LOAD VARIATION FLIGHT STYLE AND ITS IMPLICATIONS TO THE THEORY OF SOARING

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SUMMARY

A strict, generally applicable formula is derived which describes the total energy compensated climb rate $v_{c,TEC}$ of the glider dependent on the load factor vector $\vec{n}$, the wind vector $\vec{w}$ and the polar sink rate v_s:

$$v_{c,TEC} = \vec{n}\vec{w} - v_s.$$

The well-known flight technique of speed variation proves useful when smooth and widely extended lift or sink areas have to be crossed during straight flight. Load variation techniques are better suited to exploit short range lift or sink regions. A combined flight style is proposed which takes advantage of both speed and load variation. It is characterized by adjusting the average speed according to the appropriate speed command which is continuously derived using the actual value of the average climb/sink rate. At the same time, load variation is performed. For mechanical reasons, the climb rate during steady circling in a thermal is greatly influenced by an energy gain which results from the confluent air motion and which can be increased by increasing the bank angle. Possible consequences for optimiztion of sailplane design are disscussed.

INTRODUCTION

Recent soaring theory provides optimal speed commands during straight flight which promise maximum cross-country speed. The most powerful tool in this respect is the MacCready ring. The theory is based on the assumption that steady flight conditions (n = 1) are fulfilled. Because of this simplifying restriction, the applicability of the MacCready formula must be questioned when frequent dynamic flight figures are executed by the pilot, e.g. during dolphin style flight. The availability of modern, high speed, high performance gliders suggests the necessity of an update of the theory to include dynamic flight.

MECHANICS OF THE SAILPLANE FLYING IN MOVING AIR MASSES

Provided that the steady flight condition is fulfilled, the rate in height change is

$$dH_{(n=1)}/dt = w - v_s \qquad (1)$$

with vertical air velocity w and polar sink rate v_s. A general analysis, however, has to consider the general case where the load factor n differs from unity and where the glider's velocity and the wind vectors point in any given direction. The result reads rather simply (Ref. 1):

$$dH_{TEC}/dt = \vec{w}\vec{n} - v_s \qquad (2)$$

Here H_{TEC} is the total energy compensated height and $\vec{w}\vec{n}$ is the product of the wind velocity vector and the load factor vector which points in the same direction as the glider's aerodynamic force vector. A more complete derivation of the generally valid formula (2), which gives the mechanics of a sailplane flying through moving air masses, is as follows:

The equation of motion of a sailplane in a fixed coordinate system is (Fig. 1):

$$M\ddot{\vec{r}} = \vec{L} + \vec{D} + M\vec{g} \qquad (3)$$

with mass M, second derivative of the vector of position $\ddot{\vec{r}}$, lift and drag vectors $\vec{L}$ and $\vec{D}$ and the acceleration due to gravity $\vec{g}$.

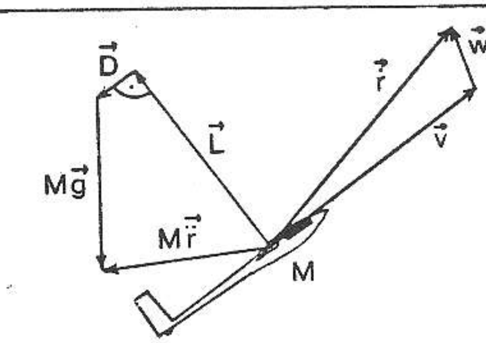

Fig. 1. Forces lift $\vec{L}$, drag $\vec{D}$ and attraction to the earth $M\vec{g}$ acting on the glider. The glider is represented by the point mass M. The sum of these forces accelerate M with acceleration $\ddot{\vec{r}}$.

