ONCE YOU START ASKING

Aviation 1

Glider Aerodynamics

INSIGHTS, STORIES AND EXPERIENCES

from ten years of reporting on science and engineering

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Airplane performance. The performance of a glider can be characterized in three ways. The number everyone primarily cites is glide ratio. This describes the distance a glider can travel from a particular altitude in undisturbed air with no thermals or sink. For example, a glider that can travel 50 kilometers from one kilometer up has a glide ratio of 1:50, or just 50 for short. My ASG-29, a modern glider with an 18-meter wingspan, has a glide ratio of 52—at least on paper. Open-class gliders of more than 25-meter wingspan can get above 60, with a few touching 70. For comparison, the Ka-6, designed in the 1950s, achieved a glide ratio of 32 with a 15-meter wingspan. The 1930s Grunau Baby had a glide ratio of a mere 17. Quite an impressive evolution.

The second relevant number is the minimum sink: the minimum vertical descend rate the glider can maintain, again in undisturbed air. My ASG-29 has a minimum sink of 0.47 m/s. You might ask what the difference is between the minimum sink speed and the best glide ratio. Why are both numbers relevant? The fact that one is expressed in terms of distance (meters distance per meter altitude) and one is expressed in terms of time (meters per second) suggests that there is a difference, and we will explore this below.

The third relevant characteristic cannot be captured by a single number—and actually, the numbers above are also slightly misleading, or at least incomplete, as we will see below. A glider's handling characteristics are also relevant. How agile is it; how quickly can it turn into a thermal? How stiff are the wings; how rough is the ride in bumpy air? How well does it maintain a circle on its own—do you have to continuously control it? How well does it handle at low speeds; what is its tendency to stall, or even spin? These and other characteristics are hugely important, because they affect how much of a pilot's mental capacity has to be spent on actually flying the airplane, as opposed to making all those tactical decisions and looking outside, scanning for other traffic. The Zacher protocol attempts to capture these characteristics objectively: it quantifies low-speed handling, the effectiveness of the controls, the distances and forces required to move them, as well as various aspects of static and dynamic stability. The academic flying organization Idaflieg evaluates new gliders according to this protocol every year at their summer camp in Aalen-Heidenheim. Handling qualities are to some degree a matter of personal taste, but I guess everybody agrees on the importance of graceful low speed handling and agility, especially in roll.

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How a wing works. Now to the physics. We all know that as a body moves through the air it experiences drag. We also know that the faster the body goes, the more drag it experiences. Furthermore, it is intuitively understandable that a body experiences more drag if the medium through which is moves is denser. And it is also clear that a larger body, one with more frontal area, experiences a larger drag force. Finally, we know that the shape of the body influences drag. In fact, the word "streamlined" literally describes the fact that the (imaginary) "stream lines" of a gas flowing around a body are aligned; if they are not, this is a sign of turbulence induced by the body, which consumes energy and thus leads to drag. Based on these intuitive observations we can write a formula for the force that affects a body due to aerodynamic drag:

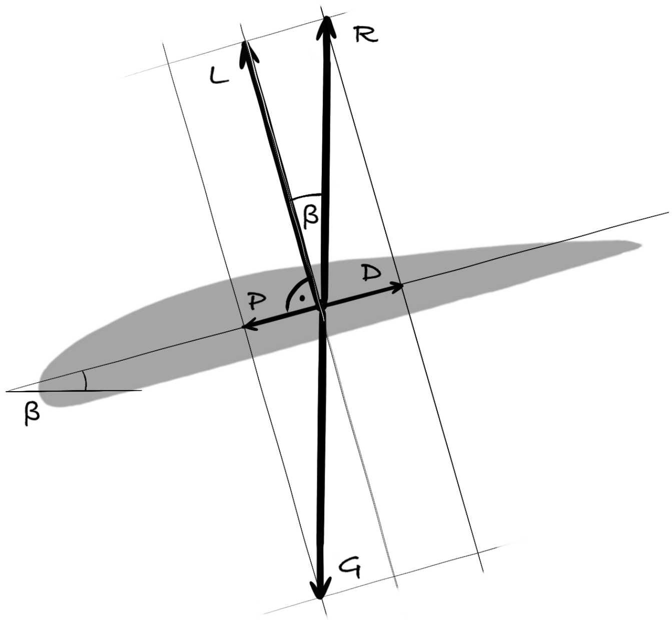
$$D = \frac{1}{2} \ \rho \ \ v^2 \ \ A \ \ c_D$$

