DYNAMIC ENERGY TRANSFER BETWEEN WIND AND AIRCRAFT

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Abstract

Wind velocities varying in space and time produce aerodynamic forces and moments and consequently changes in total energy of the aircraft. First, the theoretical background to achieve maximum dynamic energy transfer will be presented. Subsequently the energy transfer problem is discussed using a glider airplane with up- and downdrafts varying in space. The response of the glider airplane in the vertical wind has been calculated by a nonlinear simulation program on a digital computer. Manoeuvers of the aircraft, producing optimal energy transfer are connected with a high kinetic energy level of the airplane and high load factors depending on vertical wind velocities. Compared with the well known dolphin flight manoeuvers, first described by Nickel and McCready, the energy-optimal flight manoeuvers significantly increase the average groundspeed of a glider airplane.

I. Introduction

Disturbances in total energy of airplanes due to variable wind velocities endanger transport airplanes and in some cases the disturbance may lead to aircraft accidents. These undesired wind disturbances, as there are gusts and windshear, also cause stresses in the aircraft structure, reduction in handling qualities, air sickness of passengers. On the other hand wind, especially vertical wind, can be the main energy source of glider aircraft.

The problems of energy transfer between wind and aircraft can be discussed very clearly for glider aircraft due to their excellent aerodynamics and the absence of the sometimes complex influence of propulsion.

As a result of limited time, this paper shall be restricted to the energy effect of vertical wind only, although the horizontal energy transfer in windshear conditions is of great interest (1) as well.

II. List of Symbols

C_D	drag coefficient
C_L	lift coefficient
D	drag
E	total energy
g	constant of gravitation
H	height
$\dot{H}$	rate of climb
H_E	energy height
$\dot{H}_E$	specific excess power
L	lift
m	aircraft mass
n	load factor
S	wing aera
V	true airspeed
V_K	flight path velocity
V_W	wind velocity
W	weight
w_{Wg}	vertical component of wind velocity
α	angle of attack
α_W	wind incidence angle
γ	flight path inclination angle
θ	pitch attitude angle

III. Theoretical background

The total energy of an airplane is composed of the potential and the kinetic energy. The effect of rotary energy is negligibly small.

$$E = \frac{m}{2} V_K^2 + W H \qquad (1)$$

The total energy related to the aircraft weight yields the specific total energy, which is here expressed as energy-height H_E

$$H_E = \frac{E}{W} = \frac{V_K^2}{2g} + H . \qquad (2)$$

The specific excess power (SEP) results from the time derivative of the energy-height

$$\dot{H}_E = SEP = \frac{dH_E}{dt} = \frac{V_K \dot{V}_K}{g} + \dot{H} . \qquad (3)$$

The groundspeed vector $\underline{V}_K$ is the sum of the true airspeed $\underline{V}$ and the wind velocity vector $\underline{V}_W$ (Fig.1). The angle between airspeed and groundspeed vector is defined as wind incidence angle α_W (Fig.1).

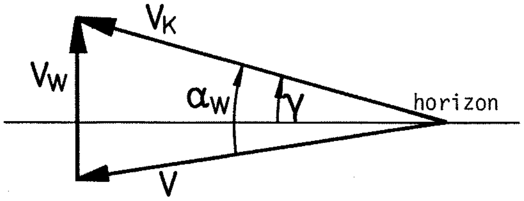

Fig.1: Velocity vectors

The equations of motion of a glider airplane in a vertical wind field can be derived from Fig.2 for a flignt path oriented coordinate system

$$m \dot{V}_K = L \sin \alpha_W - D \cos \alpha_W - W \sin \gamma \qquad (4)$$

$$m V_K \dot{\gamma} = L \cos \alpha_W + D \sin \alpha_W - W \cos \gamma . \qquad (5)$$

It should be mentioned that the lift vector is always perpendicular to the true airspeed vector $\underline{V}$ and will be rotated with respect to the wind incidence angle α_W. For example an updraft will increase α_W and therfore it yields a forward lift component (Fig.2).

