Computer-Aided Research of Different Ways Leaving a Thermal

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ABSTRACT

A dynamic computer study of various ways of leaving a thermal has been made. The principal goal was to evaluate different thermal-outs, considering cross-country flight tactics. Therefore, a few thousand flight simulations have been made. The research shows the possibility of practical utilization of vertical wind speed gradient through "dynamic" thermal-outs.

INTRODUCTION

Contemporary cross-country flight tactics enable us to determine the optimal flight parameters, but only under steady conditions. These conditions are met during a constant speed glide through air which has sufficiently uniform vertical velocity, e.g. during cruise between thermals. However, in the course of entering and leaving a thermal, today's sailplanes call for very sharp maneuvers which cannot be properly described by quasi-static calculations. Furthermore, variable vertical wind speed makes the process even more complicated.

Considering all this, it was felt that only dynamic calculations could be used to investigate different style thermal-outs. The basic equations for such calculations were set by Dr. Jozsef Gedeon (1) and they require the use of a computer. This in turn proved to be an advantage because it enabled a vast study of the influence of all major parameters on the best way of leaving a thermal.

THERMAL MODEL

The thermal model, used in this research, represents an isolated thermal with a sinking zone surrounding the core. This model also makes allowance for a certain amount of sink between thermals, i.e. -0.04 of the maximum updraft velocity. Thermal lift distribution was produced by combining four parabolic arcs; the resultant thermal cross-section is shown in Fig. 1 in non-dimensional coordinates.

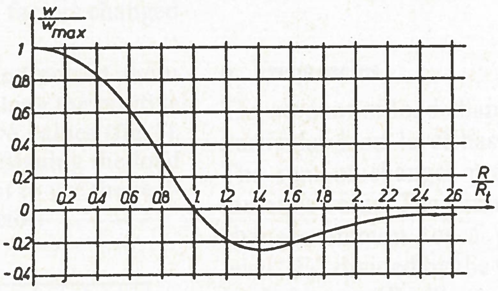


Figure 1. Thermal Cross-Section

Maximum updraft (w_{max}) and thermal radius (R_t) are free parameters.

COMPUTER PROGRAM

As has already been mentioned, the basic mathematical model was adopted from Ref. 1. This model describes the glider as a mass point (having lift and drag) that moves in a vertical plane.

Vertical wind speed profile is assumed to be known. Equations of motion are integrated by using a kind of finite element method in which a path element (Δs) corresponds to the constant length horizontal axis element (Δx). This was found to be more convenient than working with the constant length Δs. The length of Δx was chosen to be 4 meters, which is acceptable considering both accuracy and computer time. The program uses only two different integrating modes (procedures). The SPEED mode works when a V=f(x) speed function is given, which includes V=const. and V≠const. sections as well. The LOAD mode is engaged when a constant normal load factor (n) is prescribed.

To obtain the desired airspeed profile, the flight path is broken into constant speed and maneuver sections (Fig. 2).

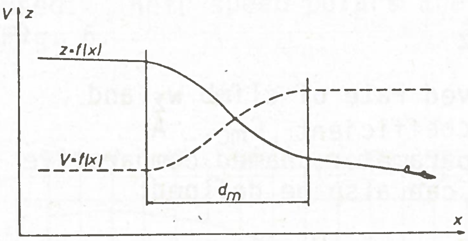


Figure 2. Flight Path Sections

At the beginning of each maneuver section, the program first determines the initial load factor (n_1) for that particular maneuver. In doing this, the following parameters are taken into account: maneuver distance (d_m), airspeeds and their vertical components at the beginning and at the end of maneuvers, mean vertical wind speed gradient, and glider performance. After obtaining n_1, the maneuver is commenced in the LOAD mode. Yet this is only the first phase of the prescribed speed change, so the flight with constant load factor n_1 lasts until a certain transitional condition is reached. This condition is merely geometrical and it was devised to ensure that the second phase of the maneuver would be as smooth as possible and without any excessive g loads.

Before starting the second phase, the program first has to find the correct speed function that will bring the glider exactly to the desired airspeed when it reaches the end of the maneuver (Fig. 3).

