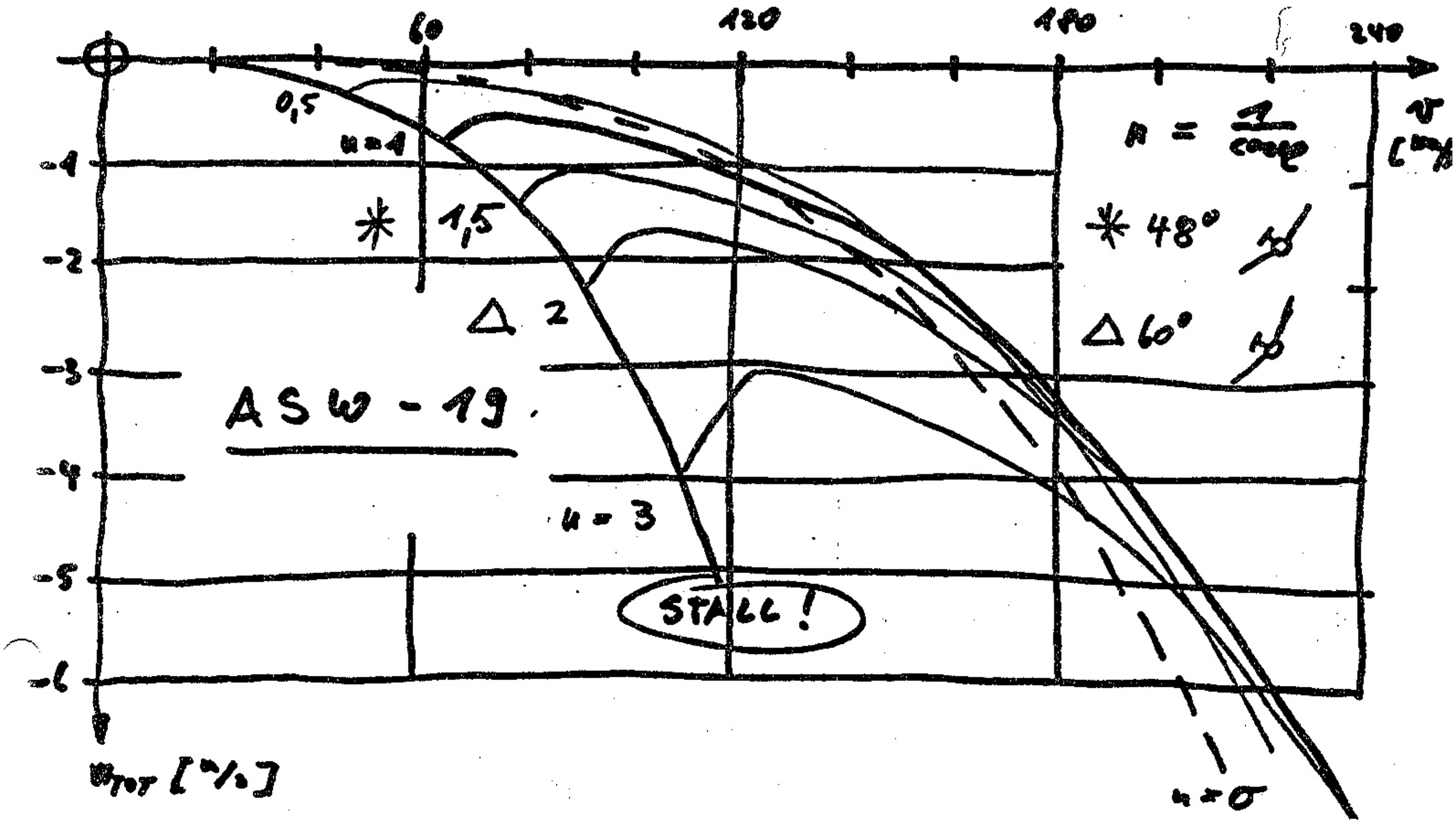

Figure 2.2: Accelerated polars

The answer is very simple: As the increased or reduced "accelerated sink rates" are due to changes in the energy balance of the plane, or - expressed in other terms - due to the changing energy loss rate of the plane, or due to its changing aerodynamic drag, they mean real energy losses. As the ideal total energy variometer will respond to energy losses or gains, alone, it will show the energetic consequences of pilot induced acceleration directly and mercilessly.

It must be added here also that the responses of the - ideal - total energy variometer to changes in load factor are not at all measurement errors like those of a poor te-probe, for instance. The additional sink indicated means a real loss of energy, which cannot be recovered.

The above described consequences of elevator action are strictly to be distinguished from, say, direct pressure changes caused by the elevator on a te-probe near to it. This would be a true measurement error: an eventual additional sink indicated in this way will be compensated by an additional climb later upon restituting the original elevator deflection. Here no energy loss would be involved.

To sum up: pulling on the stick may easily double the normal polar sink rate of a sailplane, with full consequences for the te-variometer. If the latter does not indicate the sag, it is not a good te variometer.

3. EFFECTS OF THE AIR-COLUMNS
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Tubing between pressure probe and the measuring instrument is normally of a rather complex shape. The air in the tube is always being acted upon by mass forces: gravitation and acceleration. Both forces create pressure gradients along the tube, they are maximal where the forces act longitudinally and zero, where they are under a right angle to the axis of the tube.

Gravity being an exact potential field, and acceleration for the purpose of this analysis being practically constant on board the glider, shape of the tubing between the 2 ends is of no importance. What counts is the relative height alone of the two ends in the resulting field of mass forces. This allows us to represent the real tubing by a piece parallel to the longitudinal axis of the glider, plus another one perpendicular to it. We thus can treat the pressures created in both pieces easily by studying vertical and longitudinal forces one after the other. We treat the vertical column first: (see Figure 3.0 below)

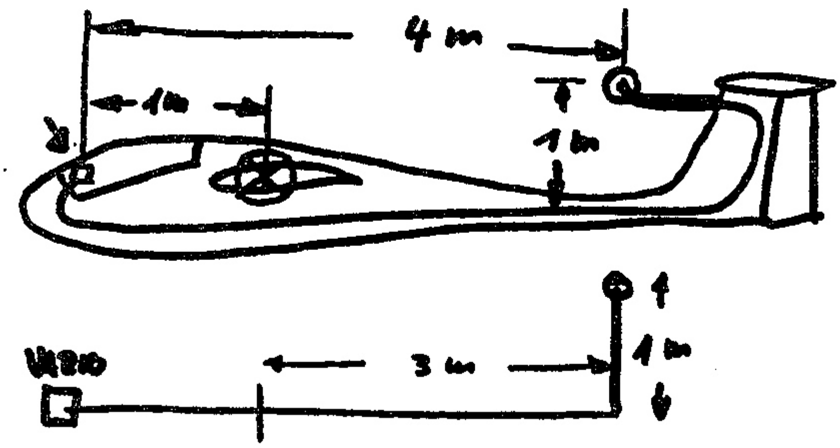

Figure 3.0: Air columns

3.1. Effects of the vertical air-column

a) Normal acceleration, or load factor:

Influence on the longitudinal column is nil. The pressure created on the vertical column is

$$\text{delta } p = \text{rho} \times n \times g \times h$$

where rho = air density
h = height of the column

Put simpler, the pressure difference created is n times the pressure created by gravity. Length h being generally about 1 m, the pressure error expressed in meters air-column is n times 1 m. In other words, the variometer will see an "altitude" change of n x 1m. As the variometer differentiates the input, its response will be nil during periods where the load factor is constant! It will only indicate changes in load factor! (it differentiates n!). The magnitude of its output will depend on its time response: A slow vario will indicate little but this for a long time, a fast one much, but for a shorter time.

Fortunately, during the manoeuvres flown in dolphin flight or during search for thermals, an increase in load factor will always be more or less immediately followed by a decrease of the same magnitude or vice versa (One pulse at the very start, one at the end of the pilot's action to change pitch angle). See also fig.3.1. This makes always for a pulse of variometer output to be followed by one of the opposite polarity. As the 2 pulses normally follow each other within one time constant of the variometer's response, they tend to be rejected effectively. This means that for most practical purposes the disturbance created by the vertical column can be neglected.

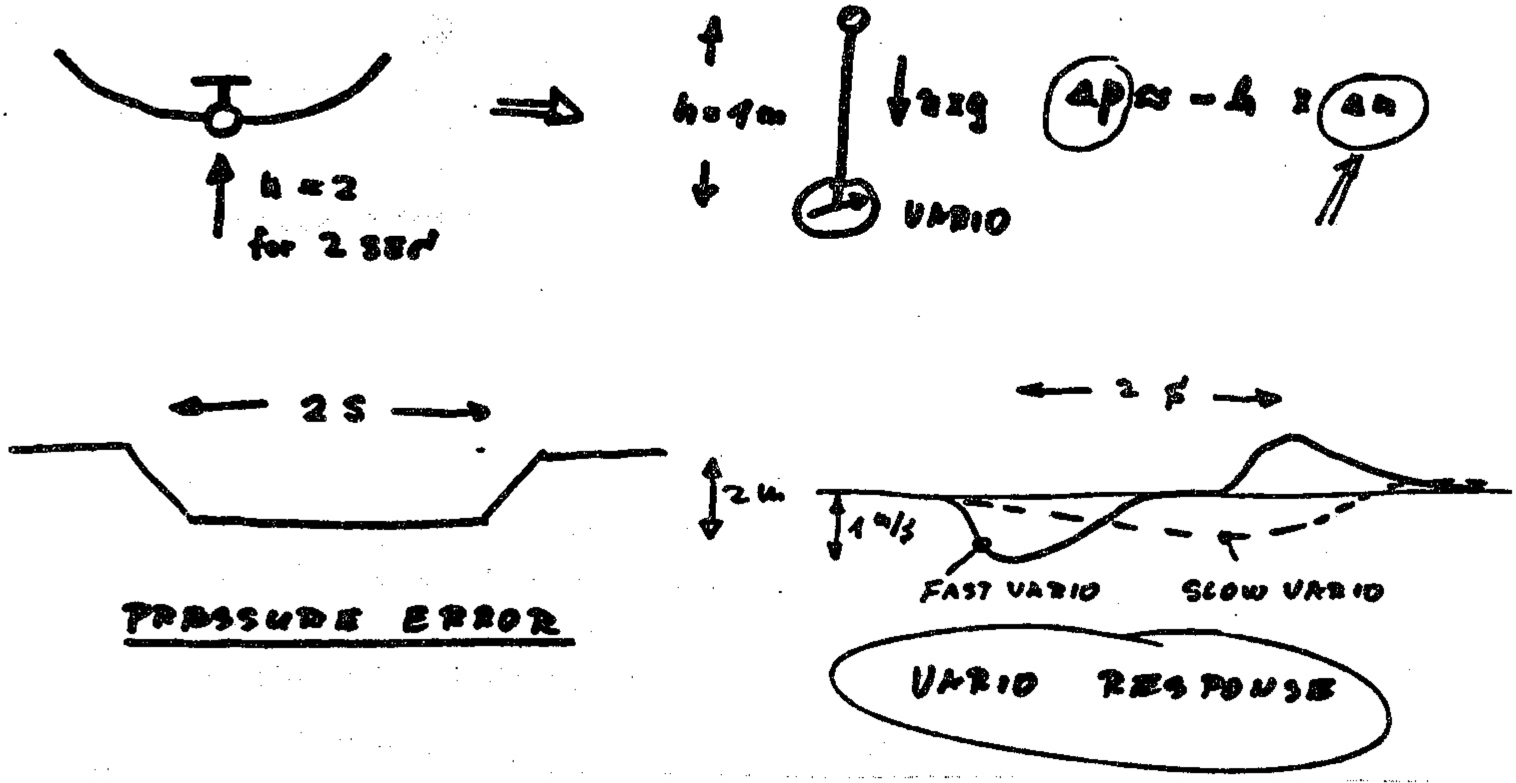

Figure 3.1: Effect of vertical air-column

b) Angular acceleration

The vertical air column normally being located in the vertical fin, far away from the center of gravity, angular acceleration of the glider will also create mass forces along the column. Simple estimation shows that the corresponding effects are smaller than the above ones by roughly a factor of 5. They are negligible.

