Glider's Climb in Turbulent Air

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Abstract

Atmospheric turbulence provides thrust to airplanes. It is shown that the thrust is equivalent to an energy gain which contributes to the airplane's compensated climb rate. Based on the lift-coefficient versus angle-of-attack curve and the force-against-wind energetic interaction of the airplane with its environment, an expression is derived which quantifies the climb rate ("gain") for a glider induced by the atmospheric turbulence. It is shown that the gain is proportional to the speed flown, the square of the velocity of the turbulent air movement, and inversely proportional to the airplane's wing loading. Quantitatively, the gain for a modern glider flying in turbulent air with alternating gust-induced load variations of e.g. (1 +/- 0.5) × g (g, earth acceleration, 9.81 m/s²) amounts up to approximately 0.5 m/s.

We discuss the gust model which is used, the role of the lengths of the gusts, and the influence of the wing's elasticity. It is concluded that glider pilots should prefer to fly through turbulent regions rather than through quiet air if they have the choice. In order to take profit from the gusty conditions they should reconsider the pros and cons of taking water ballast, as the gain due to turbulence is less with the heavier airplane, and they should prefer planes which have rigid wings.

Turbulence is a major contributor to flight energy. It should be considered in addition to the known updrafts such as thermals, slope updrafts, rotors and lee waves, and as distinct from dynamic soaring using steady wind shears. The contribution of gusty air is quantified and the theory of the best-speed-to-fly is amended to include the influence of turbulence.

Nomenclature

A	wing area (m²)
m	mass of the airplane (kg)
g	earth acceleration (9,81 m/s²)
W	weight of the airplane mg (N)
ρ	air density (kg/m³)
v	*TAS*, speed of the airplane with respect to the surrounding air (m/s)
w	velocity of the surrounding air (m/s) with respect to earth; when the movement of the surrounding air is a gust, w is the component in the z-direction of the airplane
$\lvert w\rvert$	amount of w, gust "strength" (m/s)
n	load factor, multiple of g (dimensionless)
L	instantaneous force of lift when entering the flow changes of the gust (N)
L_0	stationary force of lift at the speed v, n = 1, (N)
v_{cl}	climb rate resulting from the energy gained per second due to the flight through the turbulent atmosphere. v_{cl} is negative when a loss is incurred. Drag is neglected, (m/s)
$v_{cl\ average}$	average of v_{cl} (m/s)
α	angle of attack relative to the x-axis of the airplane (rad)
$\alpha 0, \alpha_0$	angle of attack relative to the x-axis, stationary at the speed v, (rad). Both formats have the same meaning
α^*	angle of attack relative to the x-axis (rad), at zero lift
$\Delta\alpha$	angle of attack increment/decrement when entering a sudden flow change of the gust (rad)
c_L	lift coefficient (dimensionless)
$c_{L,\alpha}$	lift coefficient at α

Superscript arrows denote vectors.

Introduction

Many contest soaring flights reveal amazingly high glide ratios during straight flight at high speed between thermals. In slope soaring with foehn conditions, pilots prefer to fly at high speeds, which seem to result in better performance, whereas lower speeds seem to be less advantageous, even though lower speeds should result in less drag.[a] The typical weather conditions in these cases are characterized by modest gusts up to strong turbulence.

[a] Personally communicated by Herbert Pirker, Vienna, who pursues the idea that high speed proves advantageous when gusty conditions prevail, as experienced during numerous foehn mountain slope soaring flights.

Turbulence is known to cause energy to be transferred to airplanes, sometimes called Katzmayr effect[1].

The work which, to my knowledge, comes closest to that presented in this paper was done by H.U. Mai.[2] In this work, the author's initial assumption was "that a sailplane may, by aeroelastic or other means, be able to absorb energy from gusts without pilot interference". He briefly explains "the thrust effect" by stating "that the lift is, by definition, always perpendicular to the instantaneous direction of the onset flow… thus the lift vector has a component in the direction of the motion, which is felt like an apparent thrust". One could perhaps anticipate that the gain in the upward gust is balanced ultimately by an equivalent loss in the downward gust, resulting in no net effect. This is not true; considering the component of the lift which is generated by the gust alone (neglecting the lift necessary to counteract gravity) for both the upward gust and the downward gust cases. The lift vectors for both of these are tilted forward, producing only positive thrust.

Mai used the equations for the mechanical force equilibrium including the basic equations describing the symmetric motions of an airplane disturbed from equilibrium flight.[3] The author applied the equations to a sinusoidal upward gust. He demonstrated an "energy altitude increase" which (in part) is the energy equivalent to the thrust effect. Computer simulations were run for a rigid sailplane, for a sailplane with a rigidly twisting wing, and for a sailplane with an elastic wing. The rigid airplane was concluded to have a slightly lower energy altitude gain compared with the flexible airplane. The results proved that the ability to absorb energy from gusts without pilot interference is not explained by the aero-elastic wing properties alone.

