DOLPHIN-STYLE SOARING — A COMPUTER SIMULATION WITH RESPECT TO THE GLIDER'S ENERGY BALANCE

by

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INTRODUCTION

In recent years, the so-called dolphin style of gliding flight has been used more and more often in contest and performance flights. Simply explained, dolphin flight is a series of climbing (in lift) and diving (in sink) maneuvers in which the pilot attempts to make the best use of the conditions while continuing to fly in a straight line. Used to effect, this style of flying leads to a surprising increase in cross-country speed over that predicted by MacCready formalism under the same conditions.

The difference is due to the lack of knowledge, until now, of the true energy transfer between a glider and moving air masses under time-varying flight conditions. Gorisch (Ref. 1) recently published a theoretical analysis of this energy exchange for both dolphin and dynamic flight styles. In this paper we present a summary of this theory, together with the results of computer experiments using the theory in a number of simple, yet realistic, flight situations. By varying the flight parameters we can draw a necessarily simple comparison between dolphin and MacCready styles, and hopefully stimulate future development of an optimal strategy of dolphin soaring.

THEORY

As mentioned, we are interested in the energy exchange between a glider and the surrounding air mass. A fundamental physical relation says that power, the time derivative of mechanical work, equals the product of the force affecting a body and its velocity. Thus, in our case, the rate of energy transfer is given by the product of two vectors: aerodynamic force and the observed velocity of the glider*. Since the former can be represented by the load factor, the rate of energy transfer must strongly be dependent on the g-loading, which in turn is under the control of the pilot. However it is obvious that a higher load factor means increased drag, thus there should be an optimal g-load, for a particular situation, dependent on the local air vertical velocity and the glider's performance. For the mathematical treatment, we make the reasonable assumption that the air mass is restricted to vertical movements only.

Gorisch's theory provides the result that:

Rate of total-energy exchange,

$\dot{E}=Mg(nw\cos\Psi-v_s)$

where M = mass of glider
g = acceleration due to gravity
w = (vertical) velocity of air mass
n = load factor
Ψ = angle between (vertical) air mass movement and the lift vector of the glider
v_s = sinking speed of the glider in still air

The optimal g-load turns out to be close to the maximum permitted g-load at the given speed, but only for reasonable instantaneous air vertical velocity magnitudes.

* The glider's velocity results from its speed relative to the surrounding air and the movement of the air itself, and is measured from the earth.

The above relation can be integrated over a time interval of Δt (providing w is constant over this interval) to give:

Total energy exchange,

$$\Delta E = M\Delta u_z w + Mg(w - v_s)\Delta t$$

The first term can be considered as a "dolphin" term, whereas the second represents the well-known MacCready term. The dolphin term is dependent on the difference in vertical speed between entry to and exit from a thermal, Δu_z.

A further expansion of Gorisch's equations into the form used for the analysis is given in the Appendix. For a fuller treatment of the theory, the reader is referred to the original paper.

COMPUTER SIMULATION

The real flight paths of a glider were calculated digitally in order to obtain relevent data such as total energy gain and cross-country speed, dependent on the g-loading profile within a thermal.

Other parameters, such as the strength of the thermal, its profile, the entry speed of the glider and its entry flight path angle could also be varied. There are, of course, only a few examples discussed here, with the aim of showing trends, but more extended evaluation can easily be performed using the program steps given in the Appendix.

The results should provide the contest pilot with more knowledge about how to get a better cross-country speed by use of dolphin techniques.

PRINCIPLES

The "flight" of the test aircraft was carried out in the vertical plane only, i.e., the aircraft's position could be expressed as a height, z, and a horizontal distance, x. The flight path is then an x-z curve, the points of which are calculated every half meter of the x-axis. The finite step width of 0.5 m leads to a negligible error of less than 1% per 100 m flight path.

The aircraft chosen for the analysis was an AS-W 15, whose polar curve has been mathematically approximated by Reichmann (Ref. 2) in the form of a parabola. From this relation we can obtain the sinking speed, $\bar{v}_s$, as a function of both the aircraft speed, v, and the load factor, n. (See Appendix)

The following initial values are inputs to the program:

(1) aircraft speed, v
(2) aircraft flight path angle, Ψ (taken in all examples to be 0^o, i.e. horizontal flight)
(3) $v_s(v)$ subroutine (description of the polar curve)
(4) w(x) subroutine (thermal profile)
(5) n(x) subroutine (g-loading profile)

The program then generates at each step the following output values:

(1) instantaneous aircraft speed, v
(2) instantaneous flight path angle, Ψ
(3) total horizontal distance flown, x
(4) absolute height, z
(5) total-energy compensated height (TEC height), H
(6) total time elapsed, t