The velocity of the glider is

$$\dot{\vec{r}} = \vec{v} + \vec{w} \qquad (4)$$

with its speed relative to the surrounding air $\vec{v}$ and the air motion vector $\vec{w}$. Let the derivative of the total energy

$$\dot{E} = M\dot{\vec{r}}\ddot{\vec{r}} - M\vec{g}\dot{\vec{r}} \qquad (5)$$

Introduction of (3) and (4) into (5) yields

$$\dot{E} = (\vec{L}+\vec{D})\ (\vec{v}+\vec{w}) = \vec{L}\vec{v} + \vec{D}\vec{v} + (\vec{L}+\vec{D})\vec{w} \qquad (6)$$

The product $\vec{L}\vec{v}$ vanishes since the vectors are perpendicular to each other. Replacing the drag term

$$\vec{D}\vec{v} = -Mgv_S \qquad (7)$$

and introducing $\vec{n}$ as

$$\vec{L} + \vec{D} = Mg\vec{n} \qquad (8)$$

results in

$$\dot{E} = dE/dt = Mg(\vec{n}\vec{w} - v_S) \qquad (9)$$

Replacing

$$\dot{E} = Mgv_{C,TEC} \qquad (10)$$

with total energy compensated climb rate $v_{C,TEC}$, the result is the same as (2).

Pilots generally are accustomed to dealing with the total energy compensated climb rate since this represents the idealized variometer reading.

We see that the climb rate depends on the product of two vectors: wind velocity $\vec{w}$ and load factor $\vec{n}$, which has the same direction as the aerodynamic force vector. The two vectors are multiplied introducing the angle Ψ between them. This yields

$$v_{C,TEC} = nw \cdot \cos\Psi - v_S \qquad (11)$$

The striking difference between this result and the steady flight formula (1) is that energy transfer during dynamic flight figures depend on two important parameters: n and Ψ, one of which, the dynamic load factor n, is under the immediate control of the pilot. I would like to emphasize that since energy transfer depends on the dynamic parameters n and Ψ, the pilot is able to take advantage of the conditions by choosing an appropriate dynamic flight style which enhances his energy balance. To do so, the pilot should be aware of the effects of sudden and repeatedly performed load changes during his course.

I will discuss certain aspects of equation (11) in order to evaluate the preferable dynamic flight figures which I suggest be called "load variation flight style." It should first be pointed out that v_S represents the sink rate of the glider due to drag; this depends on the glider's true air speed and its load factor, particularly at low speed. It is calculated according to the aerodynamic properties of the glider.

According to equation (11) the TEC climb rate varies according to changes in n even if the encountered wind velocity w remains constant. This results from the first term in (11) where n acts as a multiplier to w.

In defining the dynamic flight style, there are two parameters under the control of the pilot which are to be adjusted so that the value of the compensated climb rate $v_{c,TEC}$ is maximized: one is the load factor which should be as large as possible in rising air, the other is the angle ψ between air velocity and aerodynamic force vectors which should be small (the cos-function is close to one at small angles) through proper choice of the flight path. In other words, the interacting force between the sailplane and the air moving with velocity w should be large and point closely in the same direction. This rule provides the maximum rate of energy which the pilot can extract dynamically from the motion of the atmosphere.

The following cases are worth mentioning:

1. If the steady flight conditions

$$n = 1;\ \cos\psi = 1 \qquad (12)$$

are introduced into (11) we obtain equation (1) which therefore simply represents a special case (steady flight) of the generally applicable formula (11).

2. Energy transfer vanishes (except for drag losses) if the air mass encountered rests or, air mass moving, the load factor n is kept to zero, e.g. during parabolic flight.

3. Energy transfer according to the product $\vec{w}\vec{n}$ is positive (the glider gains energy) if a negative (downward directed) dynamic load is applied during flight through sinking air, since both factors have negative signs yielding a positive product value.

In general, negative loads are not practicable but it is worth remembering that the energy loss connected with traverse of a downdraft can be reduced if the vertical component of the load factor is maintained below unity.

4. If the encountered air mass rises, the pilot could fail to gain even that amount of energy he would get during steady flight when forced to perform a push figure. This can occur when a previous pull-up was performed in order to adjust the appropriate MacCready speed.

LOAD VARIATION VERSUS SPEED VARIATION FLIGHT STYLES

The question which I suspect is of primary interest to the pilot is: Could it be that the two flight styles, "load variation" and "speed variation," are named differently but actually represent the same kind of movement, since adjustment of the speed implies temporary alteration of the load factor and vice versa? If indeed both styles have to be considered separately, and the pilot has to choose the proper style which maximizes his cross-country speed, he would cetainly require the appropriate rules which allow him to make best use of the atmospheric conditions. Additionally, he may wish to know whether a profitable instrument assisted combination of the two styles exists.