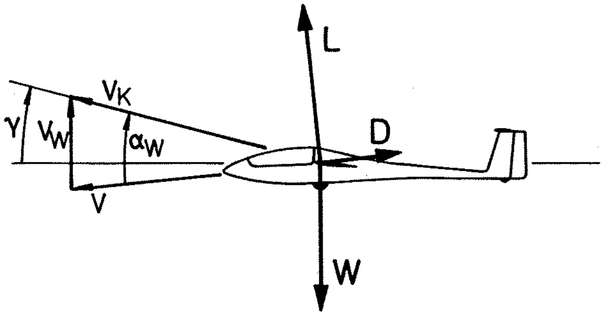

Fig.2: Aerodynamic forces and weight

We will define the load factor n

$$n = 1 + \frac{V_K \dot{\gamma}}{g} \qquad (6)$$

and the rate of climb

$$\dot{H} = V_K \sin \gamma . \qquad (7)$$

These definitions will simplify the equations of motion

$$\dot{H}_E = V \frac{L}{W} \sin \alpha_W - V \frac{D}{W} \cos \alpha_W \qquad (4a)$$

$$n = \frac{L}{W} \cos \alpha_W + \frac{D}{W} \sin \alpha_W . \qquad (5a)$$

For glider airplanes with their excellent aerodynamics the approximation

$$L \cos \alpha_W \gg |D \sin \alpha_W|$$

will further simplify the equation of motion

$$\dot{H}_E = n V \tan \alpha_W - n \frac{D}{L} V . \qquad (4b)$$

In general the wind incidence angle α_W will be small $|\alpha_W| \ll 1$. Under the constraint that the wind velocity will consist only of up- and downdrafts, the vertical wind component can be formulated as

$$w_{Wg} = - V \tan \alpha_W \approx - V \alpha_W .$$

This will reduce the expression of the specific excess power

$$\dot{H}_E \simeq - n w_{Wg} - n V \frac{D}{L} . \qquad (4c)$$

The true airspeed in dynamic flight can be derived from equation (5a) and (6)

$$V = \sqrt{\frac{2 n W}{\rho S} \frac{1}{C_L}} . \qquad (7)$$

The final formula for specific excess power will now be

$$\dot{H}_E = - n w_{Wg} - \sqrt{\frac{2n^3}{\rho} \frac{W}{S}} \frac{C_D}{C_L^{3/2}} \qquad (4d)$$

In stationary flight (n=1), the maximum energy transfer between wind and aircraft or the maximum excessed power, respectively, can be obtained at the minimum of the aerodynamic waste power $(C_D/C_L)^{3/2}$.(Fig3)

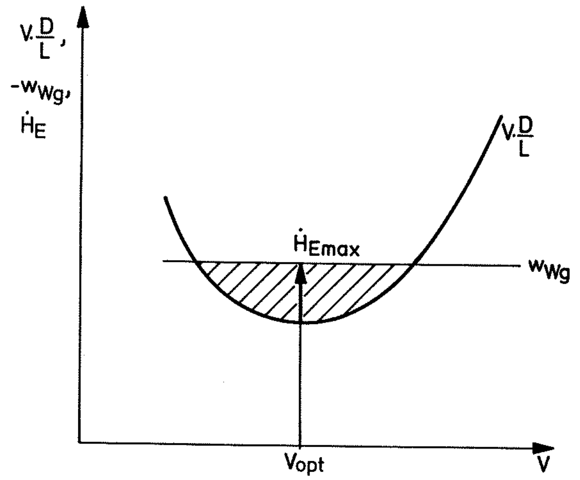

Fig.3: Specific excess power
Penaud-diagram (steady state flight)

In dynamic flight ($n \neq 1$) the transferred wind power will increase linearly with load factor. On the other hand the aerodynamic waste power will increase non-linearly with load factor. The PENAUD-diagram for specific excess power demonstrates (Fig.4) that a rising load factor will first increase the specific excess power $\dot{H}_E$. At high load factors the SEP decreases again. There exists an optimal load factor for maximum energy transfer. This optimal load factor n_{opt} may derive from equation (4d)

$$\dot{H}_{E\,max}: \quad \frac{d\dot{H}_E}{dn} = -w_{Wg} - \frac{3}{2} n_{opt}^{1/2} \times \sqrt{\frac{2W}{\rho S}} \left(\frac{C_D}{C_L^{3/2}}\right)_{min} \overset{!}{=} 0 . \qquad (8)$$

After conversion of equation (8) the optimal load factor can be written as follows:

$$n_{opt} = \frac{2}{g} \rho \frac{S}{W} \left(\frac{C_L^3}{C_D^2}\right)_{max} w_{Wg}^2 . \qquad (8a)$$

Equation (8a) and Fig.4 demonstrate that maximum energy transfer in dynamic flight will be obtained at minimum aerodynamic waste power. The optimal load factor n_{opt} for maximum excess power will increase with the square of vertical windspeed. Typical wing loads W/S, e.g. an updraft of $w_{Wg} = -2\ ms^{-1}$, require an optimal load factor $n_{opt} > 6$ for maximum energy transfer. This high load factor is not acceptable due to pilot stress.