Here, ρrepresents the density of the air, c_D is a dimensionless (experimentally determined) factor that represents the shape of the body, v is speed and enters the formula squared, A is the frontal area, and there is an additional factor of 1/2. The product 1/2 * ρ* v^2 represents the dynamic pressure and is abbreviated to q. This is the pressure due to oncoming air, and is different than the static pressure p that results from the weight of the air mass above us in the atmosphere, the one mentioned in weather forecasts. Both are measured in Pascals.

The characteristic cross-sectional shape of the wings produces an additional force: aerodynamic lift. This force is calculated in exactly the same way as drag, but the dimensionless number that represents the shape is a different one: c_L. The performance of a wing—its ability to convert speed into lift—is given by the ratio of lift and drag. Note that this ratio does not depend on speed, area or air density, because all of these are cancelled out once we establish the ratio; it is captured by c_L and c_D, it is purely a geometric property. Actually, that's not quite true. Up to a Mach number of around 0.3 we can assume air to be a compressible gas, but as we move into higher Mach numbers this assumption can no longer be made and everything changes. We also cannot completely ignore the size of the wing. As we scale up or down, the Reynolds number, another dimensionless number that characterizes the development of turbulence in airflows, changes. This is why an aircraft wing doesn't perform quite as well on model airplanes or when it is scaled down for testing in wind tunnels. For the purpose of understanding the performance of gliders, however, we can ignore these factors and stick with the claim that a wing's glide ratio is purely a matter of shape.

This suggests that a glider's performance remains the same as it flies faster. This is not true, however, for various reasons. The dominant one is that a glider has lots of parts that create drag but not lift: the fuselage with its relatively bulky cockpit at the front, its long tail, the horizontal stabilizer that generates a downward force (negative lift) to maintain overall balance of moments, as well as the interference of aircraft parts such the wings' connection to the fuselage. As the airplane accelerates, therefore, the overall drag becomes greater while the wings' ratio between lift and drag remains constant. Performance decreases, which means that the glider sinks faster. We will return to this later.

If drag is the force that slows you down, what then is the force that counterbalances it and keeps you going? Let's look at the following diagram, which shows the forces acting on a wing in a steady-state glide at some glide angle β.



I emphasize ”steady-state” because this implies that there is no acceleration, and thus no overall resulting force acting on the mass. In other words, all the forces shown above are balanced. Let's look at each of them. We start with G, the gravitational force m * g, where m is the mass of the glider and g is the well-known 9.81 m/s^2. G points straight down towards the center of the Earth. L is the aerodynamic lift produced by the wing, perpendicular to the wing's chord line. D is drag, and acts in the opposite direction to the velocity vector, which is oriented "down" the slope β. The force that drives the glider forward is marked as P in the diagram. This is in balance with the drag (otherwise the glider would slow down or accelerate) and is a component of G; in fact, it is G * sin(β). Remember the downslope force in the context of inclined planes in physics class?

So, what can we learn from this? First, a glider must fly on a downward slope, because if β was zero the forward force P would be zero. Sloping downwards is a glider's way of transforming the potential energy inherent in its altitude into forward motion. The angle β is of course directly related to the glider's glide ratio: cot(β) = L/D, where cot is the cotangent function.