First, I wish to point out that the two flight styles can be considered as aides in exploiting two different kinds of energy sources. This becomes obvious when equation (11) is integrated:

$$\int_t^{t+\Delta t} v_{c,TEC}\,dt = \Delta H_{TEC} = \int_t^{t+\Delta t} (n\cos\psi \cdot w - v_S)\,dt \qquad (13)$$

We assume the wind w to be vertically directed (upward positive) and constant during the integration limits.

The vertical component of the load factor $n\cos\psi$ is

$$n\cos\psi = b_Z/g + 1 \qquad (14)$$

with vertical acceleration b_Z.

We obtain

$$\Delta H_{TEC} = \int_t^{t+\Delta t} (w b_Z/g + w - v_S)\,dt = w\Delta v_Z/g + w\Delta t - v_S\Delta t \qquad (15)$$

Under the assumption of constant wind, we were able to solve the energy integral; see Figure 2 for illustration. It should be noted that under the common condition of varying wind, the flight path can be segmented in a way that for each segment the air velocity can be assumed constant; the total energy can then be calculated numerically.

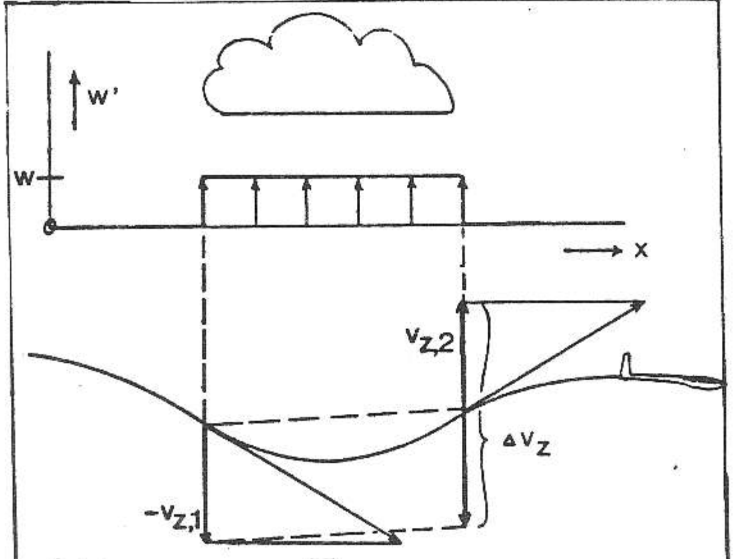

Fig. 2 Flight path through a rectangular wind profile of strength w. Load variation leads to a curved flight path and results in a significant difference in vertical speeds $v_{z,1}$ and $v_{z,2}$ at entrance and exit of the thermal.

According to the result in equation (15) three terms define the energy exchange. Two of them represent posible energy sources for the glider, whereas the third represents the energy loss due to drag. The first term depends on the atmospheric lift w and the difference in vertical speed of the glider as determined at the entry and exit of the flight path section. The second and third term represent the well-known fact that the glider's altitude alters according to the atmospheric vertical motion w minus polar sink rate v_s. We may call these terms "dynamic" and "steady", respectively.

The goal of this paper is to introduce the dynamic energy qualities into the widely accepted MacCready formalism, a formalism which has proven its usefulness throughout innumerable performance flights (Ref. 2). As was pointed out before, the appropriate flight styles which exploit dynamic and steady energy sources, and which have been named load variation and speed variation flight styles, are not compatible in the notion that both types of flying would only be separate consequences of one and the same basic maneuver. In fact, the two flight figures are inherently different. The differences most important to note are:
1. The optimal flight speed, as indicated by the MacCready ring, often varies rapidly and cannot immediately be obeyed when steep lift gradients are crossed, but can be maintained along arbitrarily far distances if required.
2. The load, in contrast, promptly responds to control movements of elevator or flaps, but constant load number deviations from unity during straight flight are restricted in time and distance because of the speed limitations of the glider.

It becomes evident from these different characteristics that the speed variation technique is most suited to take advantage of smooth and widely extended vertical lift areas found, for example, under cloud streets, in waves, when ridge soaring, or when crossing wide thermals. On the other hand, dynamic flight figures prove useful when areas of medium range vertical atmospheric motion are to be crossed by high performance gliders. This has been shown by different authors using computer simulation techniques.