Mai had used a sinusoidal upward gust. One property of turbulence is randomness, i.e. the mean velocity over time and space is zero by definition. Any gust model introduced to calculate the energy extracted from gusty air therefore should show this property. Since the shifted sinusoidal shape has a positive mean value it cannot serve as a model for turbulence. A full 2π non-shifted sinusoidal shape consisting of a positive and a negative phase complies and might have easily been entered in Mai's program algorithm. In this paper we use a simple step model consisting of one phase $+|w|$ and one phase $-|w|$ at a defined overall cycle length.

Flight tests of scale model airplanes made in gusty conditions (unmanned aerial vehicles, UAVs) demonstrated energy savings when the flaps are automatically set. Interestingly, energy savings are also seen with fixed control surfaces, indicating that the control is not a prerequisite for energy savings due to gusty conditions but, rather, acts as an amplifier.[4]

Patel et al. (Ref. 4) explain the absence of "successful demonstrated energy extraction from random gusts using an autonomous UAV" with the "inability of full-scale aircraft and large UAVs to extract noticeable amounts of energy from natural turbulence," although "pilots of a new class of ultra-light sailplanes have discovered some of the benefits achievable from carefully controlled flight through atmospheric fluctuations, also referred to as microlift soaring." In contrast to this assertion, we believe that there is no such limit on the scale; the thrust from turbulence is to be found at any scale of aircraft, including recent contest gliders.

Dynamic energy gains are known to result from "dolphin"-style soaring, where pilots enhance the flight by pulling up when crossing an updraft and pushing the stick in downdrafts, thereby maximizing and aligning the lift vector with the air movement, Gorisch[5, 7, 8] and Collins and Gorisch.[6] Generating dynamic loads aligned with the wind in the region of windshear should lead to gains. It should allow sustained flight (compare the flight of albatrosses), the flight pattern being called dynamic soaring.[5] It was suggested that the centripetal force during circling in the low half of vortex-like isolated thermals contributes power to the climb rate.[9]

The basic idea is to apply the well-known law of mechanics to flight mechanics, i.e. power equals the product of the two vectors, load and velocity. The load vector is represented by the vector-sum of lift and drag. The velocity vector is represented by the vector-sum of the speed v of the airplane and the velocity of the air w at the location of the airplane. If, instead of the lift+drag vector, the load-factor vector (multiple of g, pointing in the direction of lift+drag) and instead of the velocity vector only the wind vector w is used, the product of both yields the net total-energy climb rate, as shown in Fig. 8.

From the literature, the approach often used, such as the one from Mai,[2] is to integrate the equations of motion in an inertial system. The result is the trajectory including an energy term, which is correct in obeying the above mentioned law of mechanics. However, the power delivered, if it is to be determined, needs the integral to be differentiated. This basic physical notion is hidden in the equations and not obvious. If one is interested in optimizing flight tactics in order to maximize the energy gain (the cruise speed, for example), optimal trajectories must be found by applying sophisticated numerical optimization algorithms. Although probably correct, the outcome is subject to interpretation. Therefore, the direct approach is preferred, see Eq. (1), for solving the equations of motion subject to the effects of turbulence.

Turbulence-induced loads follow each other so quickly that their active exploitation by conscious control, like the dolphin-type flight style, does not seem feasible. Fortunately, the loads due to turbulence are always aligned with the gust flow direction so that energy gains take place automatically.

From a physical point of view, turbulence represents kinetic energy. This is true because air masses have velocities resulting in the kinetic energy term: mass times velocity squared divided by two. An airplane flying through turbulent air may be assumed to have flattened the velocity distribution of the encountered turbulent air in the airplane's wake, as the downwash diminishes the gust flow. Thus, some of the atmosphere's kinetic energy is made available to it. The opposite is well known: as an airplane leaves air moving behind, spending the energy that corresponds to the drag losses.

In this paper, based on a representative gust model, the gains which are exploited by typical gliders are quantitatively determined. Although the gains are intrinsic to any flight in turbulent air, they may be optimized, the effect of water ballast, the best speed to fly, preferable design features, and dedicated instrumentation are considered.

Upon entering (or leaving) a gust, the angle of attack will change even when the speed remains unchanged. This will alter the amount of the lift L according to the lift curve and the glider's parameters. It will change the direction of the lift vector, as the lift is always perpendicular to the instantaneous direction of the onset flow. Dividing the lift by the weight of the airplane yields the load factor n. The load factor n is a multiple of the earth acceleration g. In the terms of physics, as said before, *power* is *force* times *velocity* (both pointing in the same direction). The interacting *force* is the weight of the airplane times the load factor n. The *velocity* is the velocity of the gust. Multiplying the one with the other yields the net mechanical power received by the airplane. The mechanical power then is normalized by the weight of the airplane, yielding the net climb rate v_{cl}.