3.2. Effects of the longitudinal air column

We have found that the effects of the vertical air column are of no importance in normal thermal flight. Most astonishingly, the same does not hold for the longitudinal column.

The longitudinal column explains roughly half of an effect widely seen (the other half is due to the effect of load factor on sink rate): At the end of an ascent at constant pitch angle one will observe, at, or even before rounding the trajectory to avoid stall, that the needle of the te-variometer will climb to above zero, even if its indication has been perfect during the preceding part of the ascent phase. The phenomenon increases with increasing pitch angle maintained on the ascending tajectory. It is independant of the type of te-probe used, and it cannot be cured by modifying the pressure coefficient of the probe. The magnitude of the effect as seen on a fast variometer is of the order of 0,5 to 1 m/s during 2 to 3 seconds at a pitch angle of 10 to 15 degrees, this when using a te-tube on the keel fin. When using a tube on the fuselage, or more foreward, the effect is reduced significantly. This data suggests a pressure error equivalent to an altitude error of the order of 1 to 2 meters. (The figure looks small, however, as this error is being differentiated, it will easily disturb the te-vario signal in critical phases of thermal flight, praticularly in weaker conditions.

Effect of pitch angle

The complete measuring system is being represented by the air column parallel to the longitudinal axis of the glider and the mesuring device at one end, the other end being the pressure port. Abstraction is being made of all aerodynamic effects, only mass forces are considered. Figure 3.2 defines the parameters used. It must be mentioned here that the movement of the glider must be taken as that of its center of gravity, to be meaningfull and without ambiguities, not the one of the pilot, or the instrument.

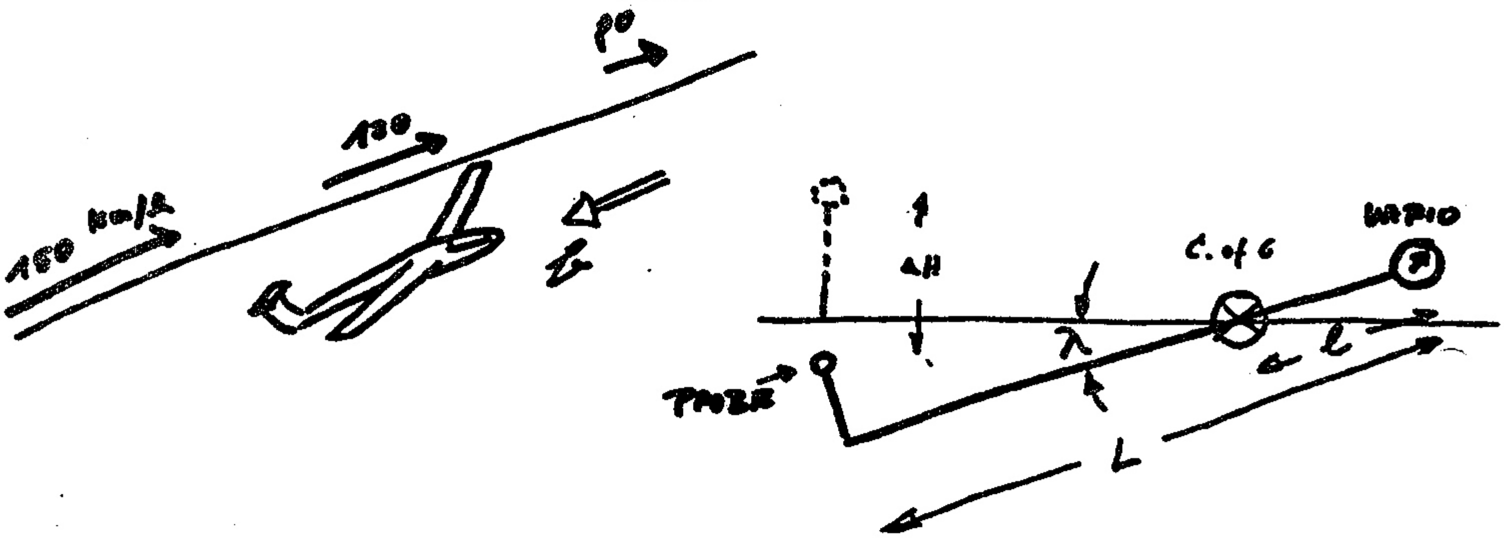

Figure 3.2: accelerated measurement system

The system being exposed to the earth gravitational field and constant acceleration, the pressure of measurement is:

pm = ps - rho g l sin lambda - rho L al

where:
- pm = pressure at the measuring device
- ps = static pressure, c.of g. of the glider
- rho = air density
- g = earth gravitational constant
- l = distance center of gravity to meter
- lambda = pitch angle of glider
- L = length of tube (air column)
- al = longitudinal acceleration of c.of g.

Case a), stationary flight

here, al is 0:

pm = ps - rho g l sin lambda

Obviously here the pressure measured is the (static) pressure at the location of the meter! (not at the c. of g.! Any bias pressure present at the inlet of the tube would be added to it).

Case b), decelerated flight on ascending trajectory

Here the acceleration input is the component of earth gravity along the trajectory, as the glider is effectively accelerated (or decelerated) along it. The influence of drag of modern gliders is much smaller, it is therefore being neglected. Thus:

$$bl = - g \sin \lambda$$

and

$$pm = ps + \rho g (L - l) \sin \lambda$$

Conclusions:
* pressure measured is disturbed by pitch angle.
* disturbance is proportional to distance between c. of g. and the location of the pressure port.
* disturbance is the static pressure difference between c.of g. and the pressure port.

In other words:

What is being measured is the pressure at the pressure port, no more that at the meter, as was the case in stationary flight.
The measurement error is due to the relative height of the pressure port measured against the c.of g.: for the altimeter it is height itself, for the variometer it is vertical speed of the pressure port relative to the c.of g.

In practical terms this means, that it is vertical speed of the pressure probe, that is effectively measured, not vertical speed of the centre of gravity of the glider, as one would think!

When arriving at the top of an ascending trajectory, a pull up for instance, the pitch angle is reduced to around 0: the glider is rotating about its lateral axis, the tail swinging up, creating an upward vertical speed at the te-probe mounted aft of the c.of g., and the te-variometer in still air will show not the polar sink rate, but a reduced one due to the vertical speed of the tail!

Magnitude of the error - it is a real measurement error - can be deduced easily. The total "jump" in error height the variometer will see, is the total height difference of the probe before and after the manoeuvre, measured against the c.of g. For an average glider this is of the order of 1 meter for a 15 degree pull up: the right order for the error sought.

Other effects

When indulging in a more complete analysis of what happens during a climb at constant pitch angle, one will find other, however less important phenomena:

Even at constant pitch angle the trajectory is not straight. The reason for this is that the angle of attack is normally negative at high, and positive at low speed, the difference being of the order of 10 degrees between maximum and minimum air speed (away from stall). This makes for a trajectory to be curved downward for an ascending, and curved upward for a descending trajectory with the longitudinal attitude kept constant by pilot action. This is strictly true for an aircraft with fixed wing section, for gliders with speed flaps being adapted to momentary airspeed this is not necessaryly so. The trajectory being curved, means that the acceleration input varies along it, in magnitude as well as in direction.

Net effect of that consists in an increase by roughly 50 % of the error found above, and in the error showing up earlier than the start of rotation about the lateral axis.

Curvature of the "straight" flight path furthermore means a load factor not remaining constant, particularly towards low speed, when angle of attack changes fast. Again this means that the errors shown by the te-vario appear earlier than expected, this time the earlier start being caused by the change in load factor.

Variation of drag plays a very small role here, as does the change in angle of attack induced by the rotation on a te-probe mounted on the tail fin, an effect which is so often being incriminated: in a reasonable manoeuvre it will stay below 2 degrees. If the probe reacts on that it is poor at any rate and should be replaced by a better one. It can be added here too that the error due to the centrifugal force created in the longitudinal tube during rotation about the lateral axis is of no importance: it is typically of the order of 0.02 m.

Remedies against the effect of the longitudinal air column

When looking at the equations, one should think that the most simple remedy against the evil was to mount the te-probe in the centre of gravity, or at least nearer to it than on the tail.

Unfortunately this will bring the probe near to the wing and the fuslage, the most formidable offenders. The fact that there are positions on the fuselage of certain types of glider which seem to work does not invalidate this general statement.

Something else must be said here: What applies to varios working on te-probes applies strictly to the case of electronically compensated te-varios as well. Deducing their output by differentiating both static and total pressures, rather than the single te-pressure, as does the tube compensated variety, they are prone to 2 errors, rather than one: the one of the static as well as the one of the pitot pressure. This does not simplify the problem.

In the absence of other reasonable solutions the only conclusion can be to live with the nuisance. One thing which will help a lot there, is to know it.

At any rate the disturbance descibed here is mostly parallel and of the same order as the accelerated polar affect, which cannot, by principle, be eliminated. It amplifies an already existing effect against which there is no remedy. Under the circumstances there is not much sense in trying to eliminate it.

4. ERRORS DURING PUSH-OVER, PULL-UP

During a push-over manoeuvre starting from low speed stationary flight, angular speed of the glider around its lateral axis increases from 0 to a maximum, it remains constant for a short length of time and decreases to zero again as soon as the desired nose down attitude is reached. At this moment also the load factor will return to a value near to 1, after having been lower than 1 during the manoeuvre. This makes for angular acceleration to be positiv for a while, then zero, to be followed by a period where it is negative. Angular speed increases from zero to a maximum, remains there for a while and decreases to zero again. Load factor follows the pattern of angular speed. Longitudinal attitude decreases with time in a ramp type fashion.

This sequence of events, which happens many times during a thermal flight, makes for 3 effects to play: vertical column, longitudinal column, accelerated polar. For the purpose of the analysis the following parameters have been used: initial airspeed = 90 km/h; attitude change to be effected = - 15 degrees; time of angular acceleration, deceleration = 0,5 s; angular speed constant for 0,8 s. Load factor during the phase with constant angular speed (the glider follows a practically circular trajectory) is 0,5. Figure 4.1 summarizes the manoeuvre.

For the sake of easy interpretation the error pressures created will be converted to altitude errors with the help of 1 mbar = 100 Pa being about equal to 8 m of air column. These altitude errors will be "seen" by the variometer, which will respond to this input.

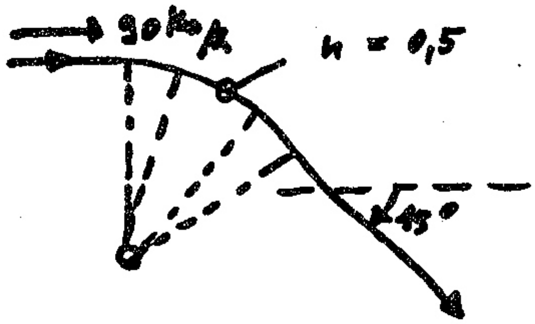

Figure 4.1: push-over parameters

A warning must be given here: It does not make sense at all to try to achieve high precision in this execise, the effects considered are being superimposed by other ones on any real glider to a more or less important degree. The latter are mainly induced by the aircraft's aerodynamics, and impressed on the probe pressures. Therefore the following analysis should be taken as a sensitivity analysis rather than as an academic study.

In order to keep length within bounds detailed calculations are not reproduced here, as they are rather simple, and based on the preceding chapters. Rather summary diagrams are considered sufficient, as are drawings by hand.

Figure 4.2. shows the 3 individual errors on the time axis, vertical axis being vertical speed (to be precise one would rather have to talk of specific energy loss rate). One clearly recognizes the double impulses due to the vertical air column. Although they look rather frightening by their height, they are relatively harmless because of opposite polarity and because they follow each other with a breif delay: They are easily rejected by the variometer's response, as can be seen in the next figure. The effect of acceleration is only about one half that of the longitudinal air column and practically parallel to it.