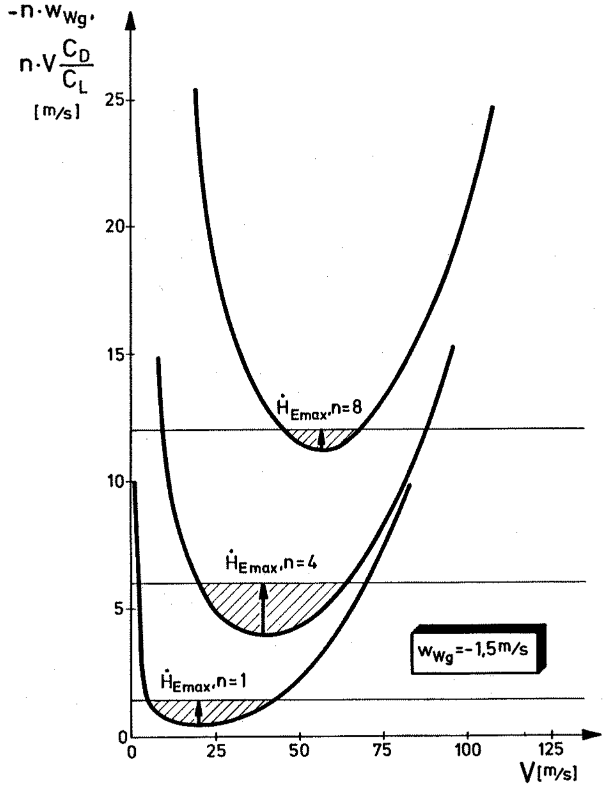

Fig.4: Specific excess power
PENAUD-diagram (variable load factor)

At the optimal load factor, the transferrable energy will increase progressively with increasing updrafts (Fig.5). The related optimal true airspeed can be derived from equation

$$V_{opt} = \sqrt{\frac{2}{\rho} \frac{W}{S} n_{opt} \frac{1}{C_{L\,opt}}} \qquad (7b)$$

The optimal lift coefficient $C_{L\,opt}$ corresponds to the minimum aerodynamic waste power $(C_L^3/C_D^2)_{max}$.

Using a glider airplane the question shall be discussed in what manner the maximum energy transfer can be realized.