At this stage it is important to point out the difference between absolute height and total-energy compensated height. In general, absolute height means the vertical displacement z from the earth's surface. It corresponds to the *potential energy* of the glider. Suppose that a glider flying horizontally in perfectly stable air performs a pull-up. In doing so it gains potential energy, i.e. height. However, as the potential energy is gained only at the expense of kinetic energy, i.e. a decrease in speed, there is no gain (or loss) in the *total energy* if drag is neglected. Throughout this discussion, total-energy-compensated height, TEC-height, means a height gained or lost due to an interaction between the glider and its surroundings, irrespective of any exchange between the potential and kinetic energies of the aircraft. Obviously, sink due to drag is a contributing factor to TEC energy change.

A test is made on the data at each step which terminates the program in a number of extreme flight situations such as stall (related to g-loading), entry to a loop, very large or small g-loads, etc. The program was tested using the case of a simple, dragfree, free-fall with an ideal glider, i.e. zero "sink" for all speeds, and the expected results (e.g. total energy gain = 0, parabolic flight path) were verified within the error margin mentioned.

RESULTS - A

As an oversimplified, but illustrative case, consider the thermal to have a width of 150 m and a rectangular profile, as also the g-loading distribution (see Fig. 1). The thermal strength was varied between 0 and 3 m/s (0-590 fpm), and the aircraft entry speed into the thermal was taken as 160 and 190 km/h (100 and 119 mph). For constant thermal strength, the entry speed was varied, and vice-versa. Fig. 1 shows the results of the calculations. The curves plot TEC-height-gain at the end of the thermal as a function of the g-load n, a parameter which could easily be varied in this computer simulation and in reality, is under the pilot's control. The case for n = 1 is then the stationary or usual "MacCready" case. "Flights" where the aircraft stalled before completing its path through the thermal are not shown.

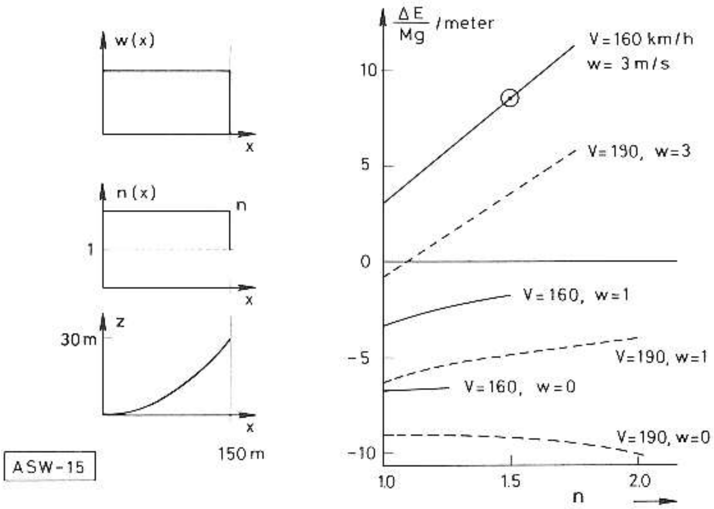

Figure 1. The total-energy compensated height gain at the end of the thermal is plotted as a function of the g-load n, which the pilot maintains during his flight through a rectangular-shaped thermal. The initial flight path angle was held at zero. Obviously by this maneuver the glider converts velocity into absolute height. At low speeds, stalling occurs within the thermal for even moderate g-loads. In this plot, the curves stop at the last value of g-load before stalling. For strong thermals we notice a remarkable increase in TEC-height gain with the g-load imposed. A characteristic flight path is shown at bottom left. It corresponds to the circled point, where the initial flight speed is 160 km/h, the thermal strength is 3 m/s and the g-load is kept at 1.5.

First to be noticed is the dependence, strong for stronger thermals, of the TEC height gain on g-load. For weaker thermals the dolphin technique has a small, or even negative effect due to the higher sink rates at high g-loadings. Also to be noticed is the fact that the curves for the two entry speeds are almost parallel, but shifted in TEC height, this being again due to a higher sink rate for 190 km/h.

To illustrate the gains possible using dolphin soaring, we can make a quick comparison with MacCready techniques. For a 3 m/s thermal (remembering that this is the true thermal strength and not the variometer reading), we assume a MacCready speed of 100 km/hr. The glider is thus in our thermal for 5.1 s, and in this time gains 11 m in TEC height. The same aircraft using dolphin flight and entering the thermal at 160 km/hr gains the same height in 3.9 s, with a g-load of approximately 1.6, i.e. the pilot can gain the same amount of energy using dolphin soaring, but cruises at a higher speed.