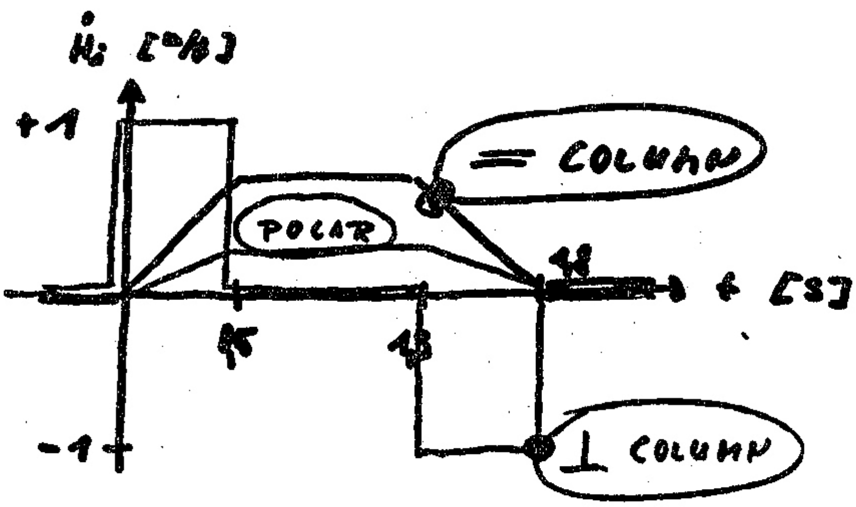

Figure 4.2: Individual effects

Figure 4.3. gives the sum of all 3 effects and the response of the variometer. When integrating the upper part of the curve, one will find a surface of about 1,6 m. This is the corresponding altitude error. One will expect the vario's response to show an equivalent integrated error. This is so: The fast vario will respond with an excursion of about 1 m/s peak, with a pulse length of, say, 2 seconds; the slow one will give a 0,5 m/s peak with about the twofold length.

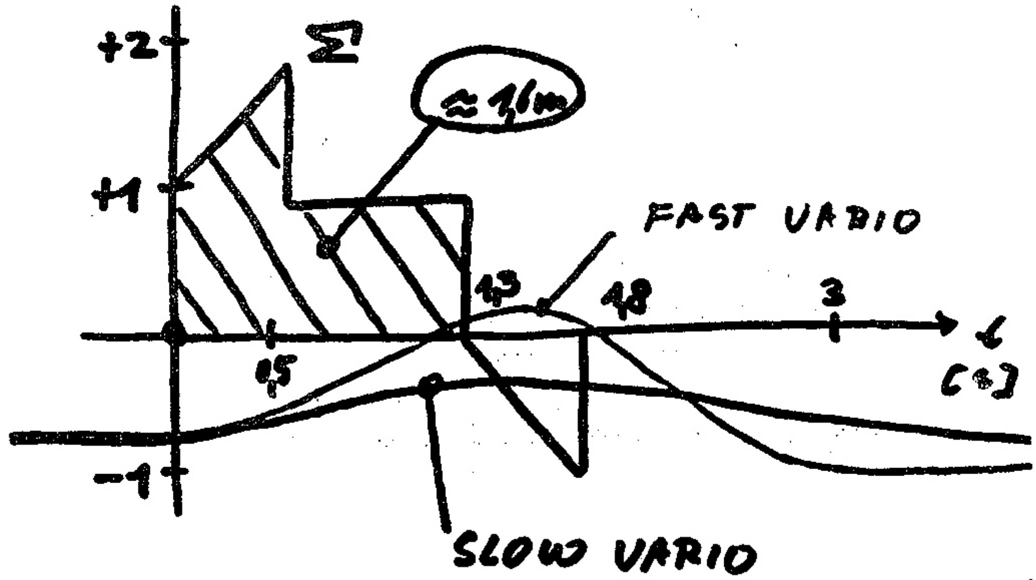

Figure 4.3: Sum of effects

The "erroneous" response of the variometer thus is not negligible in weak wheather, but might be of no importance in strong weather. This conclusion is dangerous, because in strong weather one may indulge in quite stronger manoeuvres, with the consequence of more violent errors in variometry.

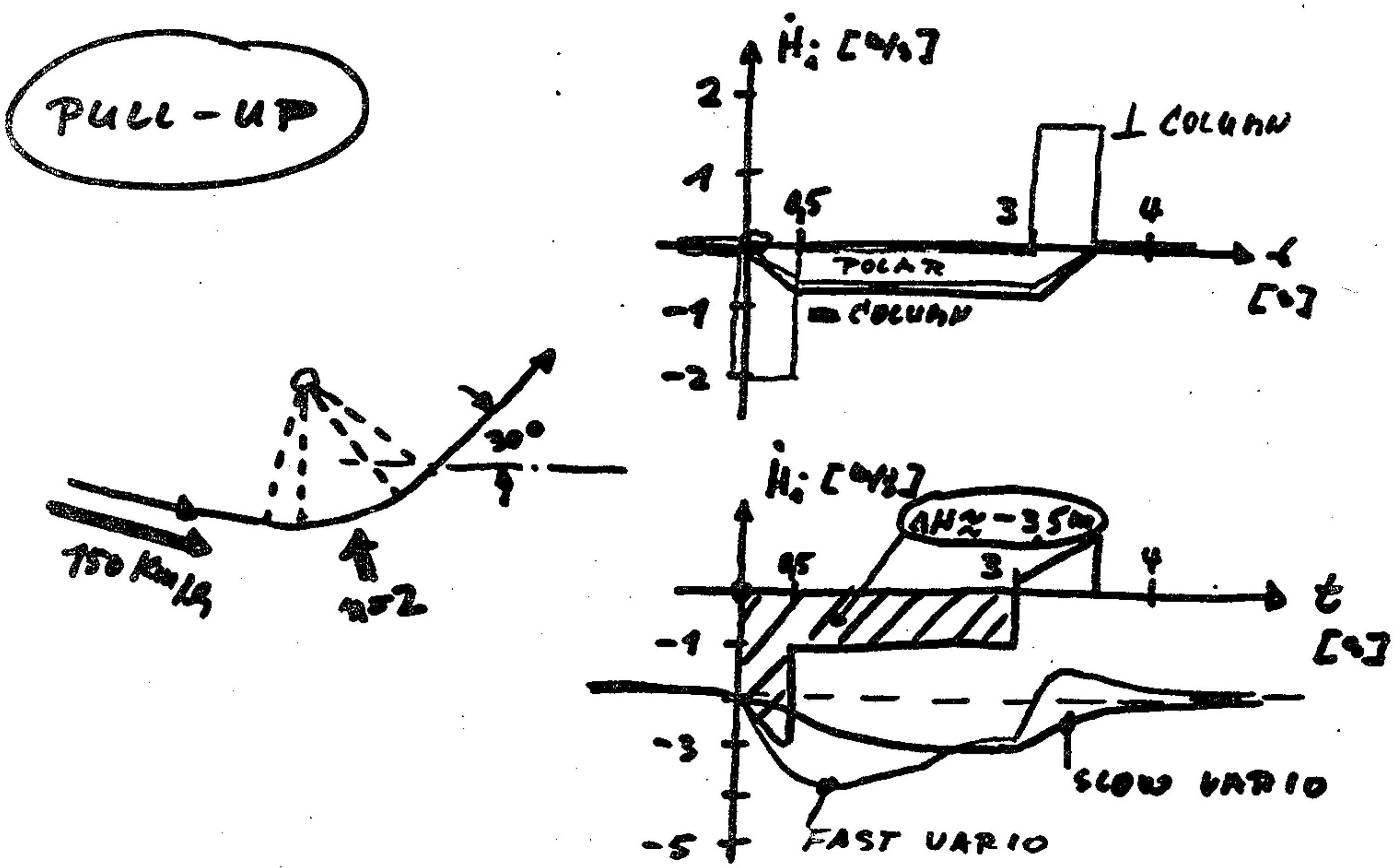

Figure 4.4: Pull-up

The effects can be considered as being of no importance as long as one adapts one's style of piloting one's glider to the meteorologcal conditions: soft wheather requiring soft manoeuvering, rough wheather demanding more violent action on the stick.

If one considers that these nuisances - they can be qualified as such - invariably appear at the very moment where the variometer's output is vital to the pilot, namely when searching for thermals or when adjusting during spiralling, one can easily come to the conclusion that they should be dealt with. However this is more easily said than done.

In order to get more insight into the interrelations of the phenomena, responses have been calculated for the inverse case, a pull-up. Figure 4.4 shows a summary equivalent of figures 4.1 to 4.3 for this case. It is clear that things have changed. Responses are not just inverse to the first case, main difference being that duration is longer, and that this time acceleration and longitudinal air column have practically equal effects (this is due to airspeed, load factor and ascent angle being more important than before). Variometer response is roughly twice as strong as in the push-over and lasts about 50 % longer.

Circumstances are different again in other manoeuvres, like the ascent at constant attitude angle for instance. Here negative and positive pulses are produced at the beginning and at the end of the ascent. The positive pulse corresponds to the response to the pull-up, the negative one to that of the push-over, the end phase is further complicated by the fast change in angle of attack happening when approaching the maximum lift coefficient. The middle phase of the ascent is free of errors of the kind.

To recapitulate essential results:

1) Errors are produced when changing attitude or load factor, in pull-ups or push-overs, e.g.
2) Errors produced can be classified as nuisances.
3) By adapting style of piloting to meteorological conditions, nuisance can be kept within tolerable bounds.
4) Fast variometers will more clearly show the phenomena than slow ones, however ~~at the expense of longer~~ duration.
5) Energy loss or -gain due to normal acceleration is being indicated by the te-variometer. The phenomenon being based on the energy balance of the aircraft itself, it cannot be done away with (energy lost is lost!).
6) The longitudinal aircolumn can be generally classified as being of a greater nuisance than the acceleration effect.

In principle the longitudinal air column effect could be done away with by mounting the pressure probe in or near the center of gravity of the glider. Going even further, one could place it ahead of c.g. to try to compensate the acceleration effect by a "negative" air column one. Although such an arrangement might calm the variometer, there are reasons to reject such a solution: number one, this could only work for a particular set of piloting parameters, for others there would be over-, or undercompensation; number two, the pilot would be lied at over the energy losses he provoked by excessive pulling, and number three the sag would only be delayed (the tube on the back of the fuselage of the Standard Cirrus does effectively that).

Compensation of the acceleration effect could make sense, however, for a netto-, or air-mass-variometer. Compensation or elimination of the air column effect, by contrast would bring an advantage in any case, as one has to deal with a true measurement error here. Yet the task is not easy.

5. ERRORS INDUCED BY AERODYNAMICS OF THE GLIDER

5.1. General considerations

The errors of te-compensation discussed so far (normal acceleration, air-columns) are relatively easy to analyse, reasonably predictable, and easy to understand. They are more or less independant of the type of glider considered. The direct effects of aerodynamics on the probe pressure - serving as input to the variometer - are of a different kind. They are essentially dependant on position of the probe relative to wing, fuselage, and tail, and on the design of the glider. Their action depends on many parameters, as regards design as well as piloting, and they are accessible to analysis to a rather limited degree only. Their importance, as experienced in practice, ranges from hardly measurable, to cases where they can totally invalidate variometry. Identifying the penomenon responsible for such a disturbance is generally difficult, the only scientific method remaining measurement in flight with systematic variation of parameters and variables measured. This method demands considerable effort and know how, it is not suited for general use.

A series of interlaced analyses and flight measurements have been carried out over several years with the aim to identify errors seen in the total energy signal, but so far unidentified, and unexplained.

REMARK:

To be clear about it: not many pilots are sufficiently knowledgeable and observers sharp enough to see that something appears wrong with the variometer. Usually one receives comments of the kind "totally undercompensated" or "totally overcompensated". Sometimes this even concerns the same system. It seems that the total energy system most perfect in the scientific sense is not necessarily the one estimated highest by all pilots. Despite this, the author thought it worth while to try to eliminate all errors at least from his own te-system. Discussions with customers also showed him that there are quite some pilots who do have a feeling for good variometer response, and who do indeed draw profit from a good system.

Under the circumstances given, the only valid method appeared to be an extended sensitivity type of analysis with experimental verification, where possible. Analysis centered around the question which pressures were created by the various elements of a glider at some distance from them. This question so far had not been posed yet, obviously because aerodynamicists designing aircraft are interested more in what happens directly on the surfaces wetted by the airstream rather than at a larger distance, for obvious reasons. Most astonishing was the far reach of the pressure field generated by a wing.