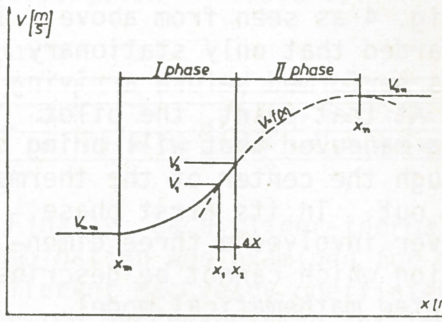


Figure 3. Speed Function

To obtain a smooth transition, this speed function must fulfil the following four boundary conditions:

$$[V]_{x_2} = V_2 \quad ; \quad [V]_{x_m} = V_{nn}$$
$$\left[\frac{dV}{dx}\right]_{x_2} = \frac{V_2 - V_1}{x} \quad ; \quad \left[\frac{dV}{dx}\right]_{x_m} = 0 \qquad (1)$$

The third degree polynomial was found to be the most appropriate form of the speed function and it reads:

$$V = C_1x^3 + C_2x^2 + C_3x + C_4 \qquad (2)$$

Coefficients C_1, C_2, C_3 and C_4 are computed from the boundary conditions (1). After the speed function is determined, flight simulation is resumed in the SPEED mode and when the maneuver is completed no correction is necessary.

Dealing with speed changes this way makes the program somewhat more complicated, but in turn enables automatic execution of a large number of simulated thermal-outs on the computer.

RESEARCH METHOD

Some common procedures were followed in all relevant flght simulations such as: All thermal leavings were assumed to begin after circling in the observed thermal with the initial height of 1500 meters. Optimal circling parameters are therefore calculated for a lift coefficient which value is 85-90% of C_{Lmax} amd the resultant values are taken as initial for a flight simulation. A typical thermal-out is shown in Fig. 4 as seen from above. It may be regarded that only stationary circling is performed before arriving at point A_0. At that point, the pilot commences a maneuver that will bring him right through the center of the thermal on his way out. In its first phase, this maneuver involves a three dimensional motion which cannot be described by the adopted mathematical model.

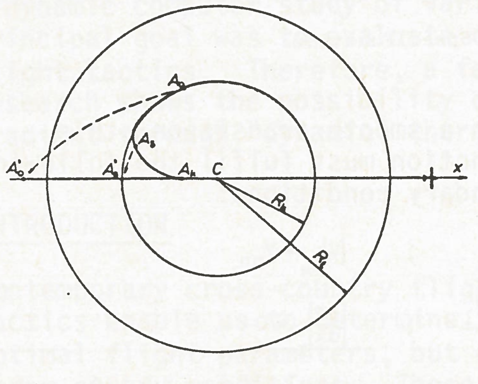


Figure 4. Thermal-Out as Seen from Above

The simplest solution was found by straightening the A_0A_k, portion of the flight path into $A_0'A_k$. To maintain approximately the same vertical wind speed distribution along this straightened flight path, as along the real one, the thermal cross-section is somewhat corrected. A part with constant thermal lift is attached to the left of the thermal core with dimensions that are given in Fig. 5.

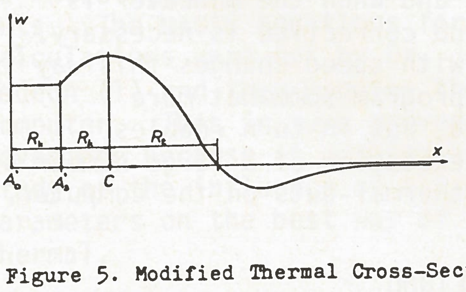


Figure 5. Modified Thermal Cross-Section

This simplification produces somewhat optimistic results, but the error tends to cancel itself because only the comparative values are taken into account. All flights that are compared to each other end at precisely the same horizontal distance from the starting point. Also, their terminal airspeeds are identical and with $dV/dx=0$. This enables us to make a comparison of two or more different style thermal-outs by merely considering the elapsed time (T) and the resultant height (Z) at the end of each flight. This can be simplified even further if we combine these two parameters into one that will directly show gain or loss of one thermal-out over another. So, a new parameter called comparative height (U_h) is defined:

$$U_h = Z - w_{mc}T \qquad (3)$$

where w_{mc} is the anticipated rate of climb in the next thermal. Its value is calculated from:

$$w_{mc} = C_{mc}w_z \qquad (4)$$

with achieved rate of climb w_z and MacCready coefficient C_{mc}. A congruent parameter, named comparative time (U_t), can also be defined:

$$U_t = \frac{Z}{w_{mc}} - T = \frac{U_h}{w_{mc}} \qquad (5)$$

Now, if we want to compare two different style thermal-outs, it is enough to establish the difference between their comparative heights:

$$\Delta U_h = U_{h(1)} - U_{h(2)} \qquad (6)$$

or comparative times:

$$\Delta U_t = U_{t(1)} - U_{t(2)} \qquad (7)$$

Actually, ΔU_h represents the height difference which results only from difference in thermal leaving, and which will be apparent in the next thermal (if w_{mc} is correct). Analogically, ΔU_t represents the corresponding time difference.

It is apparent that in such treatment of the results no attention is paid to the absolute values of energy exchange and time loss. Only the comparative values are considered, which is more suitable for practical use.

RESEARCH VOLUME

Initially, only about 200 flight simulations were planned because the time available on the college computer was limited. Fortunately, when the research was well under way, the author got access to a new CDC-Cyber 171 computer which proved to be much faster than the old college Univac. This eventually led to a vast expansion of the research program and resulted in the accomplishment of 7720 relevant thermal-outs.

During the research, several parameters were varied to examine their influence on the best way of leaving a thermal. They are as follows: type of sailplane, width and strength of thermal and MacCready ring setting. For this purpose, two types of sailplanes were used. Their speed polars are shown in Fig. 6.

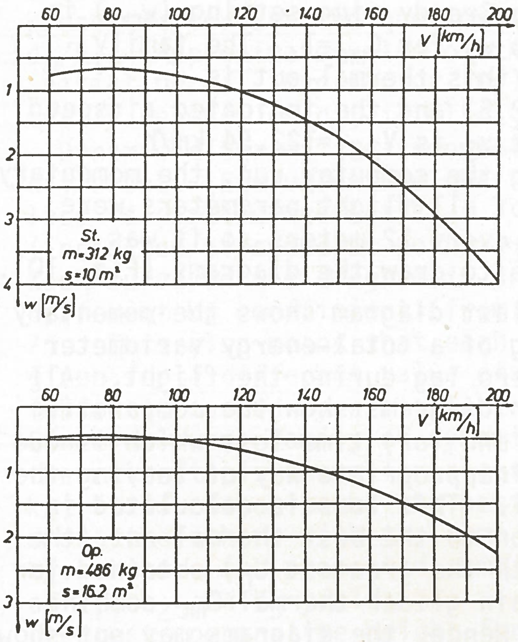


Figure 6. Performances of Gliders Used in the Research

The glider denoted as St. has the polar of a Standard Class ship very similar to that of the Std. Cirrus, while the sailplane marked as Op. shows approximately the same performance as a Nimbus 3. Glider weight was kept constant for each glider-thermal combination.

Nine types of thermals were used with maximum updraft velocities and thermal radii, given in Table 1.

Table 1.

no.	1	2	3	4	5	6	7	8	9
w_{max} (m/s)	2	2	4	4	4	6	6	6	6
R_t (m)	150	200	100	150	200	150	200	250	300

Finally, each glider-thermal combination was examined for two different MacCready coefficients (i.e. for two MacCready ring settings). These are $C_{mc}=1$ for $w_{mc}=w_z$ and $C_{mc}=0.65$ for $w_{mc}=0.65w_z$.

Regarding a general way of leaving a thermal, all executed thermal-outs can be divided into two basic groups: classic and dynamic. The classic group is distinguished by having only one acceleration section (Fig. 7) in which the airspeed is changed from circling value (V_k) to cruising value (V_{mc}). Variable parameters for this group are: location on which the maneuver is commenced (x_p) and maneuver distance (d_m).