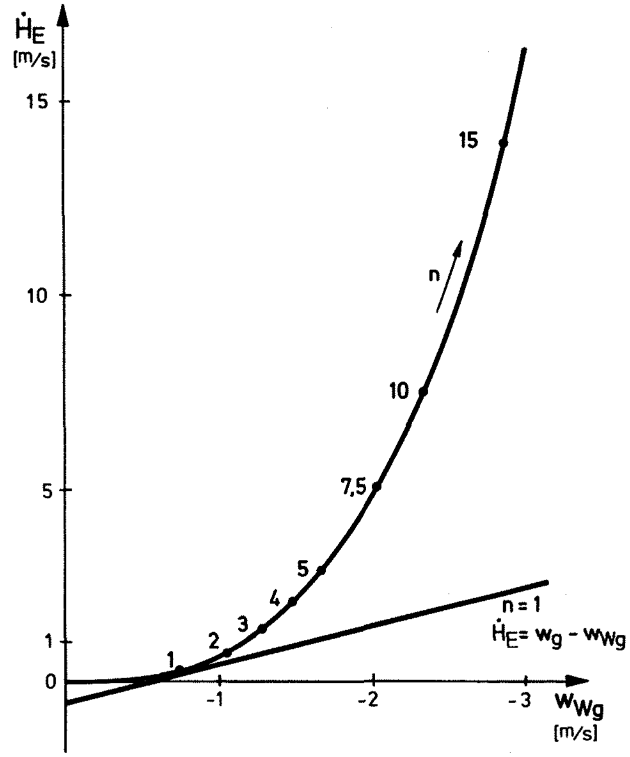

Fig.5: Specific excess power in steady and dynamic flight

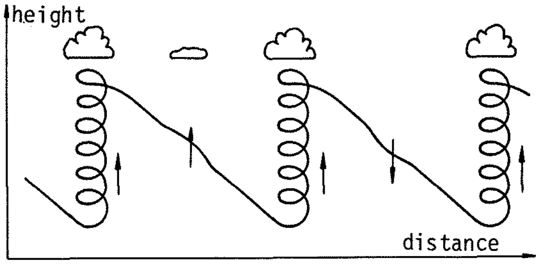

Fig.6: Typical manoeuver-cycle of a glider airplane

IV. Maximum average groundspeed of a glider airplane

A typical manoeuver-cycle of a glider airplane $^{(2)}$ is given in Fig.6. After take off, height will be gained in updrafts in circling flight with maximum rate of climb. Starting at a certain height, usually just below the cumulus cloud, distance will be gained in a gliding-flight segment with a loss in height at the same time. In the next proper updraft the manoeuver-cycle starts over again with a circling-flight. In large fields of updrafts a quasi-horizontal flight without circling turns may be possible in some cases. The calculation of the maximum average ground speed $\bar{u}_{Kg}$ of a glider airplane in varying up- and downdrafts is a difficult problem of variation calculus. This calculus problem has been solved for constant up- and downdrafts by Nickel $^{(3)}$ and McCready $^{(4)}$ thirty years ago in an ingenious simple graphical procedure. This Nickel-McCready procedure has very positively influenced the soaring flight. This procedure claims that the optimal airspeed in the gliding flight segment can be calculated from the expected rate of climb in the next circling flight as well as from the observed rate of descent in the gliding flight segment. The glider pilot has to control the actual airspeed so that the difference between optimal and actual airspeed will be small. This non-linear control loop is very stable and experienced pilots have no problems to fly the Nickel-McCready-procedure. A result of this procedure is to reduce airspeed in updrafts and to increase airspeed in downdrafts during the gliding flight segment. This variation of airspeed requires a variation of the flight path as there is no thrust available in a glider airplane. An outside observer may compare this variable flight path with flying dolphins. This flying technique was therefore called dolphin style. The variation of airspeed and flight path result in variable and sometimes high load factors. This fact is contrary to the constraint of constant vertical velocities and constant load factors in the Nickel-McCready procedure.

At the Institute of Flight Mechanics at the Technical University of Braunschweig several master thesises were contributed to optimal dolphin flight, where applied calculation procedures have been very similar. The response of the glider airplane with respect to a vertical wind field and an elevator control input has been calculated on a digital computer in a non-linear simulation program for longitudinal motion. The unknown optimal elevator deflection for maximum average ground speed is approximated by a spline function where the displacements are iterated by a parameter variation procedure $^{(5,6)}$ in a manner that the average groundspeed will be maximized. A typical result for a "1-cos"-shaped updraft is presented in Fig.7.

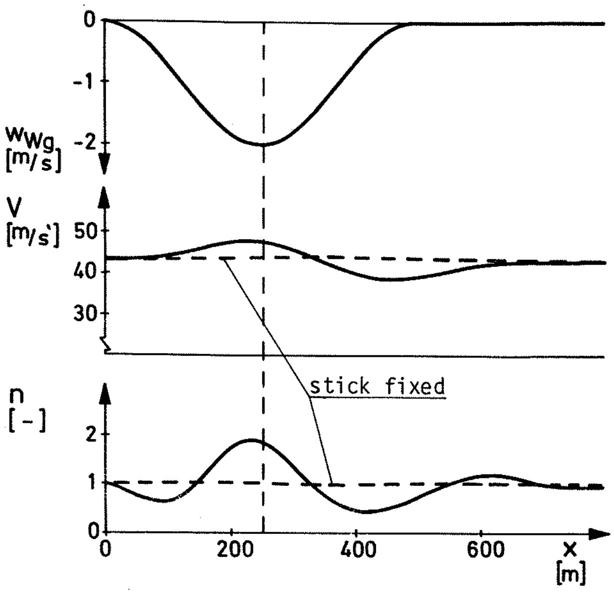

Fig.7: Optimal response of a glider aircraft in a "1-cos"-shaped updraft (case a)

Compared to this optimal procedure Fig.8 presents a simulation result in the same "1-cos"-shaped updraft with an ideal paper pilot applying the Nickel-McCready technique. The most influencing parameter is the dimension of the vertical wind field, or in other words the wave-length of the field (see Fig.7 and 8).