The Joukowski theory to calculate the pressure field around a wing type structure is really old, and on top of that very simple: a pocket computer is sufficient for the purpose. Joukowski theorie, based on a single vortex airfoil seams a reasonable choice for computation of the field at some distance, as the details of vortex distribution along the chord of a real airfoil will not have much influence on the field at larger distances. The more "a la mode" use of large computers and "powerful" models, therefore, is considered of no interest to the questions posed, certainly not in view of their excessive cost.

As Joukowski theorie is well known, calculations carried out are not reproduced here, only results are shown. For details see classic literature on aerodynamics (Schlichting-Truckenbrodt, Abbot-Doenhoff). Where necessary, influence of aspect ratio has been taken into account. For the examples, the author's Standard Cirrus has been taken as the basis.

The experimental program is being dealt with separately in order to keep things clear.

5.2. Pressure field around wing

Pressure coefficients have been calculated for 5 typical positions in the vicinity of a wing with chord C, thickness ratio 0,13, and infinite aspect ratio, as a function of lift coefficient (positions are fixed relative to the airfoil). For a good overview the results are presented in one picture, figure 5.1. Three positions have been chosen to represent points where usually te-probes are mounted (lengths are scaled for Std.Cirrus). Pressure coefficients are given in 1/1 000, it should be noted that scales vary according to magnitude of pressure coefficients.

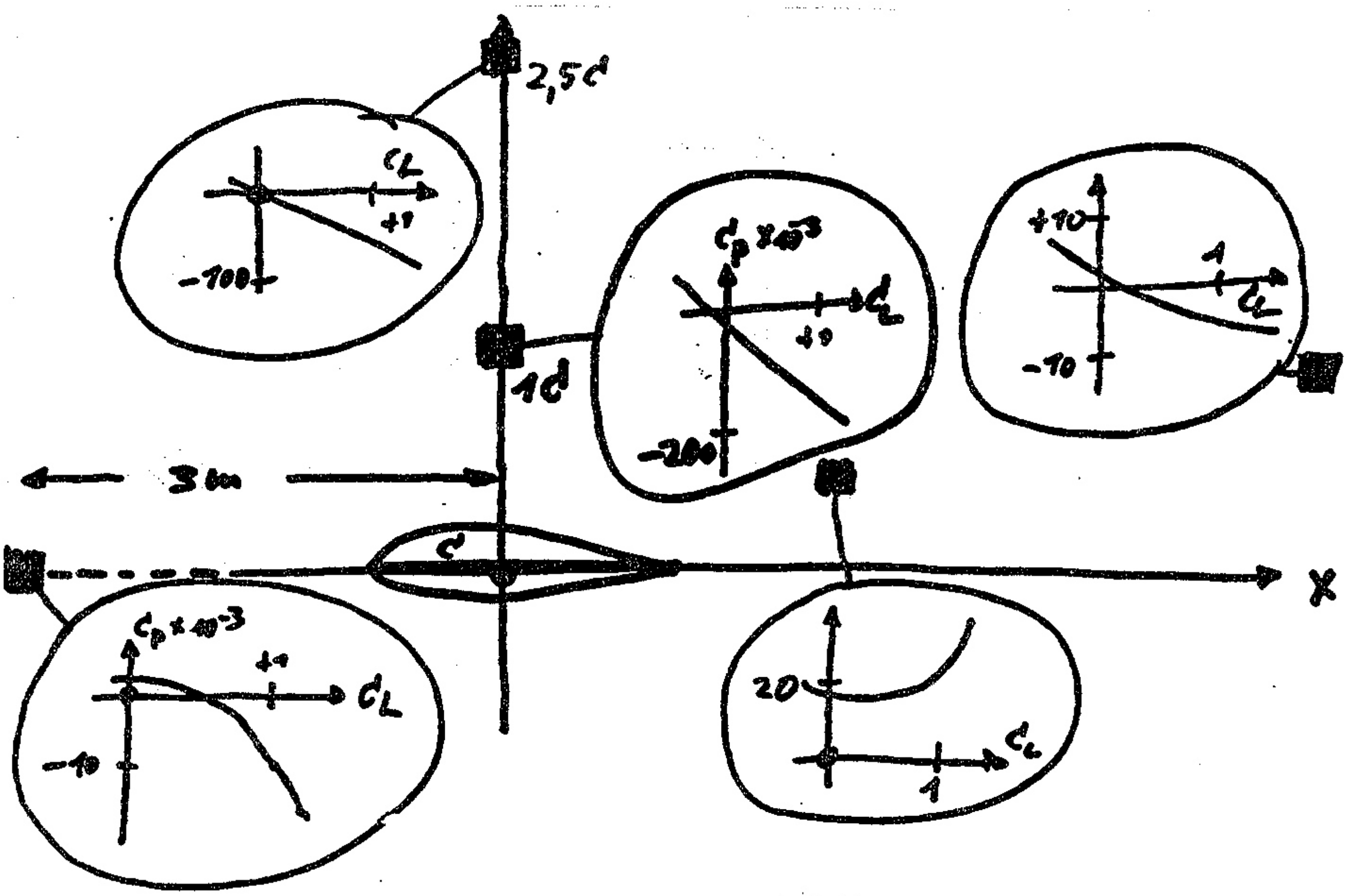

Figure 5.2: Pressure field around wing

~~Looking at points 1, 2 and 3,~~ One will notice that for the pressure coefficient to remain below 1 % one will roughly have to stay at a distance of 2,5 to 3 chord-lengths from the wing (pressure coefficients decrease very roughly like 1/ distance). Even in front of the elevator the wing will still generate a suction of up to 0,5 % of dynamic pressure, increasing the pressure coefficient of a te-tube placed there by 1 % ! (the factor 2 is due to Bernoulli's law).

It becomes clear [redacted], that positons above (or below) the wing are very poor. The pressure coefficient of a te-tube there could change by 20 % easily with changing lift coefficient. In most cases output of the te-variometer could become an indicator of lift coefficient rather than of vertical speed or energy loss rate.

The usual position on the fuselage, between wing and tail is not free of the wing's influence, in particular at high lift coefficients. This situation becomes worse with decreasing distance from the wing's trailing edge.

What should not be forgotten here: interference by the fuselage has not been taken into account.

5.3. Pressures induced by the elevator

As has been done for the case of the wing, things are presented in figure 5.3 for the case of the elevator. For simplicity of analysis the position of the pressure probe has been assumed fixed relative to the elevator. This is not really the case for the Std Cirrus, sporting an all flying tail. The corresponding error, however, seems acceptable. A very detailed analysis for the usual position ahead of the tail fin, a bit below the upper position shown in the figure, included stability calculation to determine the elevator lift coefficient as a function of air speed in stationary flight, for the Standard Cirrus. It showed a variation in static pressure coefficient of about 5/1 000 over the speed range. This compares to - 5/1 000 induced by the wing at the same position.

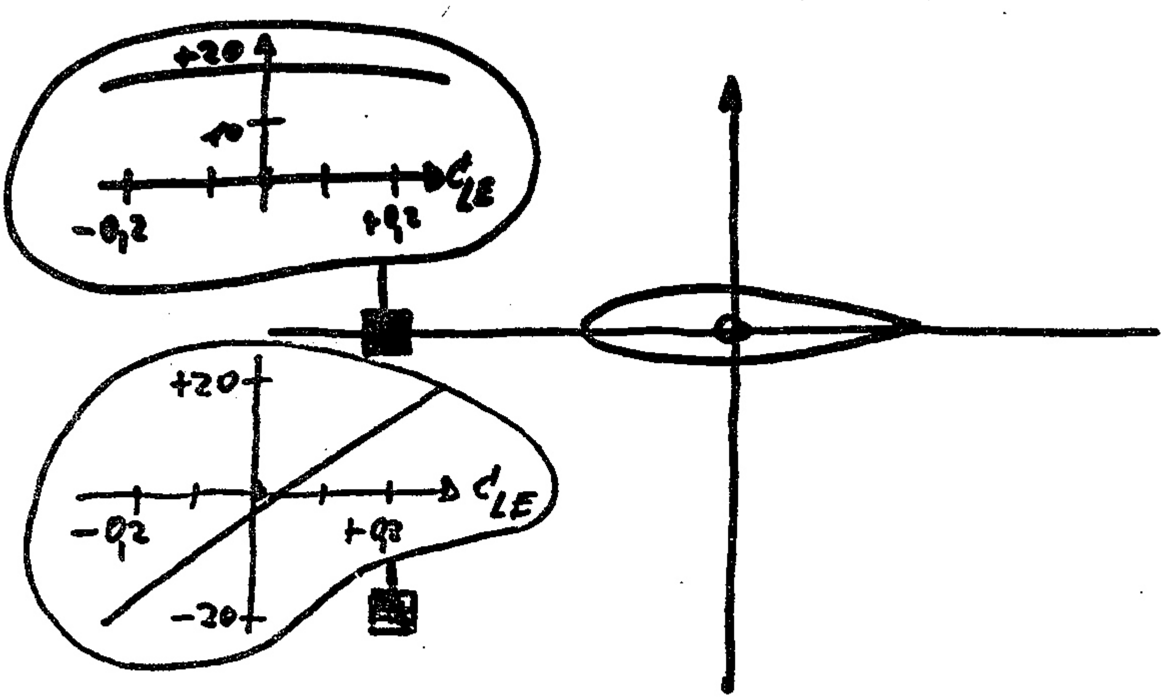

Figure 5.3: Pressure in front of elevator.

It should be added here, that lift coefficient of the elevator remains quite small over the useful speed range, for the case investigated about +/- 0,2. This makes also for a small variation in angle of attack of only about +/- 2 degrees, despite the much larger elevator control input.

When comparing the 2 positions shown, it strikes to see the difference between them: the upper one is plaqued by an overpressure of 2 %, however rather constant, whereas the lower one suffers a variation by 4 % over the useful speed-, or lift coefficient range. In the case of the upper one the evil could be corrected by mounting a te- probe with a pressure coefficient of - 1.04 rather than one with - 1.00, because the static pressure coefficient induced is practically constant. In the lower case correction does not make sense, as the static pressure coefficient varies by 4 % giving a variation in te-pressure of 8 %. This position is indeed one of the worst, giving considerable te-vario response to loadfactor and elevator control input. Obviously the position right ahead of the elevator is best, because induced pressure is at a maximum there and variation is smallest due to exactly that.

There is another snag here: Measurements showed that error pressures induced by the elevator depend very strongly on design of the horizontal tail: damped elevators deliver much larger pressure errors than all flying tails, the ratio is very roughly 5! As this is for positions ahead, this suggests that deflecting the control-fin does not much change the pressure distribution for the fixed part of the airfoil caused by an increasing angle of attack. In fact, a damped elevator experiences a much greater range in angle of attack than an all flying tail. It is equal to the range of angle of attack of the wing minus the correction for downwash, say, +/- 5 degrees.

5.4 Interference by the vertical fin

The situation for a probe in front of the tail fin is comparable to that right in front of the elevator (see fig. 5.3), input parameter here being angle of slip. There is an overpressure of 1 to 2 % depending on distance from the leading edge, in the case of a T-tail. It is less where the elevator is low on the fuselage, due to the effective aspect ratio being increased by the elevator in the T-configuration.

The effect is generally harmless, as a probe mounted there is on the line of symmetry of the airfoil, and there is little variation in the pressure coefficient, even with the vertical control fin being deflected. The effect can be compensated by adapting the pressure coefficient of the te-tube, or the gain of the static pressure channel in the case of an elctronically compensated vario.

Quite generally the vertical fin is of no concern as regards pressure errors.