A quick interlude: the angle β represents the (normally downward) glide slope, not the angle of attack α, the angle at which the airstream hits the wing relative to its chord line. When you watch an airliner landing you can clearly see that its nose is up—a positive angle of attack—while it descends towards the runway. We don't need α in our discussion yet: we'll cover it later.

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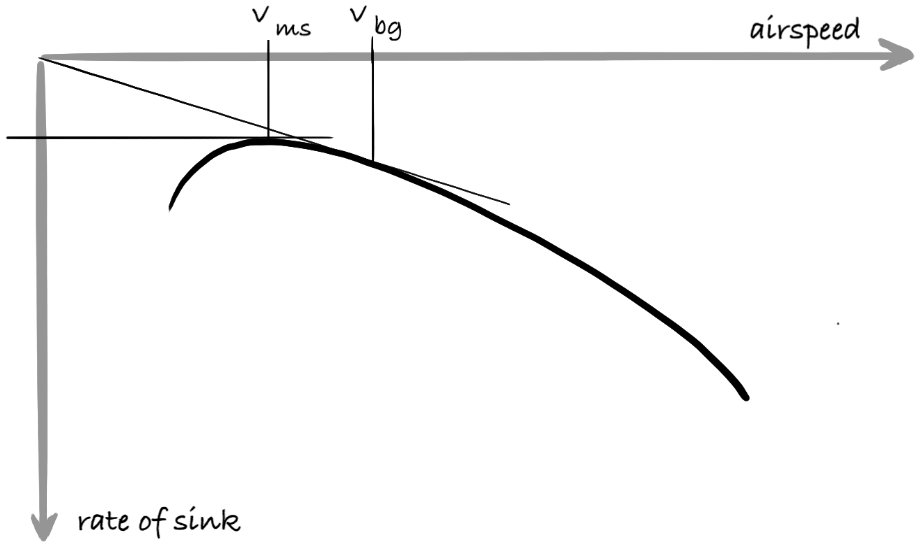
McCready's theory. Let's recap. For a wing c_L and c_D are always in the same ratio and characterize the wing's performance. In practice, however, because a glider has components that produce drag but not lift, the drag force D increases more quickly with speed than the lift force L. In other words, the glider's glide angle β becomes larger the faster it flies; its speed of descend increases. This is represented in a glider's polar curve:



The topmost point of the curve is the minimum achievable sink rate, corresponding to v_{ms}, the speed of minimum sink (the 0.47 m/s for my ASG-29 that I mentioned earlier). This is the speed you fly when you either want to sink as slowly as possible, for example on a winter's day with no thermals and you are just gliding down from a tow to enjoy the scenery, or when you want to climb efficiently, for example when circling. This speed is usually relatively close to the stall speed, which is why it is important that a glider has benign stalling characteristics: when circling in a thermal you really don't want to stall and maybe drop onto a glider circling below you. The speed of best glide v_{bg} can be found by projecting the tangent from the diagram's origin. This represents the speed you want to maintain in straight flight, because it is where the glider has its best L/D ratio.

Based on this diagram we can refine our statement about the performance characteristics of a glider. It is not just important that the glider has a good glide ratio and a low minimum sink speed. It is also important that v_{bg} is as high as possible, to allow you to go fast with little penalty. Much progress has been made in this area over the decades. Comparing the previously mentioned Grunau Baby or a Ka-6 to an ASG-29 in this respect is pointless, the speeds are too different. But even compared to the ASW-20, which is only two generations older than the ASG-29, the v_{bg} has increased from around 90 km/h to around 105 km/h—that is, you can fly 15 km/h faster without any performance penalty! For the 29 meter EB-29R it's at least another 10 km/h higher.