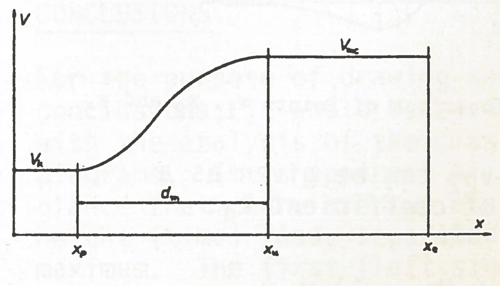


Figure 7. Classic Thermal-Out

Dynamic thermal-outs are somewhat more complicated for they generally comprise three speed altering maneuvers (Fig. 8)

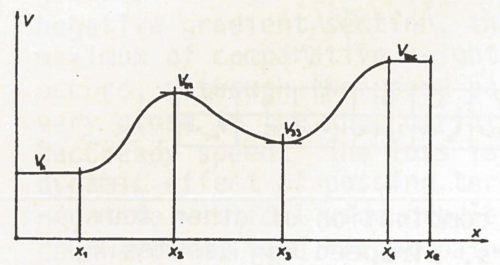


Figure 8. Dynamic Thermal-Out

which are joined to each other without any separating constant speed section. These maneuvers eventually increase the airspeed from V_k to V_{mc} only it is done in an unusual fashion.

Variable parameters for this group are: positions of points x_1, x_2 and x_3 and airspeed values V_{22} and V_{33} at points x_2 and x_3 respectively. Location of point x_4 is usually fixed except when the distance between x_3 and x_4 proves to be too short for the final maneuver. In that case, x_4 is moved farther away from x_3, but not beyond the end of the flight path (x_e).

All these parameters assume only discrete values which can be correlated with the corresponding parameter coefficients (k_i) in the following manner: Locations of points x_1, x_2 and x_3 depending on coefficients k_1, k_2 and k_3 respectively, are shown in Fig. 9 in relation to the modified thermal cross-section.

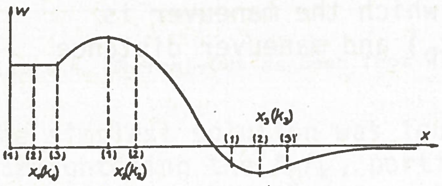


Figure 9. Locations of Points x_1, x_2 and x_3

Airspeed V_{22} can be given as a function of coefficient k_4:

$$V_{22} = V_k + (k_4 - 1) W \quad (8)$$

for $k_4 = (1...7)$ and where:

$$\omega = 0.2(V_{mc} - V_k) \quad (9)$$

This can also be shown tabularly:

Table 2.

k_4	1	2	3	4	5	6	7
V_{22}	V_k	$V_k+\omega$	$V_k+2\omega$	$V_k+3\omega$	$V_k+4\omega$	V_{mc}	$V_{mc}+\omega$

For each combination of other four parameters, airspeed V_{33} assumes k_4 discrete values that range from V_{22} to V_k inclusive.

The introduction of the parameter coefficients (k_1) enables us to form a specific family mark which reads as follows:

$$P_d(k_1, k_2, k_3, k_4)$$

For a given glider-thermal-C_{mc} combination this mark uniquely represents a family of dynamic thermal-outs in which only V_{33} is variable.

RESULTS

To get a visual idea of how all these simulated thermal-outs were performed, here is an example picked from the dynamic group. The flight is done with a ballasted St. glider (m=372 kg). The thermal is defined by: w_{max}=6 m/s and R_t=150 m. The achieved rate of climb is w_z=2.996 m/s with other circling parameters being: R_k=72 m, = 48.7° and V_{ki}=94.85 km/h (subscript "i" stands for indicated airspeed).

The MacCready ring setting (w_{mc}) is equal to w_z for C_{mc}=1. The family mark of this thermal-out is $P_d(1,1,2,5)$ and the indicated airspeed at point x_3 is V_{33i}=122.54 km/h.

During the computer run, the momentary values of all flight parameters were printed every 12 meters so it was possible to draw the diagrams (Fig. 10).