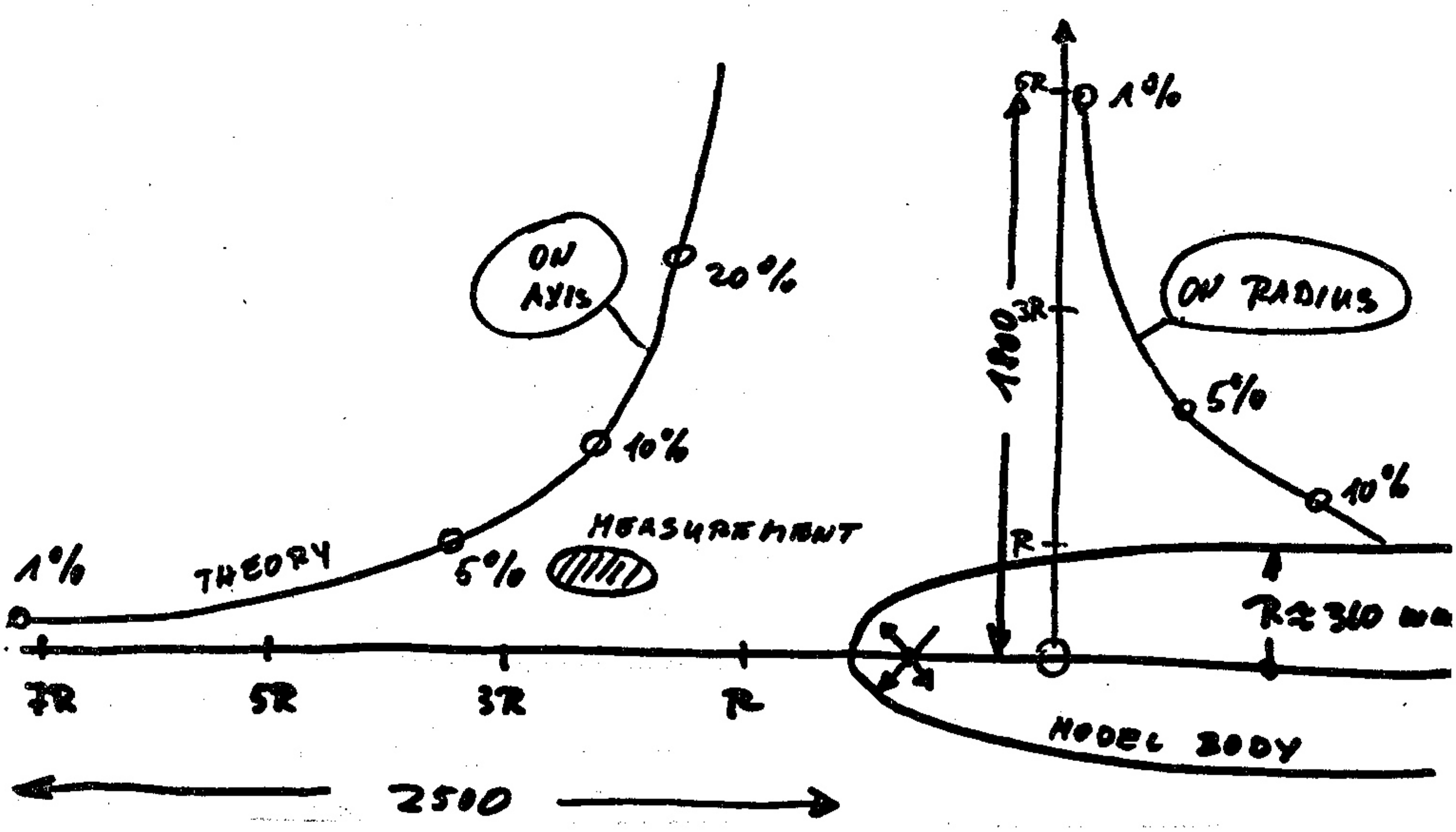

Figure 5.5.1: Pressure around half-body

5.4. Interference by the fuselage

The problem of pressures in the vicinity of the fuselage is a very intricate one due to the generally rather arbitrary shape not to be described by simple mathematical expessions. On top of that fuselages vary rather strongly from one type to the other. Fortunately, a rather classical solution to a round body with elliptically shaped nose and infinite length was found in the litterature (Schlichting - Truckenbrodt). The nose looks very much like the front part of a glider's fuselage. Combining the thing suitably with its own mirror image, a very rough analog of the front part of a fuselage can be assembled. Using the exact theory, the field of the pressure coefficient was calculated for a half-body having the average diameter of the fuselage at its thickest station. Results are presented in Figure 5.5.

The interesting thing again is the astoninishingly far reach of the pressures produced, both ahead and laterally. Real pressures will be smaller, by say, a factor of 2, as cross section of the fuselage is decreasing again further downstream. This was confirmed by a measurement taken in flight about 0.7 m ahead of the fuselage's nose of the Std Cirrus. It is marked also in Fig.5.5.1.

The combined model, more realistic overall, produces a field of the shape shown in Figure 5.5.2. Quantitative data is not given here, except for the position of the probe on the tail fin: there is an overpressure of 0,4 %, and thus of the same order as the disturbance produced by the wing. The reasoning shows nevertheless that one will have to reckon with very heavy disturbances along the fuselage, particularly in the regions of strong gradient in cross section. There are more elaborate calculations, on ellipsoids. Nevertheless the real problem is still not being solved thereby, as also these bodies are no good approximations of a real fuselage.

It is to be expected that the disturbances created by the fuselage are further aggravated by changes in angle of attack and by slip.

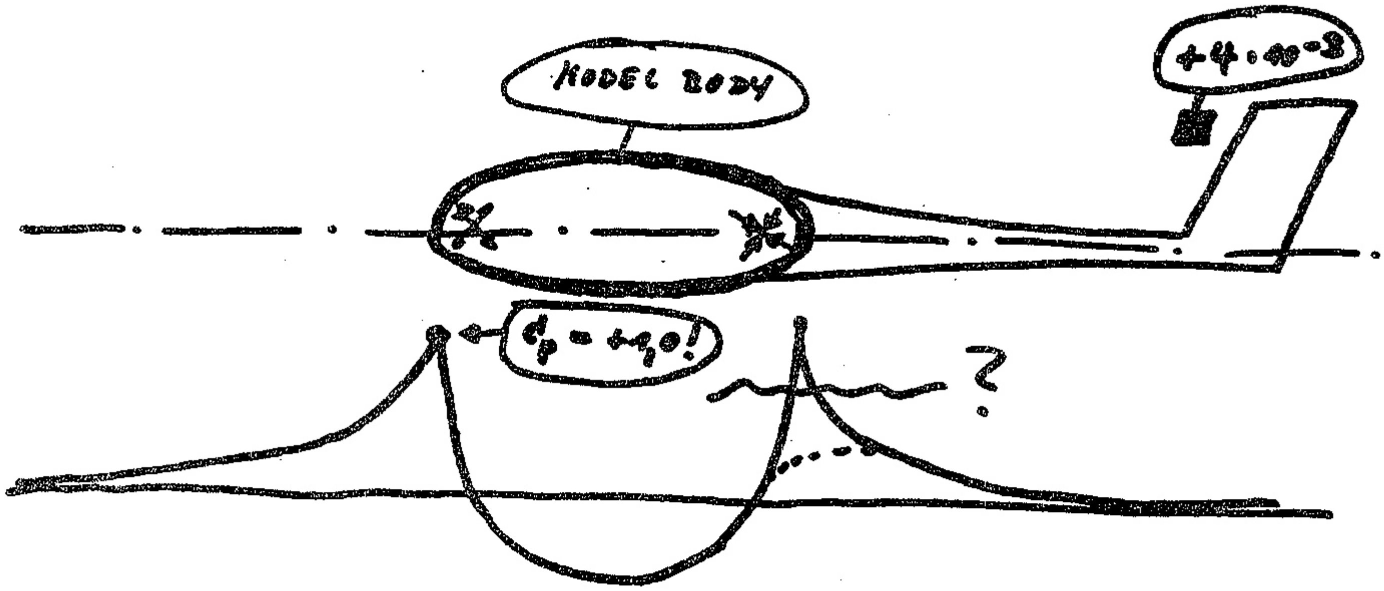

Figure 5.5.2: Pressure generated by fuselage.

Fortunately an exact solution would be of not much interest either, as there remains still the beautiful problem of mutual interference between wing and fuselage. The teachings of the coarse analysis are good enough for the purpose: One must stay away from the fuselage with any pressure probe whatsoever!

5.6. The effects of slip

a) Fuselage

Considerations in the preceding chapter left aside the question of changes in angle of attack and their influence on the pressure field of the fuselage. This question appears too intricate for the kind of study conducted here. However there is still the angle of sideslip which has an influence.

REMARK:

Side slip is not only voluntary, there is a large amount of slip induced by horizontal turbulence, particularly when thermalling: a horizontal gust of 5 m/s - which must appear in a 5 m/s thermal - will induce a momentary slip of roughly 12 degrees! It will take the pilot some time to eliminate it, and so long slip is there and may disturb variometry. Much slip is induced when pulling into a thermal at high speed for instance, certainly with some types of gliders.

On the fuselage there are 2 effects of sideslip on probes: 1) the angle of sideslip is considerably amplified, factors of 3 seem to be normal. 2) above and below the fuselage underpressures are created, on the luff side there is an overpressure and on the lee side there is suction. Unfortunately pressures on both sides of the fuselage are not equal and of opposite sign, such that they could be averaged out.

Variometry errors are caused by both, by the pressures induced by the glider, and by probes being attacked under a large angle (reaching 30 degrees easily).

As good te-probes can be very insensitive to slip, the latter problem can be coped with. The problem of the induced pressures is of a different kind. They are - amongst others - responsible for the often poor performance of compensation systems using both static and total pressures for electrical or mechanical compensation.

In measurements of static probes in a laminar wind tunnel the amplification of angle of slip on a cylindrical body could be confirmed roughly. Scaling up these measurements does however not appear to be a solution permitted: flow was very laminar in this case due to an extremely small Reynolds number. Flow around a fuselage will be characterised by a Reynolds number orders of magnitude larger, turbulence will dominate the flow here. When looking at classical solutions for flow across a cylinder, it seems justified to assume that matters are worse here, rather than better.

The measurements at low Reynolds number showed that for oblique attack of a cylinder the pressure field could be calculated rather realistically by assuming purely lateral flow with the lateral component of the flow velocity at infinite distance as the - infinite - velocity of the cross flow (in other words to neglect the longitudinal component completely).

Assuming that this holds also for the turbulent case, one can compute the pressures generated by slip on a round fuselage, by applying well known theory. The result of this reasoning is shown in figure 5.6 for the most interesting case of a tube on the back of the fuselage. Angle of slip is 15 degrees. It appears that one has an interest in staying away from the fuselage, once more. Estimation of the effect on a te-tube 300 mm high, in the usual position on the Std Cirrus, reveals an error in variometry of about 2.5 m by a 15 degree slip! (at an airspeed of 80 km/h).

As the pressure error is negative with slip, a tube having a slip error of its own of the same sign, can play havock with the pilot under the circumstances! (its effective slip angle might be, say, twice 15 degrees!).

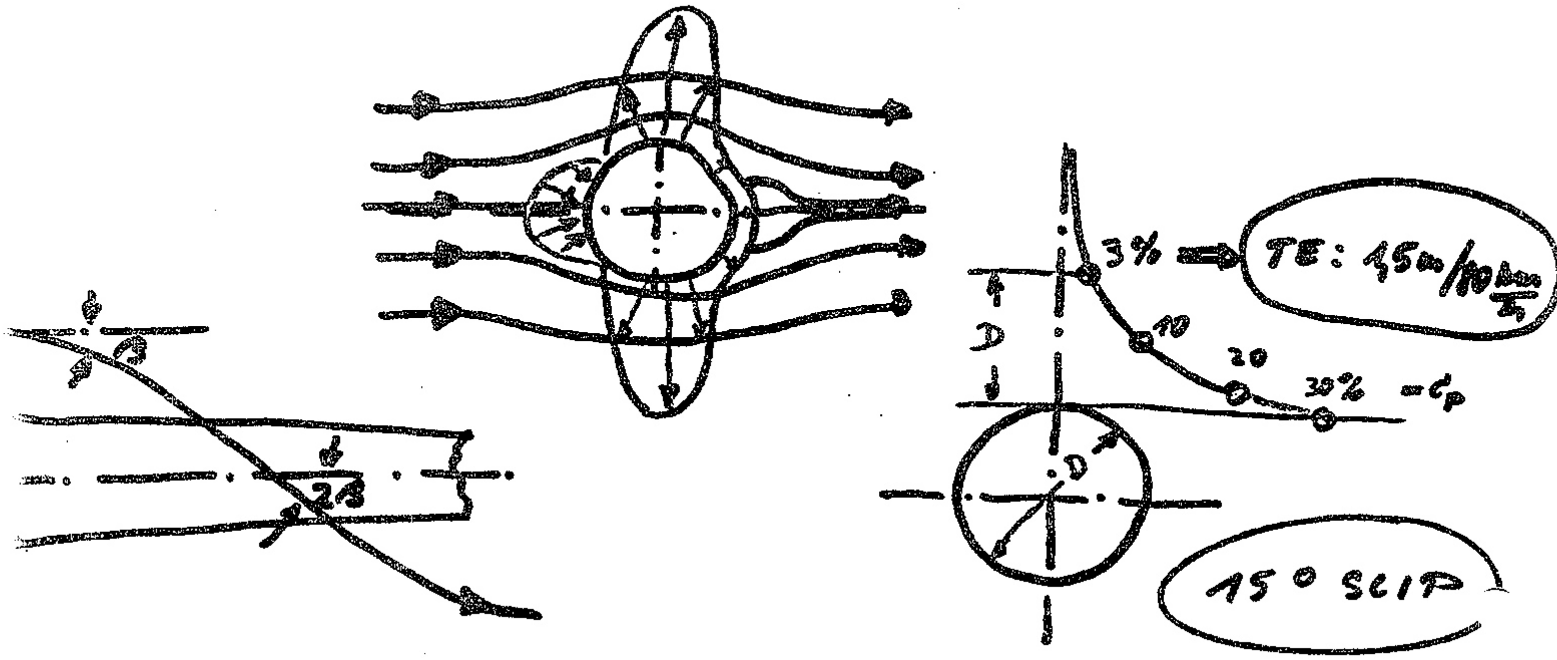

Figure 5.6.1: Pressure generated on fuselage by slip.

