A DYNAMIC ANALYSIS OF A LANDING FLARE

Putting your mass to work

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Ever since I made some discoveries about obtaining a good landing flare that I shared in a letter to the editor (August 1989) I have been intrigued by the subject. In the letter I suggested using a mental image of trying "to kick the keel" rather than the more standard instruction of "pushing out" to achieve a flare. At the time I explained it as more effectively shifting the body center of mass to the rear of the glider. While shifting your weight to the rear of the glider will achieve a stall, it will not necessarily achieve a flare. One very important factor is the rate at which your weight is shifted. We will shortly find out that *how* you shift your weight is also very important.

The key to understanding the flare process is a knowledge of rigid body dynamics. Dynamics is the study of forces acting on masses, and the resulting accelerations, momentum and energy. We will very briefly discuss some basic principles that can be applied to the landing flare, and then use them to gain an understanding of how best to use our own mass. But first we will look at some example landings.

TUBES AND ACE

In the tradition of Erik Fair's 'Right Stuff' we will watch two pilots land. The first pilot is 'Tubes'. You can guess where he got his name (it's not one he prefers - he got it from the other pilots). His landings are so bad that he recently put wing nuts on his down tubes for easy (and frequent) replacement. (I once knew a real life Tubes. The height of his humiliation must have been the day when some fellow pilots were waiting for him in the field. As he turned on final they ran out in front of him spraying shaving cream and yelling "Foam the Runway!") His right stuff counterpart is 'Ace', who does just that nearly every landing. As you may guess, 'Ace' likes his name. We all know landing requires several distinctly different skills, such as setting up the approach, knowing when to flare, and knowing *how* to flare. Much has been written about approaches. I think Greg DeWolf has already done the definitive piece on *flare timing* ('Returning to Earth', July and August 1986). Since in this article we're only concerned with the flare itself we'll assume that both Tubes and Ace have their approaches and timing down equally well.

We start by watching Tubes who is on final and upright. As the ground approaches we can see the fear he has of the impending crash. In an attempt to limit the damage he already has his legs in front of him. His hands are directly in front of him on the down tubes at shoulder height. At the critical moment he pushes forward on the tubes. The glider nose rises slightly, and then it seems the whole glider is getting in front of him. The nose starts to drop and ... well, we know what'll happen. We'll spare Tubes the humiliation of watching the conclusion.

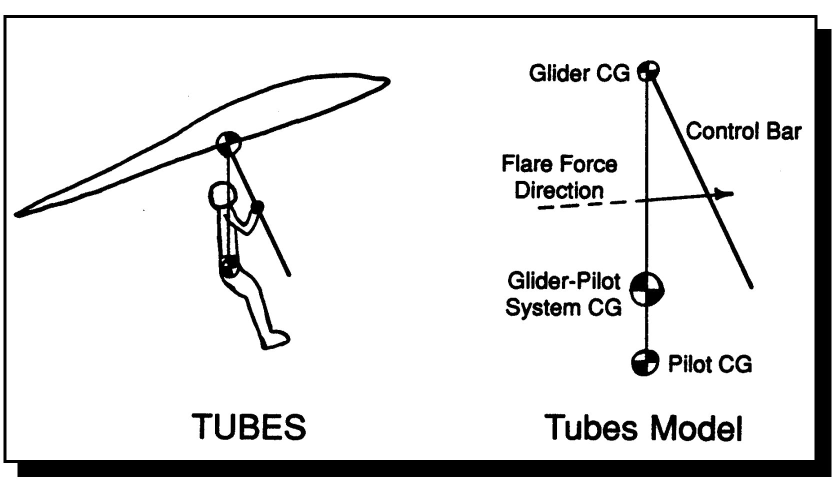
Instead we turn to Ace who is coming in right behind him. Ace is upright, but leaning slightly forward with his legs trailing behind him. His hands are at or slightly above shoulder height. When his turn comes to flare, he pushes straight *up* on the bar, although he doesn't really think of it that way. He is thinking of pushing those legs, which are already trailing behind him, as far back towards the keel as possible. The glider nose pops crisply up and comes to an immediate stop, swinging Ace in front of it into an upright position. As Ace gently drops onto his feet for a no-step landing, Tubes is already taking off those wing nuts (again).