The last diagram shows the momentary reading of a total-energy variometer with zero lag during the flight. All further diagrams show the comparative height and (or) time loss which is due to an inappropriate way of leaving the thermal. This loss is calculated in relation to the best thermal-out (the one with the greatest U_h) obtained for a certain glider-thermal-C_{mc} combination. Hence, the diagrams may not show exactly the absolute loss, but, considering the research volume, the displayed value should be fairly close to it.

For each glider-thermal-C_{mc} combination there are generally two diagrams: classic and dynamic. In all classic diagrams, the distance between the beginning of acceleration and the center of the thermal (x_{pc}) is placed at horizontal axis and given in relation to

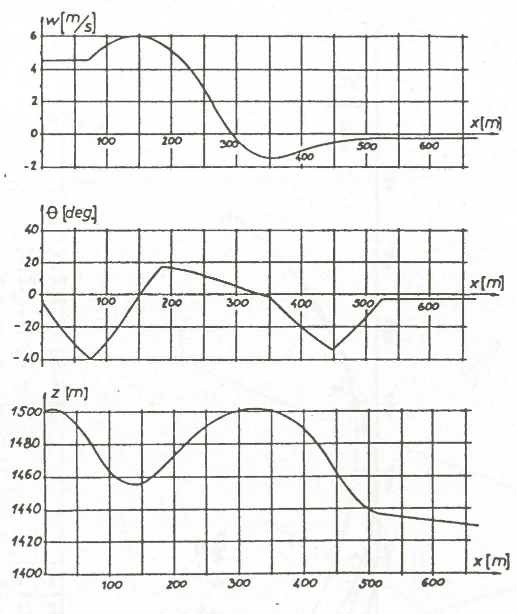


Figure 10. Example of Dynamic Thermal-Out (Part I)

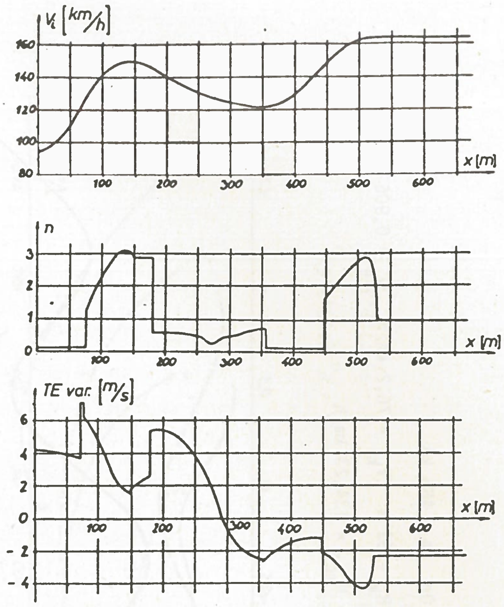


Figure 10. Example of Dynamic Thermal-Out (Part II)

the thermal radius as x_{pc}/R_t. Each curve in these diagrams is drawn for a constant maneuver distance which is presented through the quotient d_m/R_t. Approximate value of the initial normal load factor (n_1), which mostly depends on d_m, is also given.

Dynamic diagrams are somewhat different. Equivalent height (time) loss is plotted against V_{33i} (indicated airspeed at point x_3). Each curve on the diagram is drawn for a different k_4 coefficient (from 2 to 7). This also means that each curve is given for a different value ofv_{22i} (which is marked by a little triangle). Since only one family of dynamic thermal-outs is shown for a certain k_4, it is chosen to be the best one among the others with the same value of k_4. Hence, the presented combination of k_1, k_2 and K_3 yields the greatest comparative height for that k_4. The appropriate family mark for each curve is printed beneath the diagram.

On some dynamic diagrams, especially for strong and narrow thermals, some curves are not complete and yet some are totally omitted. The reason is that some thermal-outs called for too severe maneuvers and thus could not be accomplished.

For each glider-thermal combination the mass of the glider is given and so are the circling parameters. Also, each diagram has a code-mark denoting the glider-thermal-C_{mc} combination and group ("k" for classic and "d" for dynamic) to which the diagram belongs.