Gust model

Since atmospheric flow has neither a source nor a sink, it must be rotational. In our case we deal with flow at a rather small scale. Turbulent flow radii of interest are in the range of tens of meters to hundreds of meters. The lower limit should be in the range of the wing span. The upper limit should be defined to exclude the scale of thermal convection, although real thermals contain turbulence that is within the scale of interest. Then, it is assumed that the axes of the turbulent circular flow events have no dominant direction, i.e. they are randomly oriented in space. Hence, the flow directions of the turbulence are randomly distributed.

An arbitrarily oriented gust consists of its three rectangular components: One is parallel to the airplane's speed vector relative to air (x-axis), the second is oriented span-wise (y-axis) and the third is pointing upwards (z-axis). The former two interact with the small forces of slip and drag; the latter interacts with the large force of lift. The relationship of the forces of drag and lift is in the order of the glide angle, i.e. in the range of 1/30 to 1/50. Since the gust points in a random direction, its component pointing in the airplane's z-axis has the same intensity, independent of the airplane's moving direction.

The spectrum of the turbulence is quantified by the *intensity* versus the *spacial frequency*. The *intensity* is the velocity of the gust squared $(m/s)^2$. The *spacial frequency* is cycles per meter. A norm curve is called *Dryden PSD*. According to this norm curve, the intensity is 1 $(m/s)^2$, which remains constant from 1 cycle per 1000 m down to 1 cycle per 100 m. The intensity is then steadily diminishing to yield at the end 10^{-5} $(m/s)^2$ at 1 cycle per 0.1 m, on a log-log scale.[2]

A simple yet representative model would specify one intensity value at one frequency value only, neglecting all the other frequencies. This restriction seems allowable, as only the lowest frequencies (i.e. the longest cycles) have the highest intensities, sharply falling off at cycles shorter than approximately 100 m. Therefore, it seems that shorter cycles than mentioned may be neglected without sacrificing too much accuracy. However, the parameter of the cycle length needs to be considered in detail because the flight path changes considerably during long lasting gusts, and the response dynamics of the aircraft become important.

A simple gust model, consisting of a row of alternating gusts with constant velocity at a constant cycle length, is suggested. The velocity is assumed to point in the airplane's aerodynamic z-axis, which is defined as being perpendicular to the direction of the local air movement. The gust model is depicted in Fig. 1.

Dynamic gains

Straight trajectory analysis

"Straight trajectory" denotes the simplifying assumption that the gusts are so narrow that the angle of attack does not noticeably change during the travel of the glider across the constant gust half wave.

The basic relationship describing the dynamic climb rate v_{cl} is:

$$v_{cl} = \vec{n} \cdot \vec{w} = |n| \cdot |w| \cdot \cos\beta \qquad (1)$$

In this equation, the net climb rate, v_{cl}, (ignoring the glider sink rate) is the scalar product of the g-load vector $\vec{n}$ (pointing in the direction of the lift vector) and the vector of the air velocity $\vec{w}$ in the earth-connected inertial system. Alternatively, the product of the amounts of the two vectors are multiplied with the cosine function of the angle β, which lies between the two vectors $\vec{n}$ and $\vec{w}$.

Since only the gust velocity w being oriented in or against the direction of the lift is considered, Eq. (1) simplifies to

$$v_{cl} = n\,w \qquad (2)$$

As observed in the gust model shown in Fig. 1, gusts that are oriented in the flight direction (x) or in the wing direction (y) are neglected. Vertical gusts with velocities $+|w|$ and $-|w|$ follow periodically.

The g-load factor n now is related to several parameters including the gust speed w, the $dc_L/d\alpha$ slope, the speed of flight v and the lift L of the glider, as follows.

The gust cycle is assumed to consist of two parts, the one providing a constant gust speed $|w|$ upwards, the other providing a constant gust speed $-|w|$ downwards, as illustrated in Fig.

1. "Upwards" and "downwards" is understood to be related to the z-axis of the airplane. The average of the wind is zero. The longitudinal length of the gust cycle is assumed to be small; however, this parameter will be discussed later. The gust cycles are assumed to follow each other in a row without quiet intervals.

The gusts cause the angle of attack α to change by $+\Delta\alpha$ or by $-\Delta\alpha$, respectively. Because of the geometry of the two velocities w and v, $\Delta\alpha$ can be written as

$$\Delta\alpha = \arctan\left(\frac{w}{v}\right) \qquad (3)$$

and, as w is small compared with v,

$$\Delta\alpha = \frac{w}{v} \qquad (4)$$

The lift in still air, L_0, is equal to the weight, W, such that

$$L_0 = W = \frac{\rho}{2} v^2 A c_{L,\alpha 0} \qquad (5)$$

where the air density is given by ρ, the wing area by A, and the lift coefficient by $c_{L,\alpha 0}$.