We said above that v_{bg} is the speed at which you fly in cruise because it gives you the best L/D. In fact this is also not quite correct. Let's say you go faster. This means that you arrive at the next cloud sooner, which is good. But you are also lower, so you have to spend more time in this (or the next) thermal—remember, effectively at zero track speed. So which alternative is better? Arrive early and lower, or later but higher? As usual, looking at extreme values helps: if your average climb rate in thermals was zero (no thermals that day), then it's obviously crucial to stay up, so you fly slower. In fact this is what you do when struggle to get home in the evening. In contrast, if climb speed was infinite, then of course you would want to fly ahead as fast as possible, because it takes you no time to get back up.

So the trends are clear: the stronger the expected thermal, the faster you fly between clouds. If you try to work out the ideal speed exactly, however, things get more complicated: it involves several parameters, a few simplifying assumptions and about 30 lines of (not too sophisticated) math. Paul McCready did this math first in the 1950s and wrote down a formula that calculates the ideal speed to fly. He won the 1956 world gliding championship, presumably because of these insights. Today the formula is programmed into the soaring computers that are installed in most gliders. It's used as follows: as you fly, you keep track of the average climb, either in your head or by relying on the computer. You then enter this average climb rate into the computer as your "McCready value". During cruise the computer tells you the speed at which to fly for ideal performance, depending on the relative movement of the surrounding air at that particular point in time. The indication is visual and acoustic, and as a routine pilot you subconsciously control the speed to follow the McCready recommendation. It's an imperfect science, of course: you must still decide which thermals to take and which to pass on, as the computer doesn't know the distance to the next thermal and doesn't consider your altitude or your willingness to accept the risk of landing out. But at least in the care-free zone high up most pilots fly according to the speed-to-fly indicated by the "McCready in a box".

We can now once more refine our notion of what it means for a glider to have good performance: you don't just want a high L/D ratio at high speed, but you also want it not to degrade too much at even higher speeds. Looking at the polar curve above, you want the curve to be flat, which will allow you to go faster without too much of a penalty. The speed-to-fly computation in your soaring computer takes this polar curve into account, by the way, so it recommends different speeds depending on aircraft type. Again this is where a lot of progress has been made over the years.

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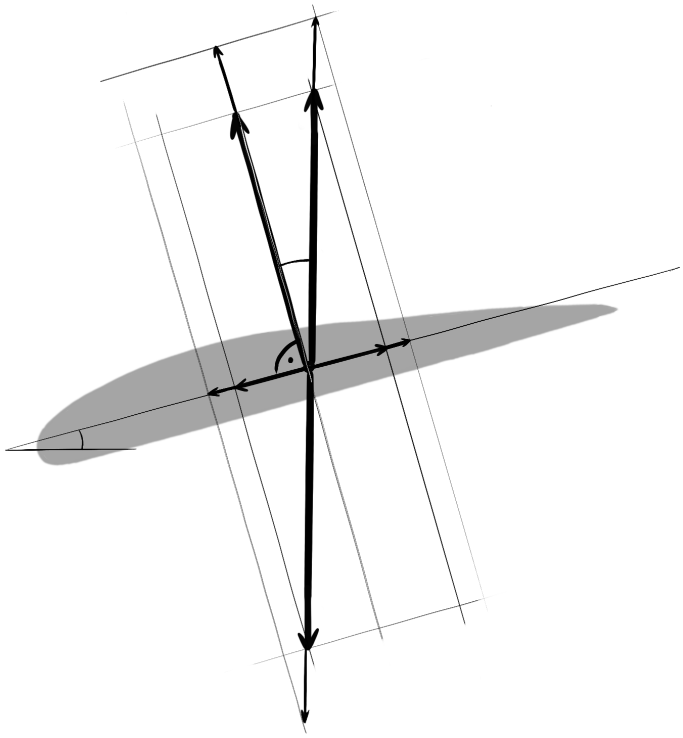
Water ballast. Are there more ways we can improve the speed at which we can fly? There are. Let's revisit the diagram that shows the forces on a wing and see what happens if we increase G, which we can do by making the glider heavier:



Remember that the angle of descent, or the L/D ratio, is purely an aerodynamic property: it is only a matter of the two shape-related factors c_L and c_D. If G is increased it has no impact on L/D, so we have to keep β the same. However, you can see that the arrows representing drag and propulsive force become longer. In other words, for the same L/D ratio you can fly faster by making a glider heavier. This is why gliders carry water ballast—it moves the best glide speed v_{bg} to a higher speed, making the glider's polar curve flatter. You tell your soaring computer how much ballast you have loaded and it will then take this into account when computing the speed-to-fly, depending on the sink rate of the surrounding air.