Collins and Gorisch (Ref. 3) have shown that the height loss when crossing a sine-shaped thermal profile of 300 m "wave length" decreases considerably if the load amplitude during a load variation flight maneuver is increased. Another paper (Ref. 4) dealt with simulated load variation flight through a series of more representative bell-shaped thermals. The thermal model was characterized by surrounding sink regions so that the linear overall climb integral was zero. The slope of the rising air was chosen according to the thermal model suggested by Horstmann. It was shown again that a consequent load variation flight style resulted in a considerable increase in cross-country speed.

In a remarkable effort, Pierson and Chen calculated trajectories through sine-shaped thermals which were optimized with respect to minimal height loss (Ref. 5) and minimal time elapsed (Ref. 6). The simulated glider was a Nimbus II at a 32 kg/m^2 wing loading. The calculated curves of altitude and lift coefficient versus range revealed two types of optimal trajectories dependent on the wave length. Type I belongs to a wave length of 1000 m (a type I trajectory has also been verified at a wave length of 750 m), and showed the typical characteristics which a speed variation flght style would exhibit, i.e. the sailplane speed is decreased with c_L up to its maximum in upcurrents to prolong the altitude gain, and increased in down currents to lessen the altitude loss. Surprisingly, a radically different type of trajectory (Type II) was attributed to a narrow wind profile wave length of 500 m (as well as to one of 625 m). "Type II exhibits an unexpected dive first, climb later - maneuver sequence," (Ref. 5). The appropriate altitude curve showed its minimum (maximum) close to the point of maximum lift (sink), indicating highest speed when the lift is strongest and minimum speed in strong downdrafts, a figure which obviously turns the rules of speed variation upside down. Accordingly, the lift coefficient representing the aerodynamic force is highest (lowest) near maximum lift (sink). This kind of trajectory obviously follows rules according to load variation flight.

These results provide a great deal of evidence that the two different flight styles, based on speed and load variation, offer rules which enable the glider pilot to exploit short and long range veritcal winds with respect to maximum energy transfer during straight fight. It also appears that the "critical" width of separation of the thermal is in the order of some hundred meters. That means that prior to traversing a thermal the pilot has to decide which flight style to choose dependent on the actual width of the thermal ahead.

Another feature of atmospheric convection is that, in general, short and long range vertical motion superimpose, leading to a variable horizontal lift profile pattern. Thus, the sailplane is subjected to long and short range lift or sink areas, making a combined flight style,taking advantage of both energy sources, seem favorable.

The appropriate strategy which I propose is straightforward. Two quantities must be introduced: the "averaged speed" and the "averaged climb (or sink) rate". The rules for the pilot are as follows:

1. Adjust the average speed according to a speed command as indicated by an averaging TEC variometer on the MacCready ring.
2. Perform load variation acording to the actual variometer reading. The speed, of course, oscillates, but its average will be maintained according to Rule 1.

For practical purposes, the average TEC climb/sink rate may be derived by electronically damping the signal and applying a large time constant. The appropriate time constant remains to be evaluated. The average speed may be calculated and displayed likewise.

This proposed flight style seems advantageous for the following reasons:

1. This flight method meets the optimization requirements of the MacCready formalism, which is also true for the averaged speed. Note: the understanding that dolphin maneuvers result from strict obeyance of speed variation rules (Ref. 2) is abandoned.
2. Additional dynamic energy can be gained by dynamic flight figures. There is no need for sacrifice of possible "steady" energy gain.
3. The combined flight style can be practiced fully by the pilot. No severe constraints impinge upon its rules.
4. Only minor modifications to present instrumentation seem necessary and are proposed herewith. These include: evaluation of the average (integrated climb/sink rate in addition to its momentary value, and indication of the according average speed command. There are possibilities of using tactile indicators or, in a more sophisticated fashion, to automatically adjust the trim lever.

5. The proposed simple pattern does not presume the pilot's exact knowledge of the wind profile he is to encounter.

Although there are good practical reasons in support of the proposed flight tactic, at least one question remains to be considered: the MacCready optimization formalism uses the plane's speed polar to derive the height loss during straight flight which, in this proposal, is supposed to be increased due to dynamic gains. Here we obviously have to deal with a "virtual" polar which includes the glider's aerodynamic properties as well as non-steady energy gains. Drawing the tangent onto that virtual polar will possibly lead to a different (average) speed command as compared to the speed which would result from using the conventional speed polar. First results from computer simulation models indicate that the difference is negligible (Ref. 4). If this finding is confirmed, we can conclude that the average speed command is simply derived from the existing speed polar.