The lift L generated while crossing the gust is

$$L = \frac{\rho}{2} v^2 A c_{L,\alpha 0+\Delta\alpha} \qquad (6)$$

where it is assumed that the gust is so short that the lift remains constant.

When entering the gust cycle, the g-load factor n is the quotient between the dynamic lift from Eq. (6) and the lift in still air from Eq. (5), as follows:

$$n = \frac{L}{L_0} = \frac{c_{L,\alpha 0+\Delta\alpha}}{c_{L,\alpha 0}} \qquad (7)$$

The relationship between the lift coefficient and the angle of attack is given by the lift curve, c_L vs. α. The slope of the linear portion of the lift curve for a two-dimensional airfoil is approximately 2π. For finite wings, the two-dimensional value should be corrected using the aspect ratio; however, for sailplanes this correction is small and the value 2π will be used here. The lift curve intersects the abscissa at the angle α^*, see Fig. 2.

The lift coefficient in still air is

$$c_{L,\alpha 0} = 2\pi(\alpha_0 - \alpha^*) \qquad (8)$$

and the lift coefficient when entering the gust is

$$c_{L,\alpha 0+\Delta\alpha} = 2\pi(\alpha_0 - \alpha^* + \Delta\alpha) \qquad (9)$$

Eq. (7) now reads:

$$n = 1 + \frac{\Delta\alpha}{\alpha_0 - \alpha^*} \qquad (10)$$

We need to replace the term $\alpha_0 - \alpha^*$ by known parameters. This is done by inserting $c_{L,\alpha 0}$ from Eq. (8) into Eq. (5) and by solving the result for $\alpha_0 - \alpha^*$:

$$W = \frac{\rho}{2} v^2 A \cdot 2\pi(\alpha_0 - \alpha^*) \qquad (11)$$

$$\alpha_0 - \alpha^* = \frac{W}{2\pi \frac{\rho}{2} v^2 A} \qquad (12)$$

Replacing $\alpha_0 - \alpha^*$ with the expression from Eq. (12) and replacing $\Delta\alpha$ with w/v (see Eq. (4)), Eq. (10) now becomes:

$$n = 1 + \frac{\pi \rho A}{W} \cdot wv \qquad (13)$$

Note that π should be replaced by half of the lift-curve slope, $0.5 \times dc_L/d\alpha$, when it is known. Equation (13) corresponds to the "Load Factors", clause 3.262 of the *OSTIV Airworthiness Requirements/Standards for Sailplanes*.[9] See footnote[b].

The climb rate, see Eq. (2), is now given by

$$v_{cl} = w + \frac{\pi \rho A}{W} \cdot w^2 v \qquad (14)$$

The average climb rate is calculated by averaging w and w^2. The average of w is zero by definition. The average of w^2 is $|w|^2$. Hence,

$$v_{cl\ average} = \frac{\pi \rho A}{W} \cdot |w|^2\ v \qquad (15)$$

[b] I refer to the 1976 edition of the OSTIV requirements. The equation which describes the "Load Factors" contains the "Gust Alleviation Factor" k, meaning that w has to be written as $k \times w$. Its value is primarily dependent on the altitude and the wing loading. Although an estimate for k for a sailplane having a mean geometric chord of 0.6m yields a value for k of about 0.6 (see p. 26 of Ref. 10), it will assumed here to have a value of 1. Further consideration of k may be worthwhile.

The average climb rate $v_{cl,average}$ turns out to be proportional to the speed v and to the square of the gust strength $|w|$. It is inversely proportional to the wing loading, i.e. weight W per wing area A, given in N/m².

Estimation: Let ρ = 1 kg/m³; wing loading W/A = 300 N/m²; gust strength $|w|$ = 1 m/s; speed v = 50 m/s (= 180 km/h):

$$v_{cl\ average} = 0.52 \text{ m/s}$$

This estimation shows that the gust-induced climb rate contributes considerably to the energy balance of the airplane.

Since power is force times velocity, we state the following identity with respect to the mean of the thrust T, the mean of the speed v, the weight mg and the mean of the climb rate v_{cl}.

$$T\ v = m\ g\ v_{cl} \qquad (16)$$

With Eq. (15) T is:

$$T = \pi \rho A |w|^2 \qquad (17)$$

The thrust per weight represents the climb angle of the airplane as opposed to the (negative) glide angle in still air. The former turns out to be inversely proportional to the wing loading W/A:

$$\frac{T}{W} = \pi \rho\, |w|^2\, \frac{A}{W} \qquad (18)$$

Curved trajectory analysis

It has been assumed that the gusts are so narrow that the angle of attack does not noticeably change during the travel of the glider through the constant gust half wave. This simplifying assumption made the calculation of the climb rate rather simple. This simplification is not justified when the gust is so wide that the airplane's trajectory becomes noticeably curved due to the long lasting acceleration in the z-direction, as illustrated in Fig. 3.