SOME BASIC PHYSICS
Here's where we get the review. Don't go away. I thought about putting in some equations and numbers, but then I realized they really weren't needed. We don't really care so much about how many pound-seconds of momentum we have - we just want to know how to land it. Most analyses begin with 'free body diagrams' (which have nothing to do with the sexual revolution) in which a body is isolated and (usually) just represented by its center of mass (or center of gravity, the 'cg'). Forces and moments acting on the body can be represented by *vectors*. We can also use vectors to represent velocity, acceleration, and momentum of the body (Vectors are those arrows that you've probably seen many times - they show both direction and magnitude of a quantity, with the magnitude being shown by length).

One of the most important principles for the discussion at hand is that of *conservation of momentum*. To illustrate by example, we will start with an explosive body (as in TNT - not as in sexy) moving through airless space in a straight line, with no rotation. Because there are no *external* forces on it there is no acceleration and therefore it moves at a constant velocity. Linear *momentum* is merely the mass of an object multiplied by the velocity and is normally described at the center of mass. *Angular momentum* is the 'mass moment of inertia' (a rotational equivalent to mass) multiplied by the rotational rate. Because there is no rotation, angular momentum of the body is zero. Now the body explodes, and chunks of it fly in every direction. *Note that there was no external force involved*. If we were to find the combined center of mass of all of these chunks at any given moment, we would find that *its location would be the same as if the projectile had never exploded. There would be no change in the total momentum, either linear or angular.* If we looked at individual pieces, they might be spinning like crazy and flying away from the center in different directions at different velocities, but if we vectorially added up all the individual linear and angular momentum vectors, the resultant linear momentum vector would be the same as before the explosion and the resultant angular momentum vector would still be zero. This is what we mean by conservation of momentum. (Don't confuse momentum with energy - while momentum remained unchanged during the explosion, kinetic energy definitely increased).

Many dynamic analyses could become very complicated if you tried to consider every little thing that happens. But we can often gain a useful understanding by simplifying certain aspects and eliminating others that have no bearing on what we are interested in. Of course there is the danger of simplifying so much as to make the solution meaningless. There's the one about the senior engineering design project where the assignment was to design an automatic sheep shearing machine. The students were all divided into competing teams who naturally kept their ideas to themselves. Only one of the teams seemed to have any ideas on how to do it and they seemed to be making good progress. None of the other teams were having much luck, so of course they were very curious. When the day of the eagerly awaited unveiling came, the team started by listing their design assumptions. The first assumption was: a spherical sheep.

Being careful not to make the same mistake, we nevertheless start by limiting our analysis to a very narrow and specific scope: finding *how we can best use the mass of our bodies to react against the mass of the glider so as to most effectively cause a sudden nose up glider rotation*. Because we are only looking at how the glider and pilot masses interact we don't need to consider weight and aerodynamic forces (they play important parts in achieving the flare, but not in how we use our mass to get the nose up). So we'll have our pilot and glider in outer space, moving along at a constant velocity and constant linear momentum. Of course the pilot is on oxygen and at a high enough altitude so as to be out of FAA jurisdiction. Some other assumptions we will make are: the glider cg is on the keel at the hang point; the pilot's cg is at the hips; the main support strap of the harness pivots at the pilot's cg; the main support strap is a rigid link (as long as it is in tension this is a good



assumption); both the pilot and the glider are (dynamically) rigid bodies; and the plane of the downtubes passes through both the glider cg and the hang point.

