How Glider Pilots Get There Faster

The optimisation of flight paths for sailplanes

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COMMENTS by Robert T. Lamson

This is the best article I have seen to date on speed flying. When reading this paper a pilot should reappraise his own technique.

1. How do you go about predicting the next thermal strength?
2. How do you estimate average thermal strength?
3. What "G" forces do you use in short wave length, high vertical velocity thermals?
4. What is characteristic of your sailplane wing response to gusts?

While the analysis is complicated, there is a dynamic response of the sailplane to a given gust that is maximized in some flexible wing combination coupled with pilot sensitivity to the use of the elevator control. Techniques in this area can be investigated and refined by team flying on practice runs.

The references included are very good and most are available through OSTIV.

INTRODUCTION

Even if they are not entirely familiar with the original theory, most soaring pilots will know about the MacCready ring and may well be adept in its use. Both the theory and the device (or its electronic equivalents) relate to very circumscribed circumstances although they are both essential to the understanding and practice of techniques applicable to more general and more realistic situations. The object of this paper is to review recent theories relating to optimum flight paths and their influence on the pilot's actions.

"CLASSICAL" THEORY & THE MACCREADY RING

The "classical" theory is based on the analysis of a single climb-glide sequence. The mean rate of climb is assumed to be known, as is the performance of the sailplane, expressed as a plot of the rate of sink against forward speed under steady conditions in still air. The net change of height is assumed to be zero. The analysis is concerned with finding the speed at which the sailplane should be flown during the glide, taking into account the effect of downcurrents, in order to maximise the overall average speed. These considerations lead to the construction of Fig. 1 on which is based the MacCready ring (Fig. 2) which enables the pilot to regulate his speed appropriately. Anthony Edwards has given an excellent historical review of these matters so there is no point in repeating them here. As a matter of interest, it is not obvious why the construction of Fig. 1, which relies on the mean rate of climb, correctly gives the instantaneous optimum speed in the presence of a varying down-draught. In fact it does (provided one has a total-energy variometer and the load factor is always near unity) but some more refined analysis is required to show that this is so.

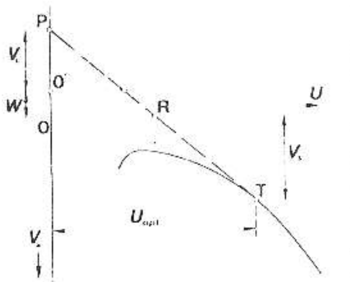


Fig 1

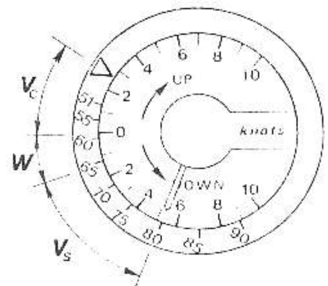


Fig 2

Fig 1 The classical construction for determining the optimum speed to fly, Uopt, after a climb at Vc and in the presence of a down-current W.

Fig 2 The MacCready ring. The datum is set to a climb of 2.5kt. The sailplane is being flown at the optimum speed of 80kt, sinking at 3.9kt through the air which is itself descending at 1.3kt.

I will assume that the reader is familiar with the MacCready ring (or corresponding electronic devices) and with the fact that a total energy variometer is essential at all times. Its indications will then depend on the motions of the atmosphere and the instantaneous speed of the sailplane but will be unaffected by the rate of change of speed. Throughout this paper, rates of climb or sink are to be taken as rates of change of energy height. We will not concern ourselves with details of the instrumentation but we will suppose that with modern equipment, whether mechanical or electronic, the pilot is fairly easily able to regulate his speed in the MacCready fashion.

The "classical" theory is very idealised indeed. If one attempts to apply it to a reasonably realistic fight in which adjacent climbs and glides do not always involve equal height changes, it becomes somewhat ambiguous. Also, there will be occasions when MacCready must be abandoned if the next thermal is to be reached. Such considerations produced a great deal of debate until as late as 1981 on what should be the "rate of climb" setting of the ring under various circumstances[2]. Should it be the average rate of climb in the previous thermal, or the final rate of climb in the previous thermal, or the expected rate of climb in the next thermal, or a vague moving average for the day? Fortunately, quite large departures from the optimum inter-thermal speed have little effect on the final average speed[3] so even pilots suffering from misapprehensions perform quite well.

In real life, there are various constraints which do not appear in the simple climb/glide analysis. There will usually be a lower height limit applied to the flight: any lower and the pilot stops trying to soar and resigns himself to landing. Likewise, there is obviously an upper limit: either the rate of climb becomes unacceptably low or cloudbase or controlled airspace intervenes.