Qualitatively, the angle of attack after gust entry decreases steadily when flying through the upward gust section of the gust cycle. This results in a steady decrease of the g-load, thereby decreasing the energy gain. On the other hand, there is a larger step decrease of the angle of attack when entering the downward part of the gust, resulting in an even smaller energy loss in this downward gust section. This effect continues to take place at every gust step encountered. The curving of the trajectory, therefore, leads to losses and gains at the same time, which suggests that the simple result from Eq. (15) still remains applicable. However, a more detailed analysis follows which quantifies the effect of the curved trajectory.

It has been found beneficial to use a numerical segment-by-segment algorithm rather than looking for analytic formulas and integrating them to determine the trajectory and the energy transfer. The gust cycle length is divided into 64 segments, which is assumed to be enough to provide sufficient accuracy. Every segment becomes a column in a spread sheet diagram.[c] Two gust cycles were run. The calculation loop for every segment starts with the angle of attack and then the local g-load is derived. The z-acceleration is integrated to yield the speed z-component that is used to derive the new angle of attack, which then starts the loop for the next segment. The energy is summed up during the second gust cycle to yield the average climb rate in this interval. Although bulky compared with a *FORTRAN* program, the spread sheet is easily adjustable and allows quick graphical illustrating. The parameters required are the air density, ρ, the wing area, A, the weight of the glider, W, the glider's speed, v, the gust strength $|w|$, and the gust cycle length. The output is the gust-induced net climb rate. Although the power gain physically emerges as a thrust, it is assumed that the pilot continually converts the thrust into height. Hence, the speed can be assumed to be held constant.

The question about the amount of correction to be applied to the resulting Eq. (15) due to a more realistic curved trajectory is now addressed by the following results. A series of spread sheets show the net climb rates versus the gust cycle lengths (Fig. 4):

Gust cycle lengths:	up to 50 m	100 m	200 m
Correction:	less than -1.8%	-4.5 %	-11.1 %

Eq. 15 needs a correction of only −1.8% when flight intervals of 0.5 s in the upward gust and 0.5 s in the downward gust are encountered, by −4.5% when the gusts are 1 s upward and 1 s downward, and long gust cycles of 2s upward and 2s downward need to be corrected by −11.1%, all at a speed of 180 km/h. The table above is true for any speed. The result is depicted in Fig. 4.

Speed polar and water ballast

The speed polar of the 18-m glider 304S Shark, shown in Fig. 5, is used for the calculations that follow. Polars with and without water ballast as given by the manufacturer are presented in Fig. 6. Several data points on the two polars were introduced into the spread sheet ("MacCready polars.xls") for further analysis. Any speed polar data can be entered into the spreadsheet and analyzed.

Multiple data points of the net climb rate at different speeds v due to the turbulent atmosphere as characterized by the gust strength $|w|$ have been added to the polar to yield the overall climb or sink rates. One result which serves as an example is shown in Fig. 7.

[c] We used Microsoft Excel v2003. The Excel file may be requested from the author, wgorisch@t-online.de.

The speed of minimum sink of the overall polar is shifted to a higher value as compared with the baseline polar. Presumably this is due to the increased amount of power received from turbulence at increased speeds.

The aim of the MacCready- or speed-to-fly-theory is to derive speed commands and give tactical guidance so that the mean cross-country speed is maximized. The usual method is to draw a tangent to the polar curve from a given climb rate on the ordinate. The intersection of this tangent with the abscissa yields the average cross-country speed. Thus, it is necessary that the average of the long-lasting up- or downdraft and the climb rate during circling (the so called MacCready climb rate) be known.

Below cloud streets and along mountain slopes under crosswind conditions, extended areas of updrafts can exist. The strength of the mean updraft should be added to the polar by shifting the polar upwards by this strength. The tangent is drawn through the point of the MacCready climb rate. It should be kept in mind that the turbulence-induced climb rate changes rather drastically with the strength of the turbulence, as the relationship is characterized by the second power (square) of *w*. A two-fold strength of the gust means a four-fold energetic gain. Since near the ground the turbulence is generated by the wind interfering with the uneven surface, it is reasonable to assume that the stronger the slope updraft is, the stronger the turbulence. Hence, a strong enough crosswind across a given slope and ground shape may be enough to allow high speed level flight while the slope updraft alone might not.

As seen from Fig. 7, a heavy glider requires a stronger slope updraft for level flight compared to a light glider. The decision to take water ballast or not seems to depend on the speed at which the two overall polars intersect, which in our example (Fig. 7) is ~125 km/h. If the conditions allow level flight at a higher speed than 125 km/h, the heavy glider seems to have better performance than does the light glider.