These assumptions are used in the sketches of both pilots and their corresponding 'models'. The models show only the centers of mass (same as the center of gravity, or cg) of the pilot and glider, the 'line of action' of the flare force, and the combined mass center of pilot and glider. Our sketches show the instant just before the landing flare is begun. The total angular momentum of the pilot-glider system consists of the sum of three individual terms: rotation of the pilot about his cg, rotation of the glider about its cg, and rotation of the pilot-glider system about the combined cg. The combined cg will continue to travel at constant velocity all through the flare motion (Remember that since we are in outer space there are no external forces such as weight, lift, drag, etc.) For this analysis we may consider the system cg to be a fixed point (zero is as good a constant velocity as any other). Before the flare has begun neither the pilot, the glider, nor the combination have any angular velocity; therefore total angular momentum is zero. During the flare the *total angular momentum remains zero*. The individual terms may be non-zero, but will have positive or negative signs and sum to zero at any given instant. (Remember the exploding body - during the explosion or flare we increase the *energy* of the system, but the momentum is not changed without external forces being applied).

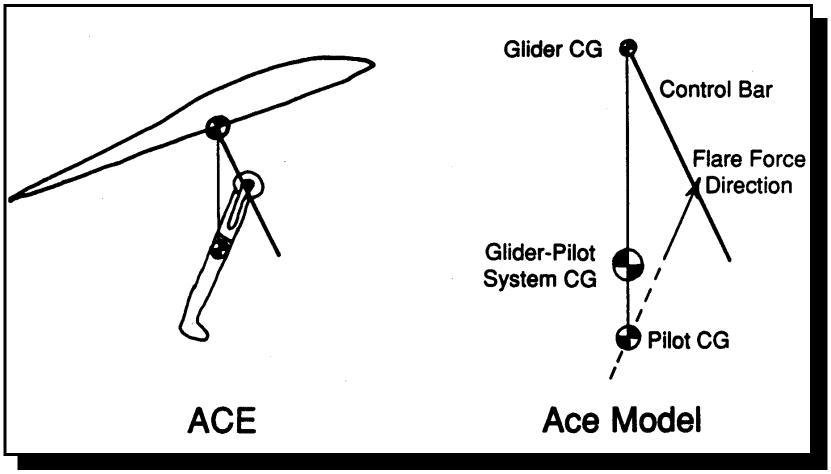
TUBES GETS A PHYSICS LESSON

Let's begin with Tubes. We see that he applies the flare force straight forward. The force that he applies does not have its direction through his mass center. Looking first at the glider, we see that the force applied below the glider cg has the effect of causing a counter-clockwise rotation of the glider. This exact same force acts in the opposite direction on Tubes. Since it acts above his cg it causes him to also rotate counter clockwise about his cg. Uh oh! Two of our three angular momentum terms are counter clockwise, meaning the third term has to be clockwise to add to zero. And this third term is: rotation of the glider and pilot cgs clockwise about the system cg, which rotates the glider out in front of the pilot. Of course if flying in air rather than space there are several things that will reduce this rotation: the increased aerodynamic drag of the raised nose would slow the glider in relation to the pilot. Also the lift on the glider and the weight of the pilot opposing each other would tend to provide a restoring moment. Nevertheless, we see that Tubes is putting a lot of his energy into getting the glider in front of him.

Let's look at some other features of Tube's method that make it undesirable. The line of action of flare force is closer to the glider cg than that of Tube's. Doing some crude calculations, I estimated that the mass moments of inertia of both pilot and glider about their respective cgs are not vastly different, so for sake of this illustration we'll just say they are the same. Angular acceleration is caused by a torque, where the magnitude of the torque is the magnitude of a force times its perpendicular distance to the cg. That means that there is a higher torque on Tubes than the glider, and therefore *Tubes will rotate faster than the glider does*. This brings us to another point: because he is leaning back Tubes already has his arms partially extended. He's limited in the range of distance through which he can apply a flare force. Now 'work' in the physics sense is a force multiplied over a distance that it is applied. Even if Tubes applies all the force he is capable of, he is limited in the total amount of work he can do. He has only partial arm extension left and is also rotating backwards while applying his force. Doing work on a system increases its energy - Tubes can't get a very 'energetic' flare. We could also point out that, because both his arms and legs are in front of him, his cg is not exactly at his hips (as shown in the figure) but slightly in front of them. This means he must be pulling *down* on the down tubes to remain upright. This does not help him achieve his flare either. Poor Tubes. We've picked on him enough. Let's look at Ace's flare now.