CONCLUSIONS

For the purpose of drawing some general conclusions, it would be best to start with the analysis of the classic diagrams. It is apparent at first glance that there are two minimums of height (time) loss, separated by a local maximum. The first (left side) mimimum is obtained when the acceleration maneuver is accomplished before entering the zone of negative vertical wind speed gradient. The second minimum appears when the acceleration is done after passing through this zone. But, if the glider is accelerated right in the negative gradient section, the local maximum of comparative height loss occurs, although the speed pattern is very close to the apppropriate momentary MacCready speed. The loss is due to dynamic effect of passing through negative vertical wind gradient with a downward inclined flight path.

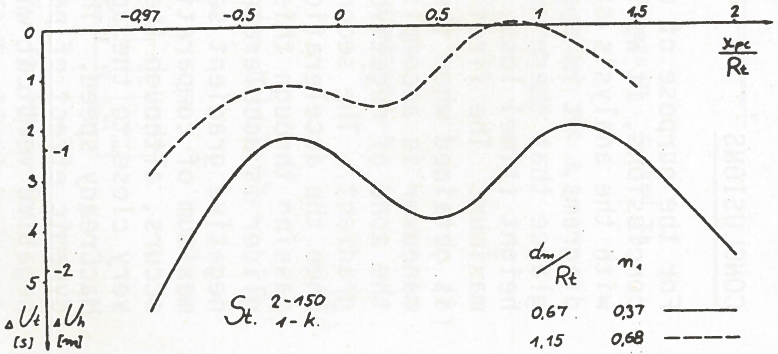
The first minimum of comparative

1. w_{max} = 2 m/s, R_t = 150 m

St. m = 312 kg

ϕ = 38,4° R_k = 73 m V_{ki} = 79,73 km/h w_z = 0,417 m/s

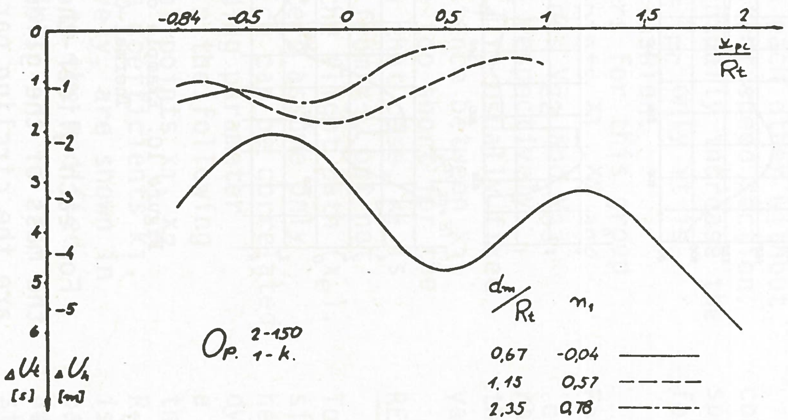
- C_{mc} = 1 => V_{mci} = 109,11 km/h



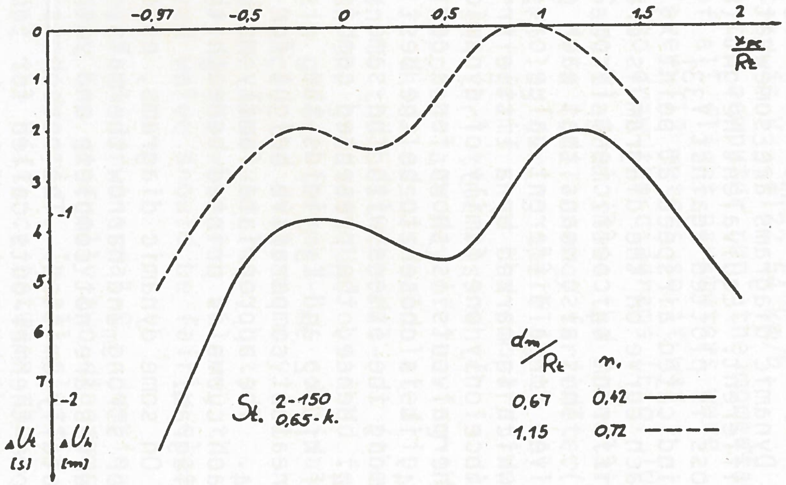
Op. m = 486 kg

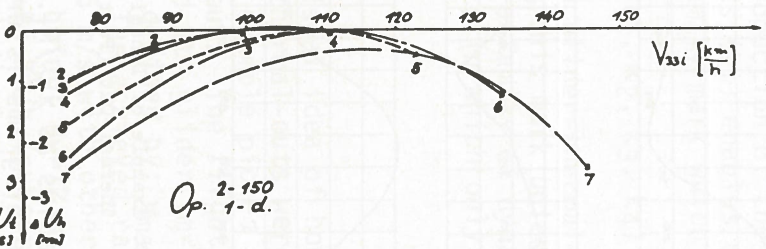
ϕ = 40° R_k = 63 m V_{ki} = 76,2 km/h w_z = 0,906 m/s

c_{mc} = 1 => V_{mci} = 134,23 km/h



- C_{mc} = 0,65 V_{mci} = 105,84 km/h





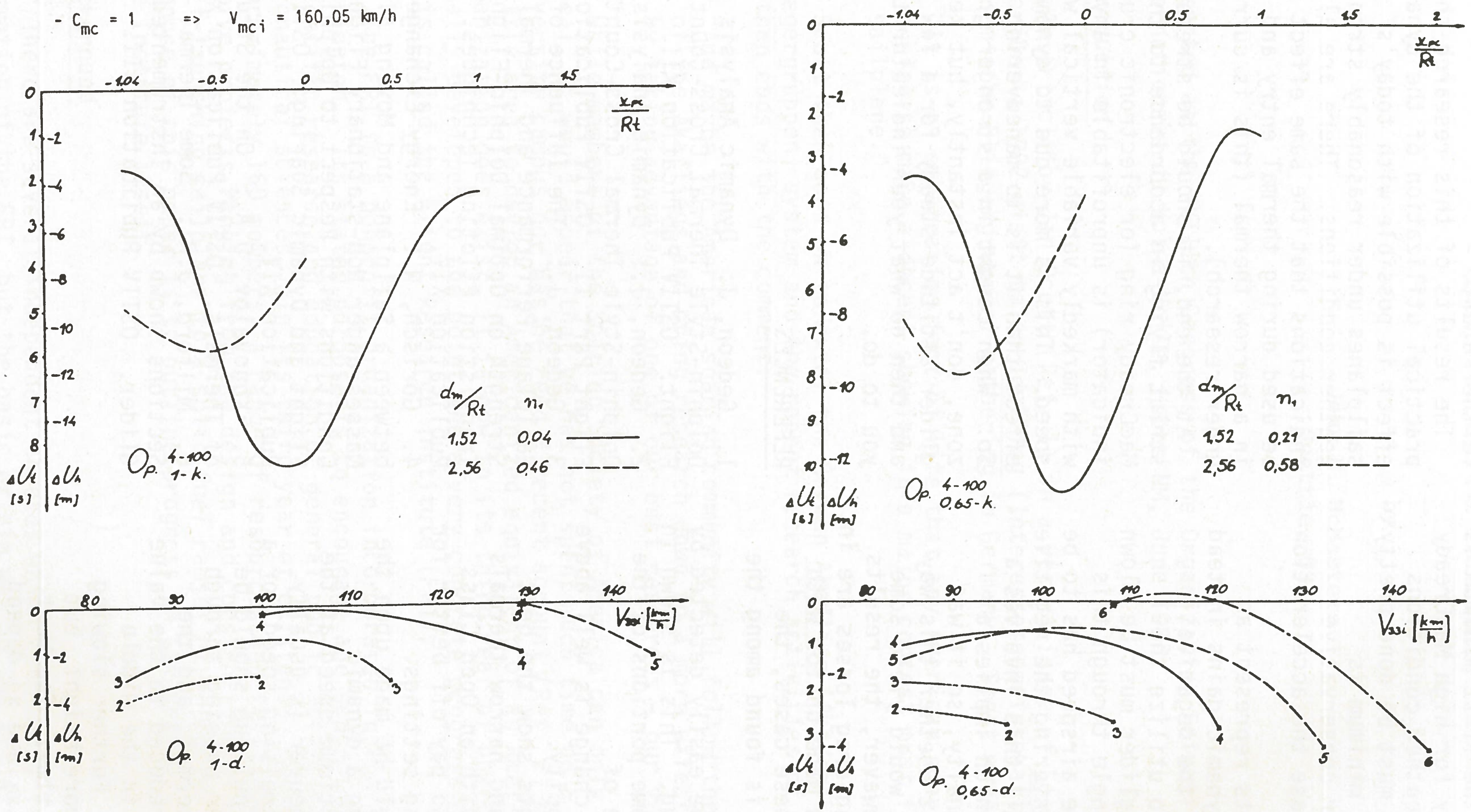
2 → P_d (2,2,1,2)
3 → P_d (2,2,1,3)
4 → P_d (2,2,1,4)
5 → P_d (2,2,2,5)
6 → P_d (2,2,2,6)
7 → P_d (2,2,2,7)