The speed polar describes the constant sink speed in still air when the stationary aerodynamic force has to balance the weight of the glider. This is not true for the mean of the velocities, when the lift fluctuates. In this case the mean sink speed is higher. This effect has not been considered.

Net climb rate indicator

The net compensated variometer reading does not differentiate between the gain from turbulence and the gain from a steady updraft.

An indicator which displays the net climb rate generated by the local turbulence alone would help the pilot optimize their flight performance. Only on-board sensor data can be employed to do this.

Direct thrust measurement

The direct method is that of measuring the turbulence-induced thrust, i.e. the acceleration in the x-direction, directly. The drag, which points in the opposite direction, must be compensated, i.e. added to the measured acceleration. An accelerometer (weight transducer, electronic balance) may be fixed to the airplane such that it measures the actual g-load in the x-direction. Since the force is on the order of the drag, the acceleration in x-direction should be rather small, about 3% of *g*. In addition, the acceleration reading should be corrected for the earth acceleration when the angle of attack changes due to the variation of the lift coefficient. An on-board processor may be programmed to perform the corrections using the indicated air speed and the vertical g-load input.

The need for correcting the variation of the angle of attack may turn out to be less critical when the output is averaged. The average of the glider's acceleration due to gravity is zero when the speeds at the beginning and at the end of the averaging interval are equal. Still, the angle of attack which pertains to this speed (in smooth air) must be applied in the calculation loop.

Load measurement

According to Eq. (1), the system must have access to the load factor, *n*, and the gust strength, *w*. The load factor is easily detected using a g-meter, but *w* is probably not directly detectable. Hence, *w* must be calculated from known data. Eq. (13) may be used to derive *w* from *n* and known parameters. Solving Eq. (13) for *w* yields

$$w = \frac{W}{A}\,\frac{(n-1)}{\pi \rho v} \qquad (19)$$

To make this calculation, the parameters *W*, *A*, or the wing loading *W/A*, are to be entered pre-flight into the on-board processor by the pilot. The air density, ρ_i, may be taken automatically from standard atmosphere tables using the momentary altitude input from the static pressure probe. The g-load, n_i, and the speed, v_i, are readings from the g-meter (in z-direction) and from the kinetic pressure probe at the time step *i*.

The result of this calculation will be correct only when the load factor, *n*, only represents the gust loading and is not disturbed by piloting actions. Averaging may level out responses to short term control actions. The time constant of averaging should be so long that the integral over the load variations due to steering is near zero, i.e., presumably in the range of 10 to 20 s. For example, the processor may be programmed to run the calculation loop every 0.1 s and sum up the energy over 10 s. At any time, $v_{cl\ average}$ is calculated and displayed, counting the last 100 loops:

$$v_{cl\ average} = \frac{W}{\pi A} \times \frac{1}{100} \sum_{i=1\ldots100} \frac{n_i\,(n_i - 1)}{\rho_i v_i} \qquad (20)$$

A twin g-load crossed sensor may be installed to cover the x- and z-axes. The described two types of measurement may be applied in order to design an intelligent system that is able to eliminate errors beyond the capabilities of any single system, and perhaps perform additional tasks like considering phases of circling, the deviation from the horizontal flight, and communicating with other electronic on-board systems.

Wing elasticity

All of the analyses made here assumed that the entire mass of the glider is equally accelerated by the aerodynamic force acting on the wing. This assumption requires that the airplane's structure is perfectly rigid. In reality every wing bends more or less under load. In this case, during a gust encounter, the wing first accelerates and bends, transmitting the accelerating force to the fuselage which accelerates until the forces are in equilibrium. This means that the fuselage, together with the inner sections of the wings, experience a delayed acceleration. Since the energy gain depends on the mass and the g-load (represented by the z-acceleration), only after a delay is some fraction of the energy gained. Only a small amount of energy is sacrificed when the gust lasts for long enough for the forces to have time to reach equilibrium. On the other hand, when the gust cycle is shorter than this, flexing wings should mean less energy gains compared with rigid wings.

Quantitatively, every pair of wings has a fundamental symmetrical bending mode frequency that is known for every glider. The phase of flexing upwards lasts for half of the bending cycle time. If the cycle time is 0.5s (=120 cycles per minute), the flexing upwards needs 0.25s to take place. At a speed of 50 m/s (180 km/h), the airplane travels 12.5m. Gust cycle lengths below 25 m are so short that they move the wing tips up and down rather than accelerating the whole mass of the airplane. A longer gusts cycle should produce thrust only with the fraction which exceeds the 25 m length. Therefore, rigid wings with a high bending mode frequency should prove advantageous compared with more flexible wings, as the former exploits short gust cycles with a better efficiency. This should not be surprising, as the short gusts are directly felt by the pilot when flying an airplane with rigid wings. In brief, the degree to which the turbulence is felt is the degree to which the turbulence is energetically exploited.