The effect can be striking. On that June day I launched without water because the day was not forecast to be that good, and I was also just too lazy. Above the south of the Black Forest I met a famous cross-country pilot in his ASG-29. We met underneath a cloud and both started racing towards the next cloud along the track, initially next to each other at the same altitude and at the same speed. We were not next to each other for long: I literally fell out of the sky compared to him. I am sure his glider was full of water. After maybe ten kilometers at 180 km/h I was several hundred meters lower—a very impressive illustration of my mistake of not taking water!

There is no free lunch, however. Water ballast obviously makes the glider heavier, so your minimum sink rate becomes higher, moving the polar curve downwards, which in turn means that you climb more slowly in a given thermal. The absolute best L/D also becomes slightly worse because of effects of the whole glider (beyond the wings). However, this is a tradeoff similar to the one involved in McCready's theory: how much water should you take on to achieve the optimum balance between increased cruise speed and reduced climbing efficiency? The better the weather, the more water you want to take on. Most pilots "guesstimate" their ideal water load based on (their interpretation of) the weather forecast. Others, such as the aforementioned Alexander Müller, always launch completely full. The rationale for this is that you can always release water if during the flight you notice that you were too optimistic, but you can never add water in flight—there's no equivalent of the KC-135 Stratotanker to supply water to slow gliders.

As before, though, it's more complicated than that. Remember that the total distance you can fly is not just related to your average flight speed, but also to the fraction of the "thermal day" you can use. So the earlier you launch and the longer you fly for the better. But early in the morning thermals are weaker, spread out more widely and often do not reach so high. Flying in these circumstances chock-full of water, with the reduced climb efficiency that this causes, can be a challenge. A heavy airplane also has a higher stall speed, is often not quite so agile, and can generally feel more sluggish—although not in pitch, because it builds up speed much more quickly. It certainly increases the risk of landing out and potentially wasting a perfectly fine flying day early in the morning.

So we can now refine our idea of good glider performance: a glider should cope well with water: its handling characteristics should not get much worse if it's fully loaded. Lots of progress has been made with this over generations of gliders. In 2017 I had an opportunity to try out the then brand-new Ventus 3. A good day was forecast, and the guys from Schempp-Hirth who briefed me that morning basically forced me to take on a significant amount of water, around two-thirds the Ventus' maximum capacity. "You need it, it's too light otherwise, and you really won't feel it in handling" is what they said. I was skeptical, but they were right. The airplane handled beautifully, and even though it was my first flight with the type, I flew 650 kilometers with an average track speed of 105 km/h. To put this into context, this was the fastest flight that day in that part of Germany, although not the farthest—a few people flew as far as 800 kilometers.

How can modern gliders fly 100s of kilometers, and why do they take water ballast to do it • How can the SR-71 fly at Mach 3 at 80,000 feet • How does it feel to fly in an F-16 fighter jet • How do computers control an A-320 and why is it so hard to fly a helicopter • How do you control 17-ton telescope mounted on a 747, and why would you do that in the first place • How is life on a miltary survey ship, and how do multibeam sonars map the sea floor • How do you inter-ferometrically combine many telescopes into one • How do you engineer a system to measure gravitational waves • What is it like to stand right under the world‘s largest optical telescope, as the dome opens, and the milky way reflecting in its giant mirrors • How do you control the LHC‘s beam • Why are models so important in science and engineering?

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