A comprehensive analysis would take into account such constraints together with varying thermal strengths and variable spacings, perhaps such that the pilot can only get to the next thermal by flying at less than the apparent MacCready speed.

OPTIMAL FLIGHT STRATEGY

Such a comprehensive analysis has been done by Litt and Sander[4] who regarded the problem as one in "discrete optimal control." Their assumptions are listed in Table 1.

Table 1

THE LITT AND SANDER ANALYSIS OF OPTIMAL FLIGHT STRATEGY: ASSUMPTIONS

1. THERMALS ARE CONCENTRATED AT SOME GIVEN PLACES UNEQUALLY SPACED ALONG THE TRAJECTORY.
2. THEIR LOCATIONS AND CHARACTERISTICS DO NOT CHANGE WITH TIME.
3. THEIR STRENGTHS ARE GENERALLY UNEQUAL.
4. THE AIR BETWEEN THEM IS STILL.
5. THERE MAY BE UPPER AND LOWER BOUNDS TO THE OPERATING HEIGHTS.
6. THE SAILPLANE IS FLOWN AT CONSTANT SPEED BETWEEN THE THERMALS.
7. NO WIND.
8. THE FLIGHT BEGINS AND ENDS AT A GIVEN MINIMUM HEIGHT.
9. EACH GLIDE IS LINEAR BUT ALL GLIDES ARE NOT NECESSARILY IN THE SAME DIRECTION.

The pilot has to decide how far to climb in the thermal he uses and the speed to fly between the thermals. Various sets of rules can be deduced, which depend on the assumed constraints. The authors considered four cases, of which the first two were not very relevant. The first assumes no height constraints at all and leads to the simple MacCready result. The second assumes no maximum altitude constraint, which leads to some odd-looking rules. The MacCready speed is always based on the climb rate in the previous thermal.

Much more realistic is the third case, where there are both minimum and maximum altitude constraints, leading to the set of rules listed in Table 2.

MAXIMUM AND MINIMUM ALTITUDE CONSTRAINTS

There may be weaker thermals between those shown: These are ignored

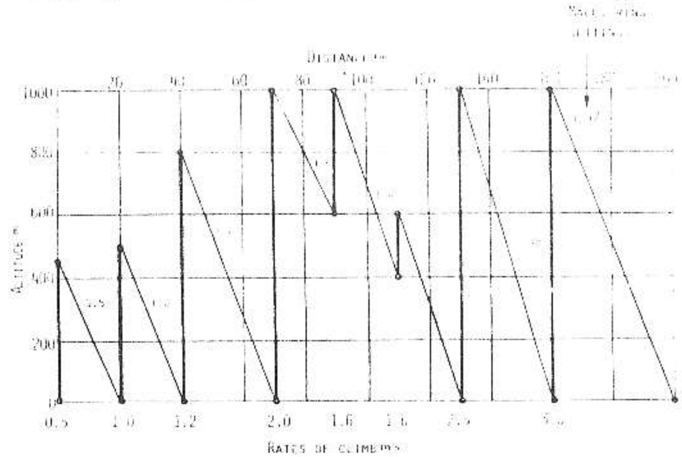


Fig 3 Diagram to show the application of the Litt and Sander rules. The thermal spacings are multiples of 10km, simply for convenience in drawing. This is a simplified version of a diagram from Ref 4

Table 2

LITT AND SANDER OPTIMUM FLIGHT STRATEGY

RULES WHEN THE STRENGTH OF A THERMAL IS THE SAME AT ALL HEIGHTS AND THERE ARE CONSTRAINTS ON BOTH MAXIMUM AND MINIMUM ALTITUDES

1. AFTER A CLIMB, FLY AT THE MACCREADY SPEED CORRESPONDING TO THAT CLIMB UNLESS THE MAXIMUM HEIGHT HAS BEEN REACHED IN THAT THERMAL.
2. IN THE LATTER CASE, FLY AT THE MACCREADY SPEED CORRESPONDING TO THE CLIMB IN THE NEXT THERMAL.
3. IF THE NEXT THERMAL IS WEAK, CLIMB IN IT ONLY HIGH ENOUGH TO REACH A STRONGER THERMAL AT THE MINIMUM ALTITUDE BY FLYING AT THE SAME SPEED AS IN THE GLIDE BEFORE THE WEAK THERMAL.
4. IF THE NEXT THERMAL IS STRONG, CLIMB TO THE MAXIMUM ALTITUDE.
5. THEN PROCEED AS IN RULE 2.
6. HAVING CLIMBED TO THE MAXIMUM ALTITUDE, THE SPEED FOR THE NEXT GLIDE MAY BE DETERMINED BY THE NEED TO REACH THE NEXT THERMAL AT THE MINIMUM ALTITUDE. MACCREADY DOES NOT APPLY.
7. IF POSSIBLE, CLIMB TO SUCH A HEIGHT IN THE LAST THERMAL THAT THE FINISH CAN BE ATTAINED BY FLYING AT THE MACCREADY SPEED CORRESPONDING TO THE RATE OF CLIMB IN THAT THERMAL. OTHERWISE, PROCEED AS IN RULE 6.