This view is in contradiction to the findings of Mai.[2] He found that a PIK-20 sailplane having a mass 350 kg, crossing an upward gust with peak gust strength of 2 m/s and gust length 50 m yielded an energy gain of 1.251 m (rigid wing) and 1.452 m (flexible wing). Mai argues that the "energy stored in the bent wing begins to lift the fuselage". This is not convincing, as the fuselage only is accelerated as long as the wing bending persists. This stored potential energy can easily be estimated by integrating the force vs. bend displacement which at the end could be rather small. Also, it may well be that this stored energy is quickly lost by accelerating the air during the wings' subsequent downward swing when the upward gust has disappeared. Besides mentioning the fact that different programs (GUST0 and GUST3) were used to run either one of the two simulations which required 7.5 hrs computer time per run to converge, we cannot explain this contradiction.

Automatic flap actuation

The energy gain from gusts can be increased proportionally by "amplifying" the gust-induced g-load. Amplifying means a quick response, which can be realized with automatically moving of the flaps along with the gust, i.e. the flaps deflect to a more positive position within upward gusts, or to less positive or even negative positions within downward gusts. One possibility of achieving this effect is to install a horizontal lever connected with the flap mechanism, providing a mass attached to the end of the lever, combined with a frictional damping element. The system functions due to the inertia of the mass attached to the lever[d].

Patel[4] describes processor-driven controls of the flaps in small UAVs. In principle, similar controls may work also in gliders.

Mai[2] has found that the static stability, i.e. the position of the center of gravity c.g. is important. The energy gain is slightly enhanced when the c.g. is located closer to its aft limit.

Any amplifying system is able to oscillate or even fall into an extreme. The design of the automatic or software-controlled flap actuator system therefore must comply with two opposing requirements, a) the response must be quick and b) it must conserve stability; oscillation or flutter must be avoided under all circumstances.

Concluding remarks

It was attempted to provide a theory of the energy gain of airplanes when flying through a gusty or turbulent atmosphere, based on a simple gust model. Turbulence contains energy which is "harvested" when encountered. Although this beneficial effect cannot be avoided, it has been ignored by the pilots' community for long time, probably because there was no detector to differentiate it from other updrafts.

Hints regarding glider design are given, new instrumentation is described, and ideas towards favorable flight tactics are provided. Every idea is based only on theoretical considerations, and future validation through development of appropriate hardware and in-flight turbulence measurements are encouraged.

Acknowledgements

I thank Herbert Pirker for his impulse to do this work and for the fruitful discussion with him. I am grateful to the students of Akaflieg München e.V. for their openness towards new ideas combined with the necessary criticism.

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[d] A similar design was realized years ago by Akaflieg München e.V. and built into a LS3 glider in order to optimize the flap deflection in response to the lift coefficient automatically. The glider is in service without any problem.

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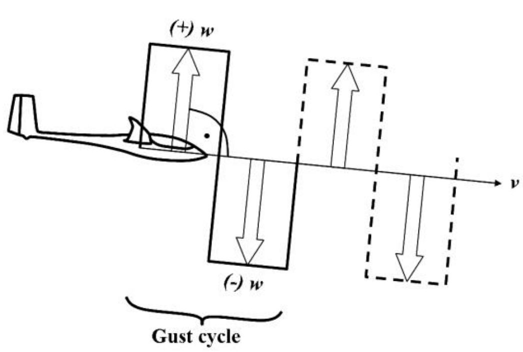

Figure 1 Gust model. The glider encounters a row of alternating constant positive and constant negative gusts of strength *w* in m/s with a certain gust cycle distance in m.

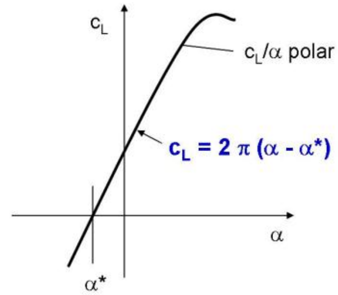

Figure 2 c_L/α-polar. The linear section is used. The slope $dc_L/d\alpha$ is about 2π (~6,28). α^* is the angle of attack which is related to zero lift. α is given in radian. Instead of 2π the lift slope $dc_L/d\alpha$ may be used.

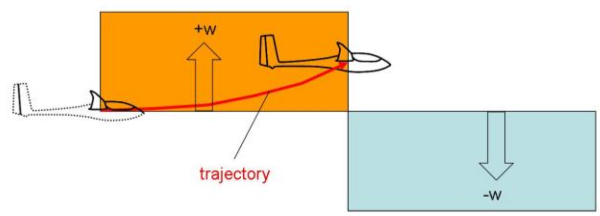

Figure 3 The increased load during crossing the +*w* gust accelerates the airplane so that the trajectory becomes curved.