A rectangular thermal is the only case where we can make a meaningful comparison. With the following cases it is not realistic, or even possible, to perform quick quantitative comparisons because of the continuously varying MacCready speed relative to the changing thermal strength.

RESULTS - B

Take now the case of a sine-shaped thermal, with no sink component, and a parabolic variation in g-loading — both with maxima at the same point, i.e. halfway through the thermal. We now speak of n_{max}, the maximum g-load attained in the thermal, and similarly w_{max}. Fig. 2 shows the results for a constant maximum thermal strength of 5 m/s (985 fpm) and entry speeds between 100 and 190 km/h (63 - 119 mph).

Again almost parallel curves are seen. The curves for 100 and 130 km/hr are shortened as only small g-loads can be applied at these speeds without the glider stalling. Fig. 3 shows the same case, but this time with a constant entry speed of 160 km/h (100 mph), and maximum thermal strengths between 0 and 7 m/s (0 - 1380 fpm).

The obvious feature is that dolphin techniques are useful only in the presence of moderate to strong thermals, where the gain of TEC height can be doubled with only moderate g-loads.

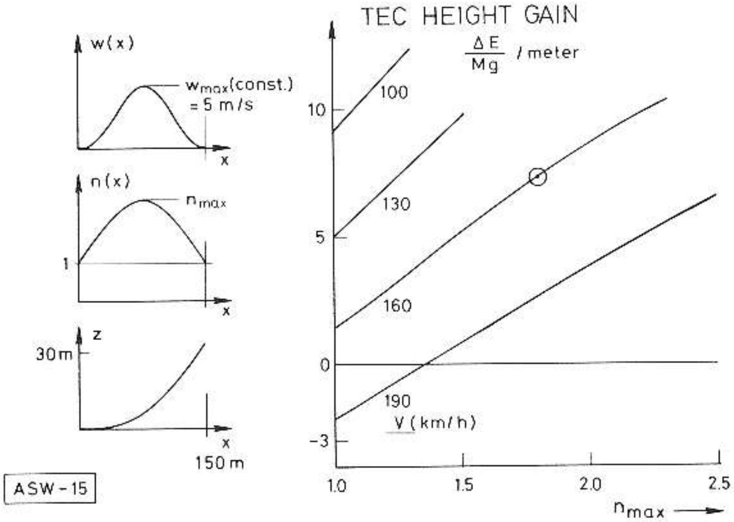

Figure 2. Figure 2 shows similar plots to those of Figure 1. Here a sine-shaped thermal and parabolic variation of the g-loading were used. The maximum thermal strength was assumed to be 5 m/s. It is shown that the same TEC-height gain at slow velocities under normal g-loads can also be achieved at high velocities under moderate to high g-loads. Thus the pilot can maintain high velocities even during the penetration of thermals, which of course increases his cross-country speed markedly.

RESULTS - C

We now show a more complicated case where the thermal is followed by an identical and opposite sink (see Fig. 4). Thus the total integrated air mass movement is zero. Accordingly the g-load in the sink zone is reduced to below one and the averaged g-load is one. This is thus an important case, illustrating the effect of dolphin soaring in what is, on average, still air. The results shown in Fig. 4 were obtained using a fixed maximum thermal strength of 5 m/s (and thus a sink of 5 m/s), and entry speeds between 130 and 190 km/hr (81 - 119 mph). The maximum range of g-loads tested was 1.7/0.3.

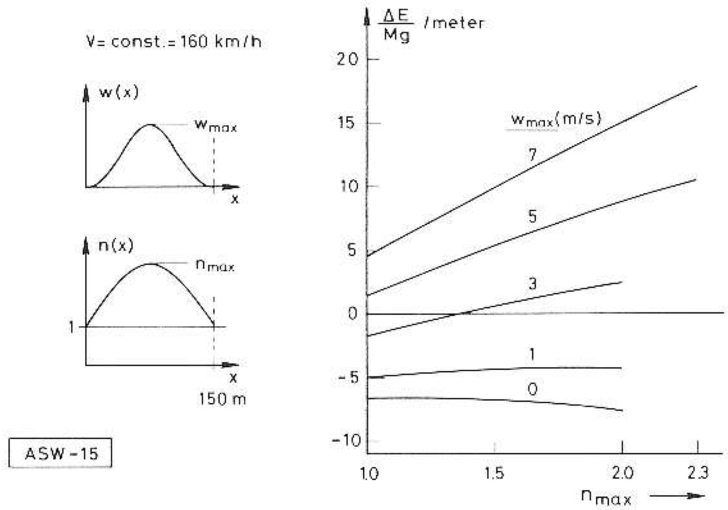

Figure 3. The shape of the thermal and the g-load profile are those of Figure 2. In this case the initial velocity is kept at 160 km/h. The thermal strength is varied between 0 and 7 m/s. Again we see that an increase in g-load over the whole thermal brings advantages mainly at higher w_{max}-levels.