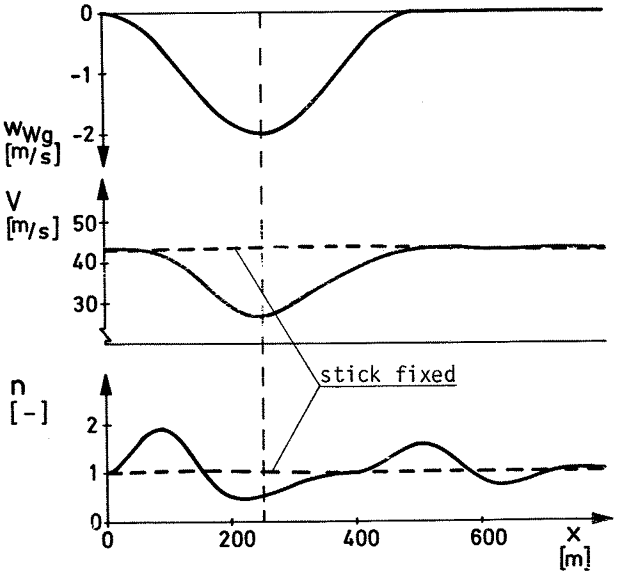

Fig.8: Response of a glider aircraft in a "1-cos"-shaped updraft with an ideal paper pilot applying the Nickel-McCready procedure (case b)

The differences in average ground speed are shown in Fig.9 for the different procedures.

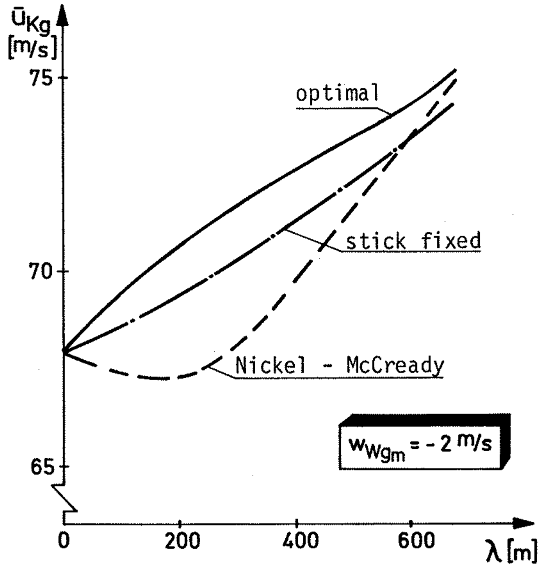

Fig.9: Average ground speed depending on vertical wind field dimensions

For small wind field dimensions the optimal procedure produces significantly higher average ground speed compared to the Nickel-McCready style. The resulting load factors are high while for large wind field dimensions the optimal load factors are small and of the same magnitude when compared to the Nickel-McCready procedure. As additional information in Fig.7, 8 and 9 the results are added for a stick-fixed elevator procedure.

A comparison of the load factors for the optimal procedure (case a) with the Nickel-McCready procedure (case b) shows the following differences. In case b the control stick, respectively the elevator, will be pulled backward in an increasing updraft (Fig.8) resulting in decreasing airspeed. The load factor will be less than one in the core of the updraft. In contrast to this behaviour, in case a the maximum load factor occurs in the core at a reasonable high airspeed. In Fig.10 the change of energy height in the updraft confirms that in case b energy height will be gained when the airplane enters the updraft and will be lost on the other hand when the aircraft passes the core of the updraft.