As regards the errors due to slip on eventual static holes on the fuselage, the author refrains from any quantitative statement. They can only be measured in flight, which is not an easy task. The problem, however is real.

b) Tail fin

Looking at the flow pattern ahead of an airfoil being attacked under some angle of incidence, one will notice that the streamlines are increasingly curved, the nearer one comes to the leading edge. The local angle of incidence increases with decreasing distance from the airfoil. The phenomenon is quite well known under the name of upwash, for the wing. Now, the same thing happens in the case of the tail when slipping. Measuring, as is usual, the angle of slip at "infinite" distance, the local angle of incidence is larger than the slip angle, how much, this depends on the position looked at.

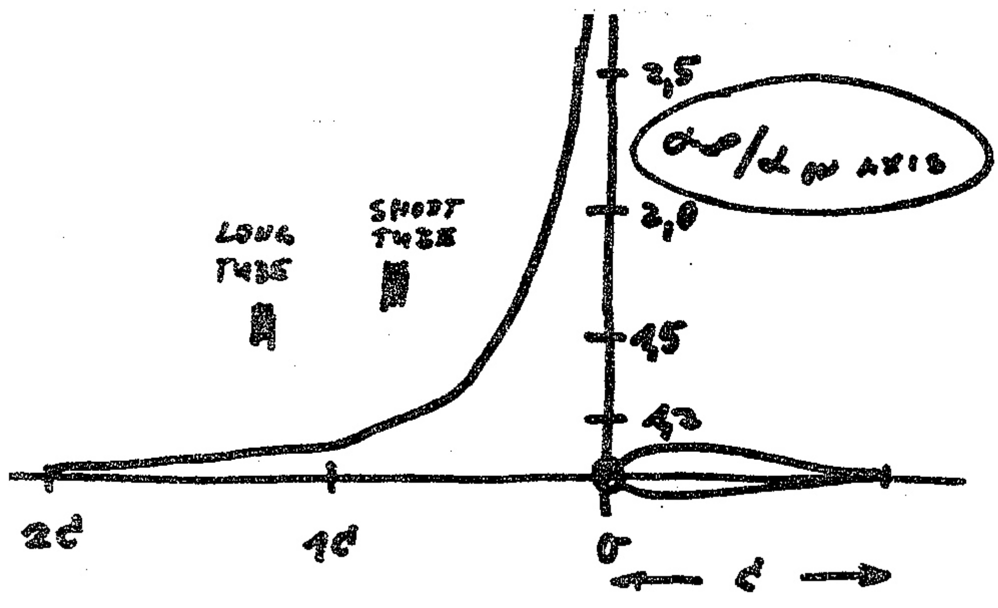

Figure 5.6.2: Vertical fin and slip

Cases interesting can be limited to those on the axis of the (symmetrical) airfoil and ahead of it, the usual position for probes. The analysis starts again with Joukowski theory. To the angles found, those generated by the free vortices induced by the vertical fin must be added. Fortunately aspect ratio is rather small for the vertical fin, reducing considerably amplification of the local angle of incidence due to the airfoil alone. Nevertheless the amplification factor is terrible for short distances from the leading edge, as is shown by fig. 5.6.2 for an angle of slip of 15 degrees.

Looking at figure 5.6.2 one realises easily that probe lengths of less than about 50 cm are no good choices. It will pay to go farther away. What must not be forgotten either: the elevator is also there, and what holds for vertical fin and slip is also true for horizontal fin and its angle of attack (see chapter 5.3). This adds to the advantage of the larger distance.

5.7. Turbulent wake of the wing.

There is much talk amongst glider pilots about vortices or the like being created on the fuselage or the wing and impinging on te-tubes, causing errors in variometry. The sum of the author's experience is that in reality there is very little of the sort. There is, certainly a turbulent wake behind the wing. This wake in the shape of a rather sharply defined sheet extends downstream, it may be coming upwards further downstream, but not very much, and only at very high lift coefficients. In many flight measurements it could be found only on one occasion: On a Ventus it would come up to about midway on the keel fin just before stall at 65 km/h. Advancing the probe by 20 cm would make the wake undetectable, suggesting that 1) it is very sharply defined, and 2) that it will not come up very high. Detection of it was most probably just due to the airfoil of the Ventus' wing allowing very large angles of attack before stall arrives definitely.

If a probe enters the wake, consequences are rather devastating due to ~~the~~ the air in the wake having lost much energy, or speed. As a reasonably reliable prediction of the wake's position is not possible so far, certainly also due to it being deformed by the influence of the fuselage, one should avoid positions below a line connecting the wing with the point halfway up on the keel fin, just as a safety measure. In positions up on the keel fin one will be practically safe against this trouble, at least on modern high performance gliders.

6. THE FLIGHT MEASUREMENT PROGRAM

6.1. General Considerations

Flight measurements were considered necessary to validate or invalidate theoretical analyses on the one hand, and to identify possible sources of errors not yet explained on the other hand. So far only states without slip have been investigated, as measurement of slip angle is not a straightforward task.

The fundamental problem was to find a spot somewhere near the aircraft where static and dynamic pressures were undisturbed. A reference probe was to be positioned there. Against the pressure it would deliver, all other pressures would be compared with the help of a differential pressure transducer. Absolute measurements are impossible in view of the extremelly small errors to be detected (resolution required is of the order of 10 cm of air column or 1 Pascal). Using suitable probes, reference pressure taken could be static, total, or te-pressure.

By analysis of the flow around the wing using Joukowski theory a position ahead of the wing was calculated where the pressure coefficient remains below 0.5 % for all useful lift coefficients. Its geometry is shown in fig.6.1.1. Distance from the fuselage has to be at least 2.5 m.

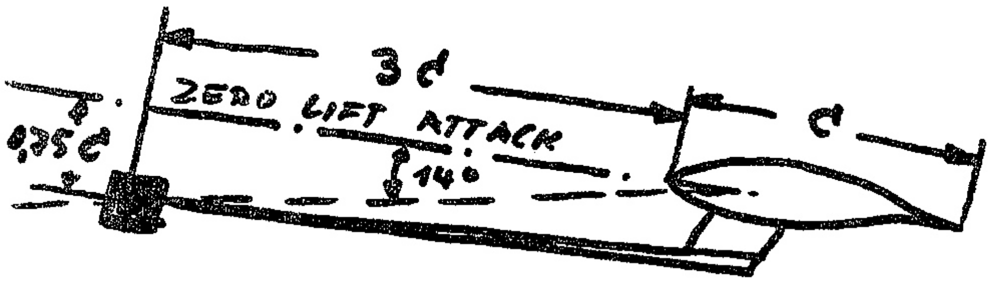

Figure 6.1.1: Reference position

A sting was fixed to the wing of the Std Cirrus, which carried the reference tubes. Output of a Prandtl type static tube was compared to static pressure delivered by the DFVLR static bomb in flight. Figure 6.1.2 shows the expected pressure coefficient as a function of dynamic pressure together with the bomb's pressure. Correcting for the error of the Prandtl tube due to angle of attack, one finds a rather constant residual difference of roughly ~~2~~ 0.5 %, value ~~equal to~~ calibration uncertainty of the bomb. For the purpose of this study the position was considered good.

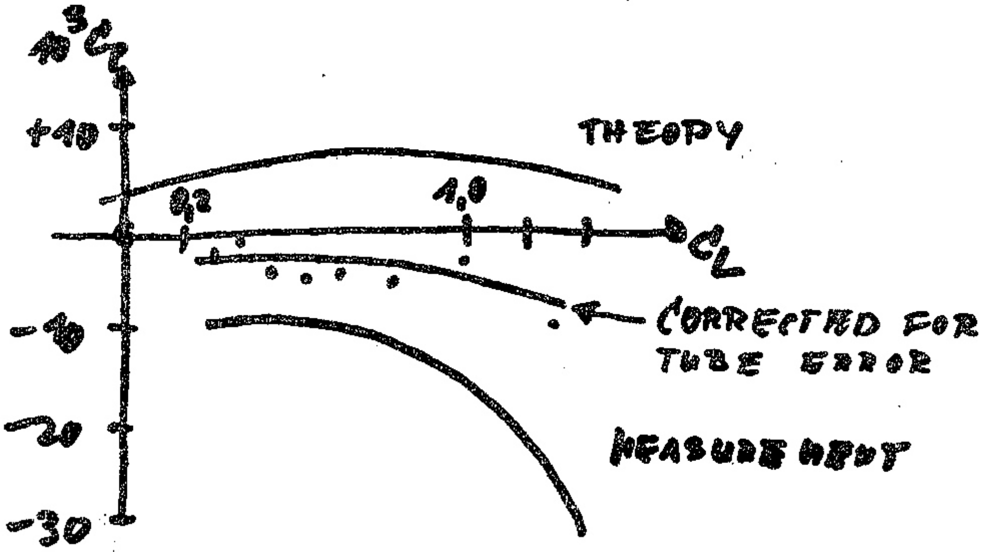

Figure 6.1.2: Reference pressure

Main advantage of the sting against the bomb is operational: any manoeuvre can be flown with it, wheras with the bomb one has to strictly maintain constant speed. The only problem encountered was proper matching of sting and wing bending frequencies to avoid excessive vibration of the sting when rolling on the ground during take off and landing.

It should not be forgotten that the sting is about 2m long. The contraption therefore is not a recommendable thing for day to day flying, as sooner or late one will stumble over it and damage it lethally.

A te-tube on it will give the best te-compensation there is, however with an error due to turning: As soon as the angular velocity around the vertical axis of the aircraft changes, which happens each time when turning in or out of a spiral e.g., there is a rather well defined and predictable excursion of the vario needle. One will get accustomed to this error very quickly and will mentally eliminate it. During manoeuvres with normal acceleration only (no turning involved), in a pull up e.g., this system will enable the pilot to follow evolution of a thermal during the accelerated phase without error. And this is quite something.

One might conclude that the same thing can be achieved by mounting the tube ahead of the fuselage. This is true, yet at the expense of mounting it on a sting as long as the one on the wing (see chapter 5.5.). Experience shows that this would be even more awkward in practice. One would almost invariable bury the probe in the ground during takeoff.

Other instrumentation used was a rather large set of probes containing pairs of static tubes, total pressure tubes, te-tubes of various design and various pressure coefficients ranging from 0.9 to 1.1, plus extender tubes and mechanisms to displace tubes up or down. The differential pressure gage used was a modified ILEC variometer with a capillary in series to the flow transducer, having calibrated ranges of +/- 50; 100; and 250 Pascal differential pressure. Other rather important instruments were a spirit level to align probes and an artificial horizon to determine attitude angle in flight and during alignment on the ground.

Nothing of the more a la mode electronic data logging equipment was used, the ancient pencil and paper method being considered orders of magnitude cheaper and faster at the end: all measurement data was written down on a knee-pad and analysed using a pocket computer, in an effort to be up to modern times.