The overall aim is to do as much climbing as possible in the strongest thermals, since rate of climb has first order effect on the average speed. This is a fairly realistic set of circumstances and the rules appear to correspond with common sense, except that in some cases the MacCready speed is based on the previous climb, in others on the next climb, and in some situations is irrelevant. Fig. 3 shows a graphical interpretation of these rules.

In the fourth case, the strength of each thermal varies with altitude, initially increasing, then decreasing. Altitude constraints are implicit in such a distribution of climb rate. The rules are listed in Table 3.

Table 3

RULES WHEN THE STRENGTH OF EACH THERMAL VARIES WITH ALTITUDE, INITIALLY INCREASING, THEN DECREASING

NOTE: ALTITUDE CONSTRAINTS ARE IMPLICIT IN SUCH A DISTRIBUTION OF CLIMB RATE.

1. THE MACCREADY RING SETTING MUST CORRESPOND TO THE INSTANTANEOUS RATE OF CLIMB AT THE HEIGHT OF LEAVING THE THERMAL.
2. THE RATE OF CLIMB AT THE HEIGHT OF ENCOUNTERING THE NEXT THERMAL MUST BE THE SAME.
3. THE PREVIOUS RULES 6 AND 7 APPLY.

For a pair of thermals with given distributions of climb rates, at a certain distance apart, this rule leads to a unique solution which gives the height to leave the first thermal, the speed to glide, and the height to meet the second, as shown in Fig. 4. These rules appear in Reichmann's book[5] and had been deduced some years earlier by Anthony Edwards[6].

Although Litt and Sanders assume still air between the thermals, it seems reasonable to suppose that in the presence of a down-current, one simply follows the MacCready ring, having set it in accordance with these rules. It is noteworthy that although the

RATE OF CLIMB VARIES WITH HEIGHT

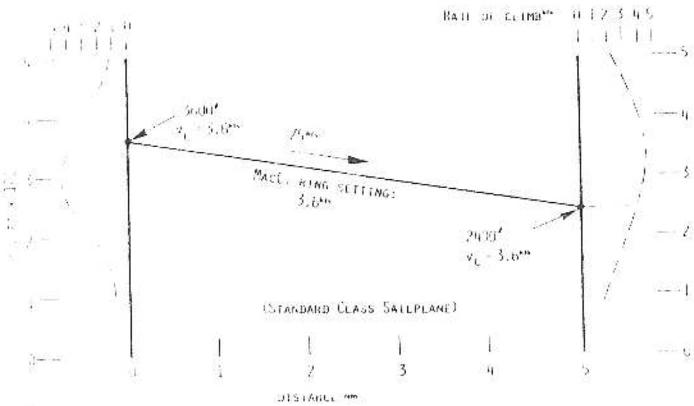


Fig 4. Diagram to show the application of the Edwards/Reichmann/Litt and Sander rules when the rate of climb varies with height. For the sailplane considered there is a unique trajectory, as shown.

classical analysis was based on very restrictive assumptions, the result is still relevant.

None of the above rules can actually be used precisely as stated because they involve powers of prophecy. In particular, the most realistic requires an ability to forecast the location of the next thermal and the distribution of rate of climb with height. Some form of calculator would then be required to achieve a rapid solution.

Although formally impossible to apply, this result is very useful if only as a guide to more intuitive behaviour. It is clear that the good contest pilot must do something quite close to this in practice.

DOLPHIN FLYING

The "classical" theory is usualy written as if any atmospheric motions between the thermals are down-currents. In fact it applies to vertical atmospheric motions both upwards and downwards so when flying through a weak thermal, the pilot should reduce speed according to the indication of the MacCready ring (provided, of course, that the speed shown is not unrealistically slow). In doing so, he extracts some energy from the atmosphere. Flying straight through thermals, perhaps pausing to circle in the really strong ones is, of course, frequently practised under cloud streets and can result in very high speeds.

Taking the simple case of a cloud street, with some prescribed distribution of vertical velocities, the questions which arise are: is continuous flight possible subject to some condition like zero net loss of energy height? If it is, how should the machine be flown so as to maximise the speed?