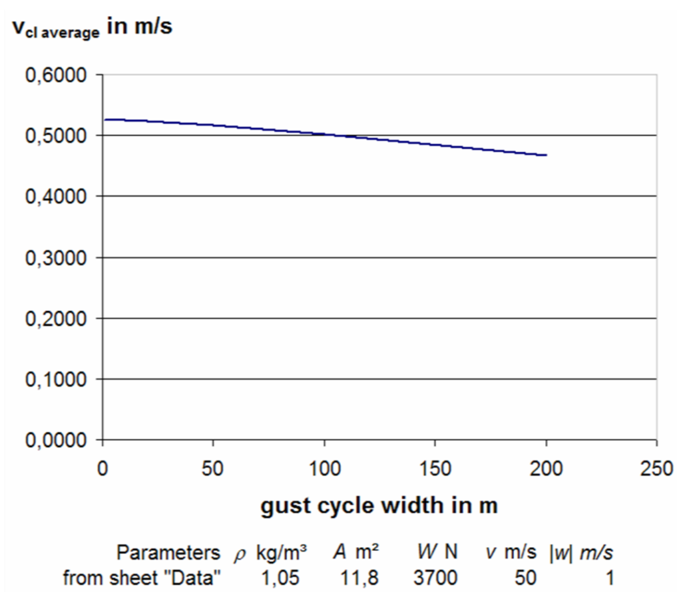

Figure 4 Average climb rate versus gust cycle length. Parameters are as shown. Result from Excel spread sheet, file name "climb rate vs gust cycle width.xls", see footnote b.

Figure 5 Glider 304S “Shark”, 18 m

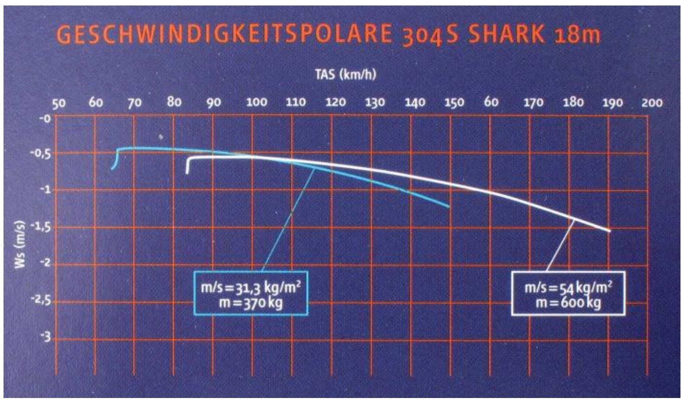

Figure 6 Advertized speed polar of the glider 304 S “Shark”. Wing loadings are as noted.

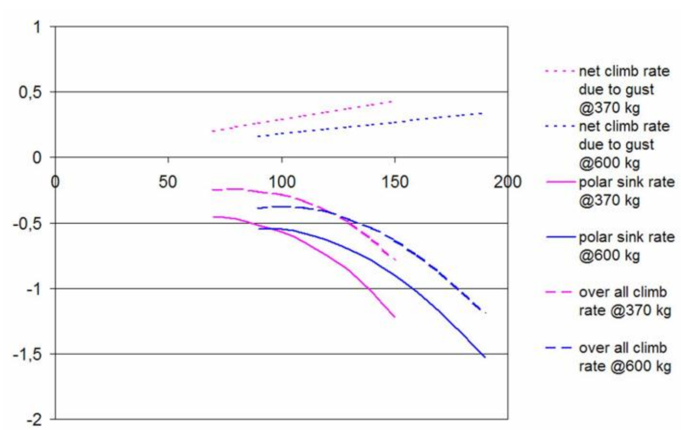

Figure 7 Polar sink, net climb and overall climb rates versus the speed *v* (km/h) with and without water ballast. The gust strength is 1 m/s and the gust cycle length is 50 m.

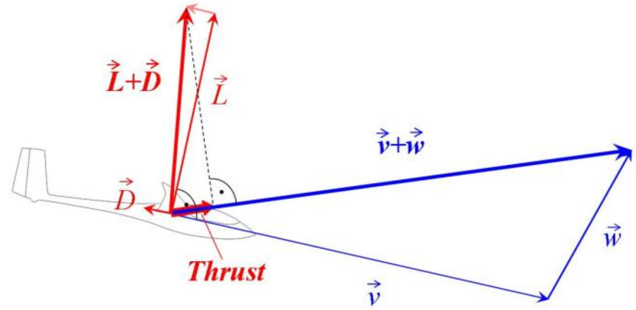

Figure 8 Force-velocity diagram. The thrust is determined by the component of the force vector $\vec{L}+\vec{D}$ which points in the direction of the velocity vector $\vec{v}+\vec{w}$. The velocity vector is the vector sum of the speed vector $\vec{v}$ which is defined in the surrounding air and the wind vector $\vec{w}$ which is defined in the inertial system. Lift $\vec{L}$, drag $\vec{D}$.