Firstly it is noticed that all curves lie in the negative TEC-height-gain region. This only to be expected where the average thermal strength is zero, and for stationary flight we should only see a TEC height loss due to the aircraft's sink. However, even a small variation in g-loading during the "flight" makes a large difference in height lost. For example, the case of v = 160 km/h and n_{max} = 1.7 results in a TEC height loss, over a 300 m path, of only 1 m. This implies an effective glide ratio of 300 during the calculation interval and an average cross-country speed of 135 km/h (84 mph). The flight path curve again shows the case for the circled point, where the aircraft leaves the test region with a nose-down angle of 5^{0}.

DISCUSSION

Firstly, to summarize, we have performed a simple preliminary analysis with reference to a new theory of energy exchange during dolphin soaring, using the *basic flight technique that in rising air one increases the g-load, and in sinking air, one decreases it.*

This simple pattern leads to interesting gains in total-energy compensated height over

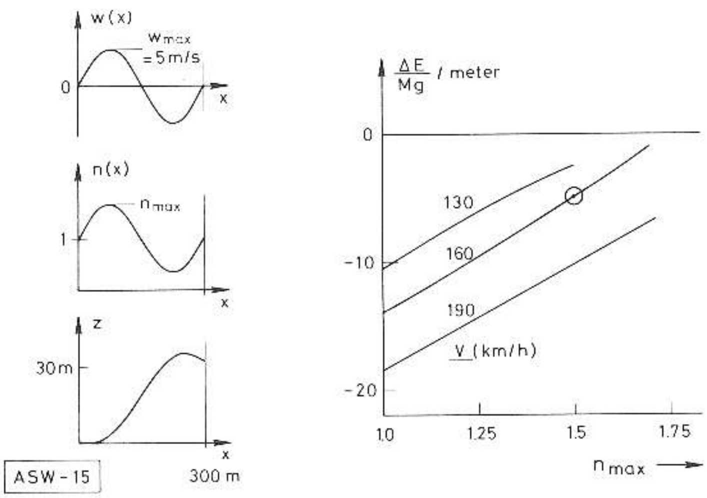

Figure 4. Now the "thermal" profile is a complete sine-wave. The average air-mass movement is zero. We only observe energy losses, but these losses can be reduced by using the indicated g-load profile. The favorable case which might even not represent the optimum, leads to an effective glide ratio of about 300 and an average cross-country speed of 135 km/h.

those to be explained by MacCready theory. The gains, for the competition pilot, can be expressed in terms of the time saved by the dolphin flight maneuver and also by the TEC height gain, remembering that time saved can be converted at the next opportunity to a thermal climb gain during the same interval.

Recent MacCready-based theories of dolphin type of soaring (e.g. see Meyer (Ref 3) and Pirker (Ref 4) more-or-less assume the following simplifications:

(a) Not taken into account is the varying drag due to minor changes in g-load arising from variation of glider speeds.
(b) Energy exchange dependence on the above mentioned are not considered, although it is important as shown here
(c) MacCready calculations are overestimated in that a pilot obviously cannot suddenly alter his speed on entering a thermal, as requested.

It is obvious that we have greatly simplified the shape of a thermal, but the errors are not so great as to have pronounced effect on the results. In fact, the computer program would allow for any special thermal shape requested. Additionally we avoid the above-mentioned simplifications; we have developed a computerized simulation of *real* flight movements in a vertical x-z plane with variations of g-loading and vertical air current profiles.

It is also important to realize that useful gains with dolphin soaring are possible without straining pilot and aircraft, at reasonable speeds, and in thermals pilots are likely to meet.

It is not yet clear whether the optimum results will come from a point of maximum g-load that does not correspond with the thermal maximum. Another question regarding the smoothness of the load profile remains unanswered, but we hope that an optimum technique may be soon evaluated. The use of this simulation computer program together with variation theory might be helpful for such a more sophisticated investigation.

In a third step one might also account for the pilot's reaction time and his lack of knowledge about individual thermals encountered. In this case one looks rather for a best strategy than for an optimum flight path.