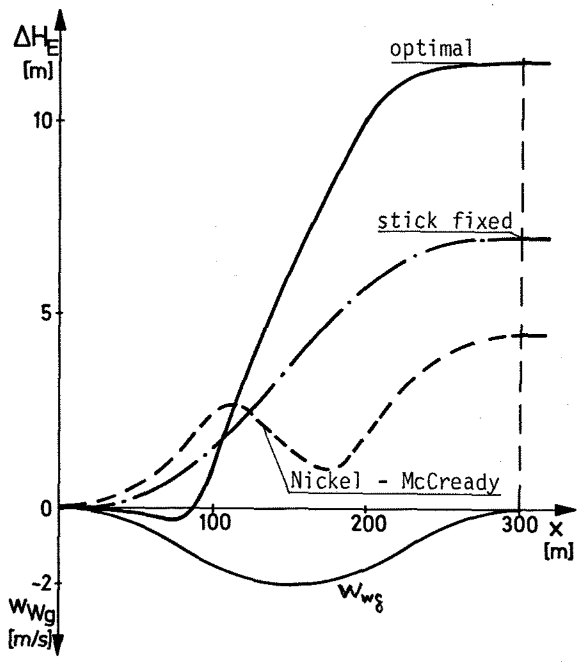

Fig.10: Change of energy-height in an updraft

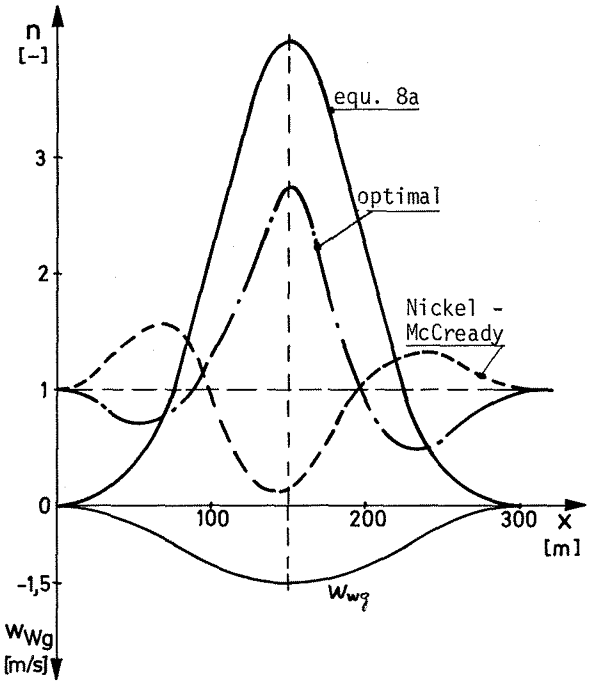

Fig.11: Load factors for different manoeuvers in an updraft

In the optimal manoeuver (case a) the greatest benefit in energy height can be obtained in the core of the updraft. The resulting energy height will be greater for the optimal manoeuver (case a) compared with the Nickel-McCready procedure (case b).

A comparison of the load factors for case a and b in the updraft (Fig.11) with load factors for maximum specific excess power (see equation 8a) shows that for a maximum average ground speed of a glider airplane the energy optimal manoeuver should be aspired. Within small vertical wind fields and at a high kinetic energy of the glider airplane these energy-optimal manoeuvers could be realized in an ideal manner. Large vertical wind field dimensions and low kinetic energy do not permit to fly an energy-optimal manoeuver for a long period without losing to much airspeed and stalling the aircraft. In this particular case, the airplane should increase airspeed before entering the updraft in order to have enough kinetic energy available for an approximative energy-optimal manoeuver.

V. Recommendation and outlook into the future

The relationship between energy-optimal flight manoeuvers and maximum average ground speed of glider airplanes can be stated. The main parameters, which are of influence, can be derived analytically. However, no applicable procedures and cockpit displays for flight guidance and control exist to enable pilots to soar energy-optimal manoeuvers. In addition, it is quite unknown, how and how long a pilot can endure alternating high load factors. The pilots may be advised for achieving a high average ground speed in soaring flight to apply the Nickel-McCready procedure only in large vertical wind fields and to keep the stick-fixed in medium and small wind fields which frequently occur in Central Europe (Fig.12).

Successful glider pilots have already flown almost optimal manoeuvers on the basis of their immense soaring experiencing and have only applied the Nickel-McCready style with caution.

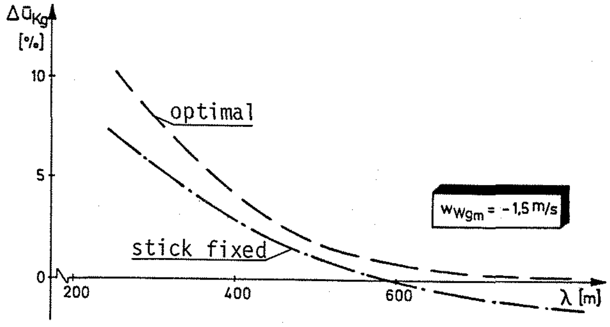

Fig.12: Gain in average ground speed compared with the Nickel-McCready procedure

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