By considering the case in which the cloud street lies along the desired track, I made a modest contribution to this matter by applying the calculus of variations[7]. The result showed that one should proceed in the MacCready fashion: set the ring datum to some climb figure and then fly according to its indications. But what climb setting? The setting now appears in the calculations as something much more abstruse than some preceived rate of climb: it is the reciprocal of a Lagrange multiplier whose value depends on the characteristics of the whole cloud street and the constraints. In practice, it would have to be determined by trial-and-error.

At that time some similar analyses appeared eg.[8,9] which assumed - as does the "classical" theory - that, from the point of view of the sailplane's performance, the lift is substantially equal to the weight. On the other hand, from the point of view of the pilot's actions, it was assumed that he could instantaneously change speed to correspond with the MacCready indications. It became fashionable to indulge in fairly abrupt pitching maneuvers when adjusting the speed so that the flight path became markedly undulatory (and emetic), like that of a dolphin. Another little analysis[10] showed that this was very reasonable: if properly conducted, the sharper such maneuvers were, the less the energy loss due to the changes in induced drag. However, if significant portions of the flight path were to include flight at a load factor (the ratio lift/weight) other than unity, this represented a marked departure from the original assumptions.

Clearly, the whole matter was getting

too complicated for the simple analytical approach so various persons, notably Gedeon[11,12], Pierson[13,14,15], de Jong[16,17] and Dickmans[18] indulged in computerised calculations of great complexity. They all considered an isolated portion of the flight path with a specific distribution of up and down-currents. The distribution assumed by Gedeon, Dickmans and de Jong represented a fairly realistic isolated thermal whilst that of Pierson was a single sine wave. The general conclusions are similar and, since Pierson's results are easier to visualise, we will consider them in more detail.

He considered the problem of traversing such a vertical velocity distribution so as to minimise the total height loss, with specified initial and final conditions of flight and observing the stall and maximum speed limits[15]. Similar calculations were also carried out with maximum speed as the desired end[14].

In both cases, with fairly long wavelengths (1km), the maneuver is qualitatively what one would expect: slow down in the ascending air so as to spend more time gaining energy; speed up in the descending air to reduce the time in which energy is lost. If the wavelength is long and the vertical velocities not too great, the speed adjustments will all be quite gentle and the result will be substantially the same as MacCready's (Fig 5). But with short wavelengths and large vertical velocities, the optimum maneuvers are fairly abrupt. For example, in one of de Jong's examples, where the up-current has a diameter of 200m and maximum strength of 5m/s, the maximum load factor was about 7 1/2!

Not only are these conditions very far from the unity load factor assumed in MacCready flying but it turns out that the variations in load factor, quite apart from any accompanying speed changes, increase the extraction of energy from the atmosphere.

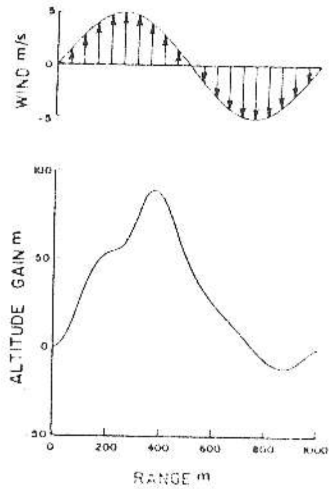


Fig 5. Optimal trajectory for free but equal boundary conditions. W_A = 5m/s, X_f = 1000m, h_f = 0.

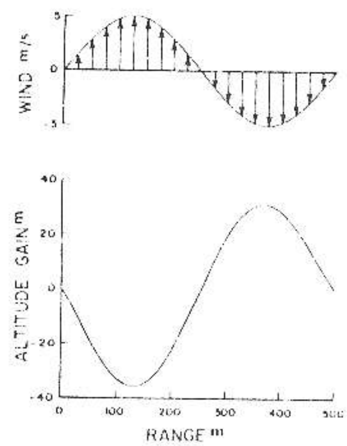


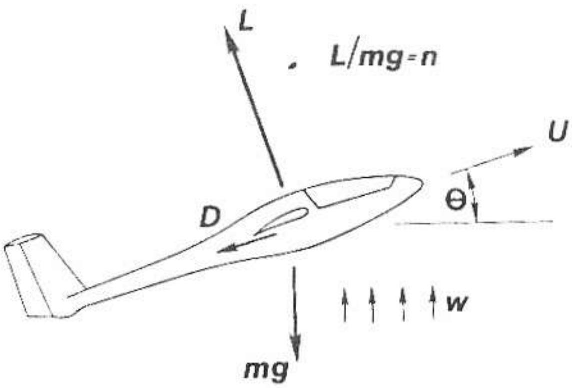
Fig 7. Type II optimal trajectory free but equal boundary conditions, W_A = 5m/s, X_f = 500m, h_f = 0.