6.2. Pressure ahead of fuselage

For this measurement the sting carried a Prantdl type static tube of 6 mm diameter, nose of the fuselage of the Standard Cirrus carried an identical tube of length 700 mm. Difference of the pressures was measured over the useful speed range. (static pressure for the air speed indicator was cabin pressure, which was found to be much more precise than the usual pressure taken on the fuselage under the wing).

Figure 6.2 shows the pressure coefficients found as a function of lift coefficient. The roughly 5 % overpressure predicted is verified, seen the difficulty of defining position on the longitudinal axis of the model used. One also sees that there is a variation of roughly 2 % which does not seem to be very smooth in reality, indicating that there will be some trouble hidden in the signal of a te-probe placed there, certainly when considering that its pressure coefficient would be falsified by twice the static pressure error (due to Bernoulli's law).

This position is not a good one for a probe.

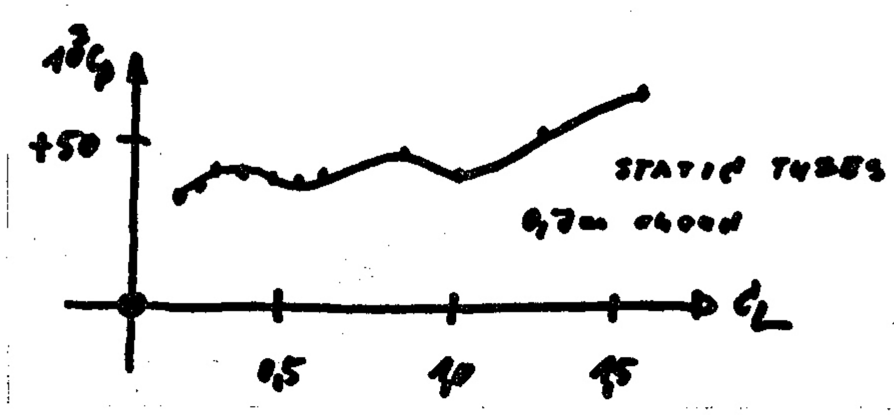

Figure 6.2: Pressure ahead of fuselage.

6.3. Back of the fuselage

Here the sting carried a te-probe with a coefficient of - 1.00, creating a perfect te-pressure. On the back of the fuselage, about 20 cm behind the trailing edge of the wing (position foreseen by the manufacturer) a te-probe with length (height) 300 mm was mounted. Its pressure coefficient was - 0,9 to compensate for a rather large offset there. The pressure coefficient measured is shown in figure 6.3 as a function of lift coefficient. One clearly sees the influence of the wing: underpressure created is about 0.15 divided by 2, say 7 % at high lift coefficient, and about 2 % at low lift coefficient.

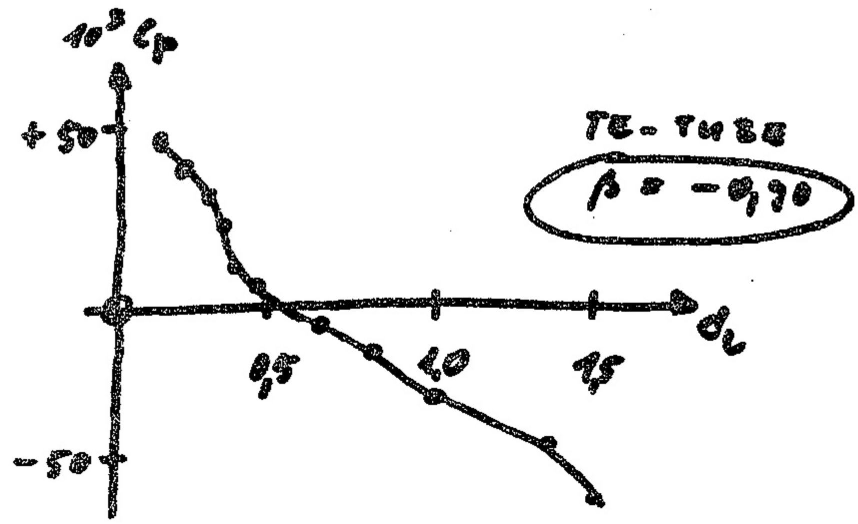

Figure 6.3: T-e pressure on the back of the fuselage

This type of dependance makes that in a pull-up the acceleration-, and longitudinal-column-effect is cancelled to a degree. This can make for a very nice response of the te-vario, for small amounts of normal acceleration. The penalty will be paid in full when pulling into a thermal at some stronger acceleration: as long as one pulls the thermal appears stronger on the vario than it really is, and as soon as one releases on the stick the lift seen earlier converts into a terrible sag. Thinking that it was just a gust and nothing else, the pilot quits a potentially reasonable lift.

The author himself was cheated several times this way before his suspicion got aroused and he did the measurement which revealed the rather hideous nature of this probe.

This is not a good position. However, when used with caution it can do.

6.4. The wake of the wing

As a start, total pressure measurements were carried out on nearly all positions to verify the sound nature of flow in the point being looked at. Whenever turbulence or friction was to play a role, an energy loss of the streaming air would have to be entailed. Potential theory with its agreable consequences would be at a loss in this case. Energy loss itself was to be detected by a loss in total pressure. In all cases but one potential flow was present under all measured circumstances. Total pressures would agree to within a few Pascal, the precision of the differential pressure meter used. (Adding to this incredible precision is certainly also the fact that total pressure probes are very accurate, and insensitive to oblique attack).

Figure 6.4 shows the singular case encountered when measuring the conditions on the tail of the Ventus. The total probe used was 670 mm long and plugged into the base originally provided at 290 mm below the axis of the elevator fixed fin. Pressures were absolutely equal down to an airspeed of 70 km/h, below this speed a very sharp loss in total pressure at the tail took place as depicted in the figure. It is also clear that stall was not yet reached then. In another flight length of the probe was increased by 200 mm. The phenomenon completely disappeared. This suggests that the vortex sheet shed has a very sharply defined upper boundary, and that it furthermore does not come up higher than to a certain mark, even in progressively deeper stall.

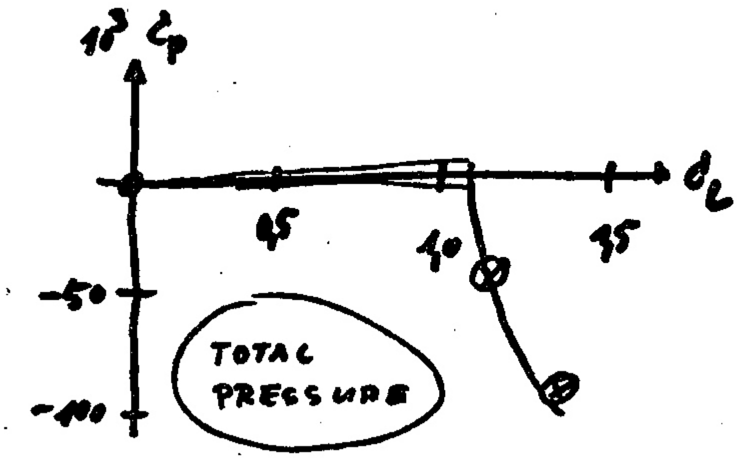

Figure 6.4: Wake of the wing

Analysis done suggestes the pressure loss, a te-tube at the position would produce, to be some 15 % of dynamic pressure. Needless to say that a vario connected to it would give nonsensical readings. As the state would certainly be reached at least sometimes during spiralling at low speed, this position is to be avoided under all circumstances. It is very poor also in other respects, so nothing is lost.

6.5. Positons on the tail fin

Having seen that more or less all operational positions except the one on the tail fin are poor choices, measurements were concentrated on this position.

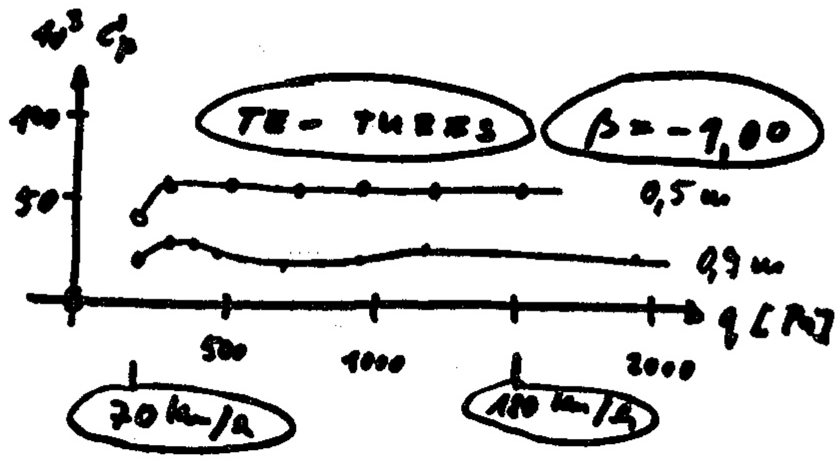

Figure 6.5.1: TE-pressure in front of elevator, Standard Cirrus

Figure 6.5.1 shows results of a test with te-probes of coefficient - 1,00 on both sting and tail of the Standard Cirrus. Pressure coefficients are given as a function of dynamic pressure. In this rather coarse scale the pressure coefficients look pretty constant. As expected, increasing length of the probe would reduce the error considerably. Influence of the elevator is rather small, as it is of the all flying type.

Figure 6.5.2 shows the result of an effort to do away with the constant error by increasing the tube's coefficient by 6 %, this with the short tube length. As one can see, the result is not bad (see the scale!), particularly at low speed, where the errors are smaller than detectable by the differential pressure meter. There is some error left at high speed, it can be reduced by increasing length of the tube (not shown here).

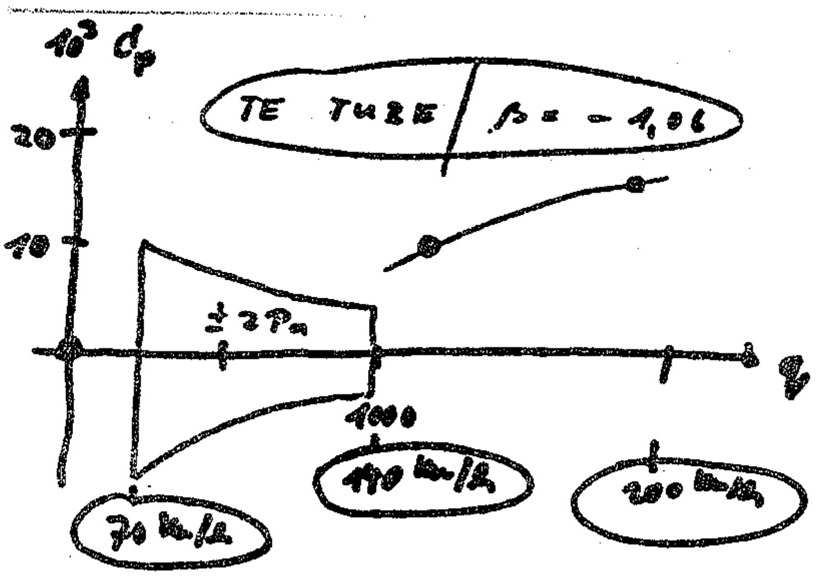

Figure 6.5.2: Te-tube adapted to tail fin, Standard Cirrus

Figure 6.5.3 shows static pressure at the same location. One sees that it is certainly not constant. Remembering some of the values predicted by analysis:

contribution of	verical fin:	+ 2 %
	horizontal fin:	+ 1 %
	fuselage:	+ 0,4 %
	wing:	- 0,5 %
	sum say	3 %

one will admit that all cannot be wrong. It also interesting to note, that the te-pressure error is about twice the static error (there might be a very small error of the two static tubes involved: the angle of attack of the aft one being smaller than that of the front one, due to downwash of the wing).

Similar measurements on the Ventus show completely different results. This is due to the horizontal fin having a fixed front fin (see chapter 5.3.), and the wing having speed flaps. Their actuation changes moment of the wing and by this lift coefficient of the elevator. Another problem, cured in the meantime, was position of the probe being too far below the elevator.