THERMALLING

So far we have dealt exclusively with straight flight techniques between thermalling. Will dynamic movements also help augment energy extraction during circling in a thermal (Ref. 7)? In my opinion it is very important to draw attention to an effect first discussed by B. Woodward (Ref. 8) some years ago, to which little attention has been paid. An additional amount of energy can be gained during circling flight when there is a confluent air flow which is defined as that component of the air velocity vector which points towards the center of the thermal at the level where the glider is circling. Occurence of confluent motion within the three dimensional flow pattern of isolated thermals ("bubbles") has been verified through cloud observation (Ref. 9) and experimentally (Ref. 10). Figure 3 shows the vectors of force and wind together with their vertical and horizontal components.

If we introduce them into equation (9) we obtain:

$$\dot{E} = M_g(w_c \tan\beta + w_v - v_s) \qquad (16)$$

or, introducing the climb rate v_c:

$$v_c = w_c \tan\beta + w_v - v_s \qquad (17)$$

with confluent air movement w_c, bank angle β, vertical wind w_v and sink rate v_s, according to the circling polar of the glider.

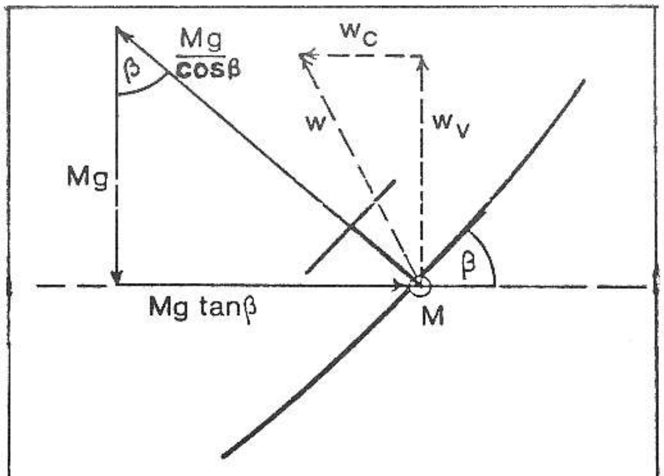

Fig. 3 Forces acting during steady circling fight; bank angle (a). Actual thermal wind components providing energy to the glider. Vertical wind component w_v and confluent wind component w_c (b).

The result shows quantitatively how the confluent motion contributes to the energy transfer during circling. The angle of bank β is important in this respect. For example, at a 45° bank the tangent function equals one; the TEC climb rate then depends on the sum of vertical and confluent air velocities.

The energy contributed by confluent motion has not been acounted for in recent evaluations. Accordingly, thermal models proposed so far are restricted to vertical wind profiles only. This may be due to the understanding that only vertical winds contribute to the glider's potential energy and, beyond that, no energy gain was believed to be significant. As we can see, this is not true.

The energy term $w_c$tan is not be be defined as a dynamic term since steady circling flight with constant speed and constant bank angle is assumed. There is no reason why additional energy gains should not be possible by executing dynamic load variation figures. In doing so, the pilot should keep in mind that the aerodynamic force vector should point nearly in the same direction as the air moves. This direction must not be vertical, necessarily, because the air movement includes varying horizontal confluence as well.

Equation (17) is important for the optimal design of gliders. It is generally accepted that a glider's climb properties be evaluated from a suitable model of the vertical wind profile and the glider's circling polar. In general, the results based upon these assumptions rather strongly favor a low minimum speed. Comparably large wing areas have been evaluated to be optimal for a 15 m span glider. It is important to note that the fraction of the energy gain, due to the confluence, increases when the bank is increased. To date we know little of the velocity gradient of the confluent motion. However, it is clear that there is no horizontal inflow at the center of the thermal, thus its maximum occurs at a distinct radius. It seems that gliders which exhibit a low sink rate at a relatively large bank angle are well suited to exploit confluence. Slightly elevated minimum speed may prove less detrimental with respect to the achievable climb rate, as generally supposed, as long as the glider remains within the confluent ring-like zone.

From a more general theoretical evaluation of optimal glider design, which takes the confluence into consideration, I expect results which show a significant trend towards aspect ratios and elevated wing loading.

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