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APPENDIX

Consider the forces acting on a glider in flight (Fig. 5)

Given the initial data of the aircraft's speed and flight path angle, we can calculate the two components of the velocity vector (initially w = 0!):

(A 1) $u_x = v \cos\Psi$

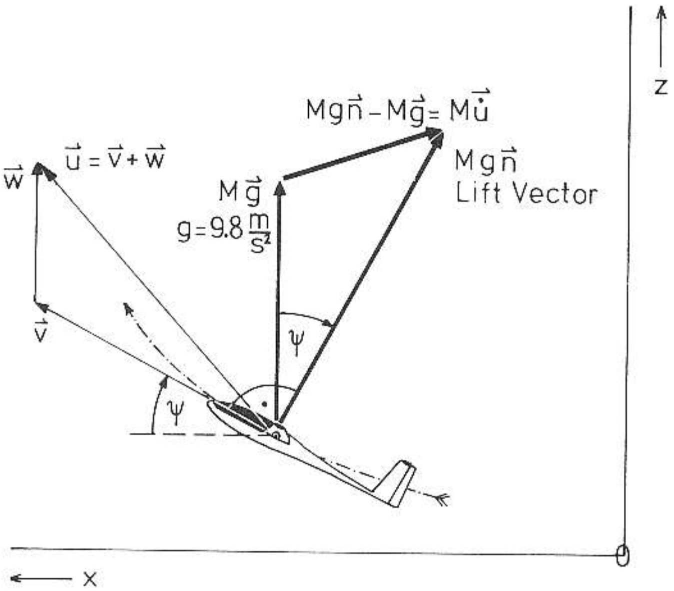

Figure 5. v means the glider's speed relative to the surrounding air mass which itself moves vertically with the speed $\vec{w}$. Both combine as $\vec{v}+\vec{w} = \vec{u}$; $\vec{u}$ is then the true velocity of the glider with respect to the earth. The angle Ψ is that between the $\vec{v}$-vector and the horizontal or, similarly, between the lift vector and the vertical. The g-number, $\vec{n}$, defines the lift vector, Mg$\vec{n}$. (g$\vec{n}$-$\vec{g}$) is one acceleration, $\dot{\vec{u}}$, which changes path velocity vector, $\vec{u}$; another one is given by the drag (refer to relations (A 10) and (A 12)).

(A 2) $u_z = v \sin\Psi$

Now the time taken for the glider to cross an elemental distance Δx is:

(A 3) $\Delta t = \Delta x / u_x$

From the thermal profile subroutine we get the thermal strength at a penetration x, w(x):

(A 5) $w = w(x)$ Subroutine

Then the new value of Ψ, at the end of the interval Δx, is given by:

(A 6) $\Psi = \arctan \frac{u_z - w}{u_x}$

This then gives the new speed by:

(A 7) $v = u_x / \cos\Psi$

We now get the g-load n (x) and calculate the sink rate $v_{s,n}$ with the appropriate subroutines:

(A 8) $n = n(x)$ Subroutine

(A 9) $v_{s,n} = v_s\left\{v/\sqrt{n}\right\} . n^{+3/2}$

The sink rate v_s at a given speed v has been approximated by Reichmann (Ref. 2) for an AS-W is glider:

$$v_s\left\{v\right\} = -0.00082\ v^2 + 0.13048\ v - 7.4836$$

km/h for v in km/h

The sink rate is corrected for g-load n as in (A 9).

We now calculate Δu_z

(A 10) $\Delta u_z = g\ \Delta t\ (n \cos\Psi - 1 - \frac{v_{s,n} \sin\Psi}{v})$

Where $g\ (n \cos\Psi - 1) \hat{=}$ vertical component of centrifugal and gravitational acceleration and $g(v_{s,n} \sin\Psi)/v \hat{=}$ vertical component of drag-induced deceleration.

Then the new value of vertical speed is:

(A 11) $u_z := u_z + \Delta u_z$

And the new value of horizontal speed is:

(A 12) $u_x := u_x - g\ \Delta t\ (n \sin\Psi + \frac{v_{s,n} \cos\Psi}{v})$

(see (A 10) for analogous explanation)

The total-energy-compensated height change over our interval is:

(A 13) $\Delta H = \frac{w \Delta u_z}{g} + (w - v_{s,n}) \Delta t$

The following variables must be summed at the end of each loop:

(A 14) $T := T + \Delta t$; Time
$H := H + \Delta H$; TEC height
$x := x + \Delta x$; horizontal position
$z := z + u_z \Delta t$; absolute height, vertical position

This sequence comprising (A 3) to (A 14) then represents one complete calculation loop.