Figure 6.5.4 shows te-pressure in the low position on the fin, using a tube of normal 470 mm length, and having a pressure coefficient of - 1,06 to compensate for pressure offset. Flap setting was 0 for the entire measurement to keep things simple. In the most used speed range variation of pressure is 4 %, the corrective offset of 6 % is good. Although the gradient is relatively strong

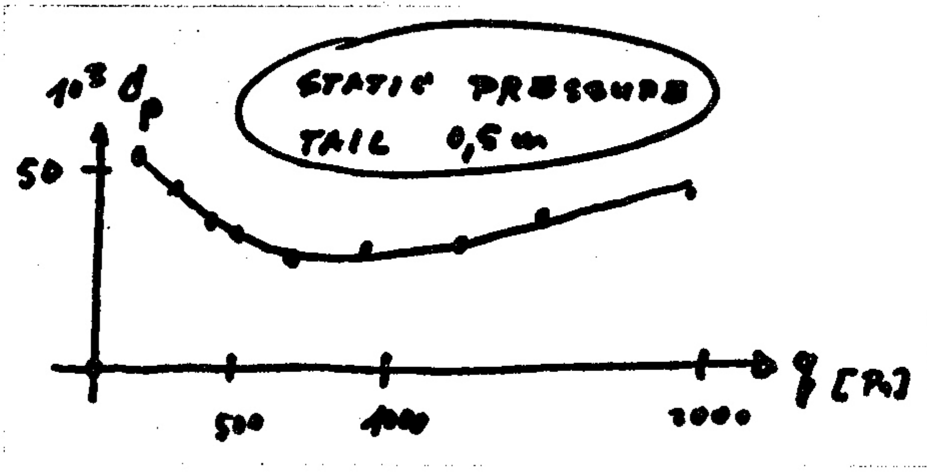

Figure 6.5.3: Static pressure ahead of tail fin, Standard Cirrus

the error could most probably be tolerated in cases where the wing lift coefficient does not vary rapidly, meaning in soft flying. A harder style of piloting will produce disturbing vario errors. Reason for the problem is pressure created by the elevator (increasing wing lift coefficient causes increasing lift coefficient of elevator, this again increases local static overpressure below the elevator, at the probe. On top of that speed decreases relatively at the probe, decreasing its suction).

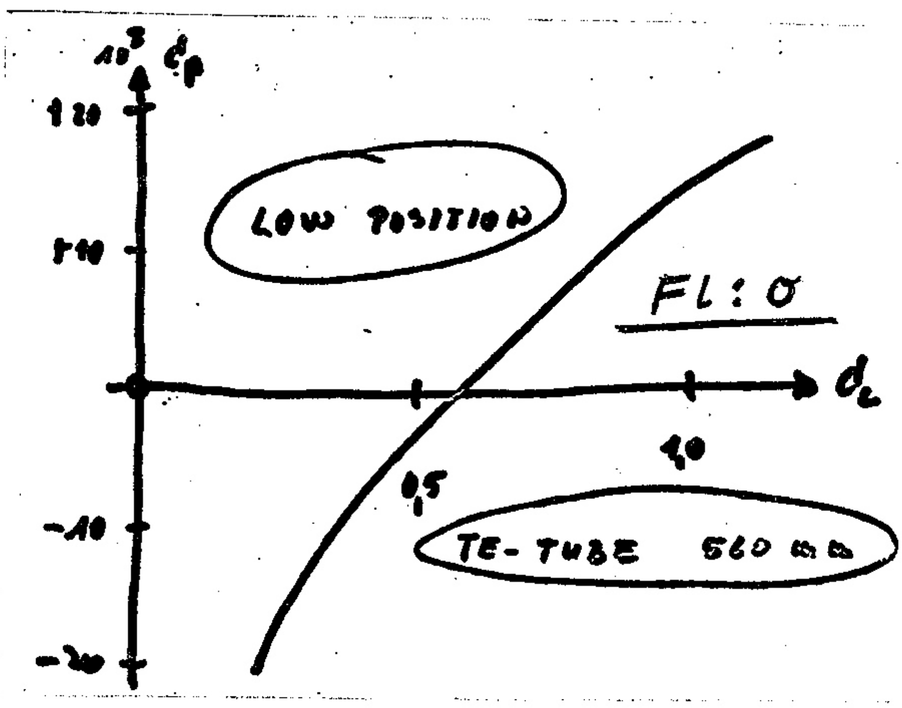

Figure 6.5.4: Te-probe on tail fin of Ventus, flaps fixed

Result of the effort to improve things is given in the next figure. It shows static pressure of a probe extended to 1020 mm ahead of te elevator and 90 mm below it (the te-tube above was 560 mm ahead of the elevator and 290 mm below). This time the horizontal axis is dynamic pressure rather than wing lift coefficient.

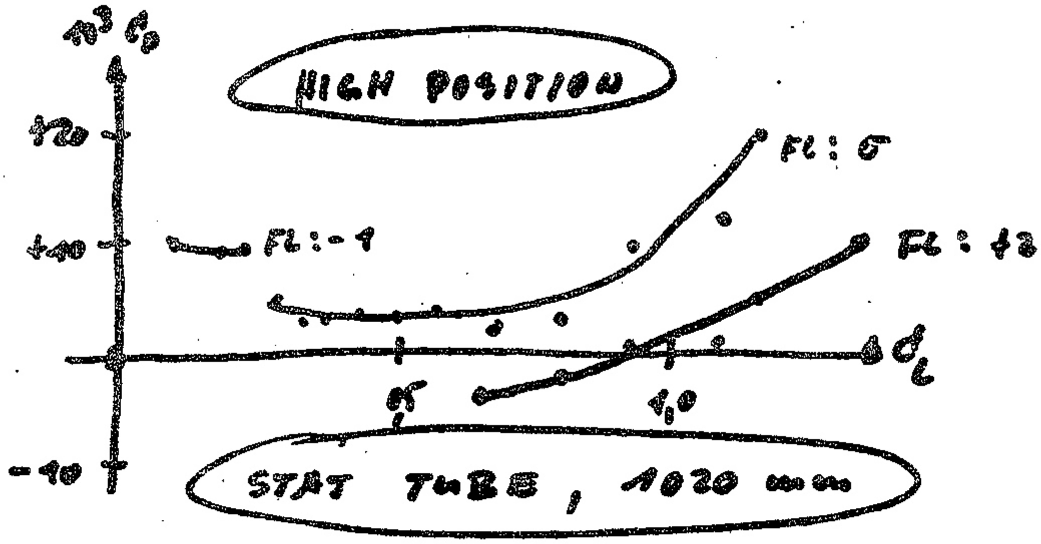

Figure 6.5.5: Static pressure, best position ahead of fin, Ventus

Things have considerably improved, praticularly when setting the flaps as it should. The mechanism by which the flaps act on the static pressure at the tail can be explained 2 ways: 1) by action of wing-moment and lift coefficient of the elevator, and 2) by direct change of the static pressure field created by the wing at the location of the probe. Resolution of this question would require more experimentation.

Teachings which can be drawn from this:

1) Fixed fin elevators create larger pressures around them than all flying ones.
2) Probes should be positioned such that their measuring head is as near to the plane of symmetry of the elevator fin as possible.
3) Probes must not be too near to the elevator (500 mm for a damped elevator is rather short).
4) Optimum distance will be different for different planes.
5) It pays to set flaps correctly, also for good te-compensation.

6.6. Verification of the Air-Column Effect

At the beginning of the investigation the author had not yet found the rather simple explanation of the air-column effect given earlier in this paper, whereby the value measured is vertical speed of the probe, not the one of the variometer, or centre of gravity. He thought, then, that the effect could be done away with by measuring at the probe itself and then transmitting the signal to the cockpit electrically, avoiding the action of acceleration on the column. Accordingly a vario transducer unit was built into the foot of the probe and tested in flight. For comparison, the pneumatic output of the very same probe was conducted to a variometer using an identical transducer, but situated in the cockpit.

The flight test was a dismal failure. The 2 outputs could not be made to differ except in a vigorous turn type of figure with extrem pulling, where a difference of some 20 cm/s could be seen (fast variometer response was used, with a time constant of 0,7 seconds, second order filter). However the positive result of a negative test was demonstration that, a) the vertical column is of no importance in normal flight, and b) that indeed vertical speed at the probe is being measured.

In another experiment effect of the air-column can be beautifully demonstrated. This is with total pressure probes both on the sting and the tail. As both tubes are in absolutely clean potential flow their outputs are absolutely identical as long as the aircraft is in stationary flight. The differential pressure meter between them reads strictly zero, meaning less than +/- 2 Pascal or +/- 20 cm of air-column. When on an inclined trajectory the pressure difference shown is exactly that of the air-column height between the probes on the sting and on the tail. Towards the end of an ascent at about 15 degrees the typical value of about 30 Pa will decrease due to increasing flattening of the trajectory upon reaching high lift coefficients. The vario will see this input and differentiate it to produce the error described earlier.

The theory is thus confirmed by experiment.

6.7. The Effect of Rudder

A pilot suggesting that there was an influence of rudder control on the vario, a test was carried out to determine whether there was indeed an influence. This was done on a routine test flight with the Ventus with the sting mounted. A total of 3 varios were operating: one from the sting, one from the tail, and one from the back of the fuselage.

As giving rudder in one direction constantly would make the glider turn, and an eventual effect could be masked, full rudder was given alternatively to the right and left with a period of about 1 sec in each direction. Was there an effect of rudder, then a periodic signal would have to be seen on the vario hooked up to the tail probe, but not on the others. Nothing of the sort happened. However something different and quite astounding: All three varios would increase their stationary rate of sink by roughly 40 cm/s! (airspeed was about 90 km/h).

This suggests that full actuation of contol surfaces can increase polar sink rate by terrifying amounts.

A second more serious test was carried out with again the sting, this time carrying a static tube as did the tail. Differential pressure was measured between the two. Giving full rudder would produce a disturbance of less than +/- 2 Pascal, meaning practically zero. Airspeed was about 100 km/h.

It seems justified to say that there is practically no influence of rudder on te-indication. (This is certainly due to the angle of attack of the fixed vertical fin not changing until after some time when the plane starts turning, and due to the probe being on the axis of symmetry.)

6.8. Other experimental Results

Another theoretical finding was proven in flight: dependance of the visibility of the various effects on response of the variometer. Effects clearly visible with a fast response (0,7 s; second order) would be smeared out when a first order 3s response was selected. This certainly explains why the phenomena discussed here have been overlooked so long, as most pilots have been accustomed to the response of the classical moving vane type of variometer having a first order response of 3 to 5 seconds.

7. CONCLUSIONS
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Consequent application of the knowledge gained in the investigation reported has allowed the author to trim the total energy system of his own sailplane to a high degree of perfection. The system allowed him to evaluate the evolution of a thermal he just decided to pull in, at any moment during the accelerated initial phase and the following ascent, this with high reliability.

A number of pilots have used some of the techniques developed to their advantage. On the other hand, it must be said, there is a large number of pilots who are insensitive to the kind of errors discussed here.

Application of the insight gained does not cost anything on top of what has to be done at any rate for any total energy system, and it will do away with some of the nuisances.

Knowledge of the effects which are unavoidable will increase security with which a pilot can interpret his variometer's signal, at no cost.

Operationally the position of the te-tube on the tail fin of a sailplane seems best, although it requires some caution, in particular as concerns length of the tube and its vertical position relative to the elevator. It is generally less prone to serious trouble than positions near to the fuselage or wing.

The big problem left is turbulence: There is so far no remedy against it, except intelligence and feel of the pilot. Its influence is of the same order as strength of thermals, if not stronger. The author feels that this is another reason to take much care of one's vario system: one will be more in a state to correctly tell a gust from a lift observing the vario's response, as parasitic effects are no longer present.

Another problem is still left over, but of a lesser concern: the influence of slip induced by turbulence on a vario's response. This is strictly a problem of probes in the case of compensation by tube. It can be regarded as solved, because te-tubes very insensitive to slip do exist. It is more difficult to treat in the case of systems using static pressure for compensation from sources on the surface of the glider. These pressures are much more sensitive to slip than te-probes. What adds to it, they are more difficult to predict, and unfortunately, also to measure. (The well known Prandtl tube being optimised for the measurement of dynamic pressure, rather than for static and total pressures separately, is roughly 10 to 20 times more sensitive to slip than a good te-tube, as regards te-compensation.)