Op. m = 486 kg

$\phi = 51{,}1^0$ $R_k = 52$ m $V_{ki} = 84{,}2$ km/h $w_z = 1{,}871$ m/s

$-C_{mc} = 1$ => $V_{mci} = 160{,}05$ km/h

$-C_{mc} = 0{,}65$ = $V_{mci} = 144{,}77$ km/h



$2 \rightarrow P_d$ (1,2,1,2)
$3 \rightarrow P_d$ (1,2,1,3)
$4 \rightarrow P_d$ (1,2,2,4)
$5 \rightarrow P_d$ (1,2,3,5)

$2 \rightarrow P_d$ (1,2,1,2)
$3 \rightarrow P_d$ (1,2,1,3)
$4 \rightarrow P_d$ (1,2,2,4)
$5 \rightarrow P_d$ (1,2,3,5)
$6 \rightarrow P_d$ (1,2,3,6)

height loss gives a shorter time, but also a lower height than the second. Generally speaking, the first minimum is more appropriate only for high MacCready settings in strong weather conditions and the acceleration must be done pretty sharply. The second minimum is invariably better for conservative flying and in this case the acceleration should be gradual.

Dynamic thermal-outs represent an attempt to produce dynamic gains instead of dynamic losses in the negative gradient section. To utilize the dynamic effect, the glider must be flown in a certain climb angle through this zone. Therefore, the airspeed has to be increased prior to entering the negative gradient section. All this involves a lot of maneuvering which implies a considerable drag penalty, so it was impossible to predict whether this way of leaving a thermal would yield some benefits or not. However, the results show that maneuvering drag losses are in many cases more than made up for with dynamic gain. In these cases, the optimal thermal-out is found among the dynamic ones.

Dynamic gain can be easily detected by TE variometer reading. This is shown in Fig. 10, where in some portions of the flight path the rate of total-energy-height change is well above the net updraft velocity.

Dynamic thermal-outs show the best results for strong and narrow thermals and when performed with an Open Class sailplane. They also pay off better for higher MacCready ring settings.

Some comments should be made upon the best way of executing a dynamic thermal-out. The optimum speed at the end of the first maneuver is usually near the MacCready cruising speed, or a little less. Next, pull-up should be started shortly after passing through the center of the thermal, and the airspeed should be reduced to the value that lies somewhere in the middle between V_{22} and V_k. Further slowing down would extract more height, but would cost too much time. The best locations of points x_1 and x_3 depend on the magnitude of desired speed changes, while the position of x_2 is nearly fixed. Generally, for greater speed changes x_1 and x_3 should be farther apart.

The results of this research show that practical utilization of the dynamic effect is possible with today's sailplanes under reasonably strong weather conditions. There are also indications that the same effect could be used during thermal entry and climb in a narrow thermal (this is currently under research).

At the end, it should be stressed that strict flying in accordance to the MacCready ring (or electronic cruise indicator) is unprofitable in any zone with markedly variable vertical wind speed. This is more due to dynamic effect than it is to maneuvering drag. So: When caught in a stronger gradient zone, don't act instantly, but keep the glider attitude steady for a few seconds and then do what your indicator tells you to do.

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