Fig 5. This is a maximum speed trajectory with zero overall loss of height. The pilot slows down and gains height in the lift and dives to gain speed through the sink generally in the MacCready fashion. (Reproduced from Ref 14.)

Fig 7. This is a maximum speed trajectory with zero overall loss of height. The wavelength of the vertical air motion is now 500m, compared with 1000m in Fig 5. The pilot dives first in order to perform a pull-out in the lift followed by a push-over in the sink: an "anti-MacCready" trajectory. (Reproduced from Ref 14.)

This is explained elegantly in papers by Gorisch[19,20]. The results are as follows: If a sailplane is flying steadily, descending at some constant rate of sink relative to air which is ascending, then the rate of gain of energy height is simply the rate of ascent of the air less the rate of sink of the sailplane, as one would expect. But if the sailplane is indulging in a pitching maneuver with a load factor other than unity, the situation becomes that shown in Fig 6. If the angle between the lift vector and the air motion is small, then the load factor acts as an amplifying factor on the air velocity. We can indeed increase the apparent thermal strength just by pulling the stick back. Moreover, it may still be possible to extract energy from descending air by applying a negative load factor. It all looks rather improbable but it is indeed correct provided that unsteady flow effects are neglected.

For a given sailplane, there will be a load factor, depending on the speed and the rate of ascent of the air, which maximises the rate of gain of energy



$$dh_e/dt = nw\cos\Theta - V_s(U,n)$$

Fig 6 Rate of gain of energy height at a load factor n when traversing air rising with a velocity w The rate of sink Vs is appropriate to the forward speed U and the lift L which is n times the weight.

height. The point is that the rate of sink term is really the effective rate of loss of energy height by the sailplane at the prevailing speed and load factor. Increasing the load factor increases this rate of loss: if the load factor is too high, this effect will outweigh the "amplification" of the thermal strength. The optimum values turn out to be quite high: for a Standard Class glider flying at 80kt and meeting air rising at 4kt, the optimum load factor is about 4.5. Such load factors can only be sustained very briefly: even at a load factor of 3 and an initial speed of 80kt, the machine is pointing vertically upwards after 2 1/2 seconds. However, this interesting theory does explain the following results of the computer calculations:

(a) For long wavelengths (1km or more), the optimum trajectory requires MacCready-style speed variations with relatively little variation in load factor.

(b) For short wavelengths (1/2km or less), the optimum trajectory looks quite different (Fig 7). On encountering the up-current, the pilot should dive and perform a pull-out in the rising air, followed by a push-over in the sinking air. This is because the gains due to load factor variation now predominate. The consequential speed variation might be described as "anti-MacCready".

(c) There appear to be some intermediate conditions for which either type of trajectory is "optimum".

TENTATIVE RULES

Apart from the simplest application of the MacCready ring, all subsequent techniques require powers of foresight, perhaps even of prophecy. The pilot only has limited powers of foresight: he can listen to pilots ahead of him on the radio and he can look at the clouds. But he certainly does not know the distribution of thermal strength in the detail required. Nevertheless, such analyses are useful and may suggest rules which, although not exactly correct, may give something close to the ideal result without involving prophecy. Gorisch[19], for example, is suggesting the rules shown in Table 4.

Table 4

DOLPHIN FLYING

GORISCH'S TENTATIVE RULES

1. ADJUST THE *AVERAGE SPEED* ACCORDING TO THE SPEED COMMAND OF THE MACCREADY RING FITTED TO AN *AVERAGING* TOTAL-ENERGY VARIOMETER.
2. PERFORM LOAD VARIATIONS ACCORDING TO THE *INSTANTANEOUS* VARIOMETER READING. THE SPEED VARIES, BUT ITS AVERAGE SHOULD BE MAINTAINED ACCORDING TO THE PREVIOUS RULE.

Presumably one could add that the MacCready ring setting should comply with the Litt-Sander rules.

The Gorisch rules leave the time-constant for the averaging to be determined and here there is scope for further work.

CONCLUSION

During the last few years, considerable advances have been made in understanding optimal strategies for cross-country flying using atmospheric convection. The MacCready concept has been clarified and the dynamics of dolphin flying are well understood. There are indications that more satisfactory instruments together with rules for their use may emerge from these considerations. The optimisations considered here are not the only ones to have received recent attention. There is, for example, the whole matter of using cloud streets when they are at some angle to the desired mean track eg, [21].

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