ACING PHYSICS

We see from the model that the line of action of Ace's flare force acts *through* his cg and therefore doesn't directly cause any rotation about his cg. He is able to apply his entire mass to creating a force. Therefore for a given rate of arm extension Ace will be applying a much larger force than Tubes is capable of (Note that instead of using a 'bench press' motion as Tubes does Ace uses a pushing-straight-up-over-his-head motion). Because he starts with his hands at his shoulders instead of partially extended Ace has a much longer range of motion over which to apply the greater force he is capable of. Ace can easily put much more work (energy) into his flare without trying nearly so hard as Tubes. For a good example of an Ace flare, see the cover of the December '89 magazine. Notice that the pilot's arms are in direct line with his body, and even with the keel vertical his arms are still not fully extended.



Note that by applying his force through his cg, Ace is causing his whole body to rotate clockwise about the hang point. While the pilot's moment of inertia about his cg may be about the same as that of the glider, *his moment of inertia about some other point than his cg is much greater*. If we considered Ace and his harness as a rigid body pivoting about the hang point (which strictly they aren't - but we're making a point here) we'd find a moment of inertia *nearly 10 times that of the glider*. That means that the glider is going to do most of the rotating, which is a very desirable thing.

Let's look at conservation of angular momentum. The glider has counter-clockwise momentum. We can see that in this case the pilot's angular momentum is clockwise and thus subtracts instead of adds as in Tube's case. The third term will still consist of clockwise rotation of the system about the system cg as before, but with a much smaller magnitude. In addition, the higher nose angle in a real life atmosphere will quickly cancel that effect.

HOW TO MAKE IT WORK

Whether you understood all of the above or not, you should still be able to draw some conclusions that you can apply to your own flares:

* Just prior to flaring your body should be leaning slightly forward, legs slightly trailing
* Hands should be placed at or even slightly above your shoulders
* The flare force should be exerted directly up above your head, not straight out in front of you. As you start your flare, your body should be straight. Think of a line drawn from your feet straight through your body and out the top of your head. Your hands should be moving parallel to this line throughout the flare. (You could also think of lifting a barbell over your head versus doing a bench press.)

I still maintain that the easiest way to remember all of this is to merely keep the mental image of "kicking the keel". If we think about trying to touch the tip of the keel with our feet we find that we are already leaning forward with our hands high up on the control bar. Our natural tendency is then to push straight up and swing our entire bodies rearward about the hang point.

EMERGENCY PROCEDURES

There are two situations that can still occur: you flare too early or too late (or forget and revert to a Tubes flare).

<u>Flaring too soon</u>: you've achieved a vigorous flare, only it was too soon. The glider nose is pointed at the sky and your feet are a long ways off the ground. As I mentioned in the letter, imagine yourself being strapped to the keel while still hanging in your harness and with the glider's nose pointing straight up. Your cg will be near the trailing edge of the wing. As long as your cg stays there it will be very hard for the glider to nose over. Your goal then, if you find yourself emulating the space shuttle at take-off, is to push and keep your body as far back against the keel as possible. <u>THIS MEANS KEEP YOUR LEGS AS FAR BACK THERE AS YOU CAN GET THEM!</u> Providing you don't wimp out you'll drop straight down to land on your feet. But if you even think about letting your legs come forward Alcoa's stock will jump another couple points.

<u>Flaring too late or too wimpy</u>: OK, so you forgot everything you just learned. You *almost* had a good flare, but your arms are stretched straight out and there's nothing left that you can do as the nose starts to fall. Or is there? If your legs aren't as far back as you can get them you still have a chance. We discard our model of the pilot as a 'rigid body' and create a new model that makes the pilot two pieces, hinged at the hip. Now rapidly throw your legs backward, pivoting at the hip. What you've done is cause a larger clockwise angular momentum term (that of your legs). The reaction is to increase the counter clockwise (nose up) momentum of

the glider. If you weren't horribly late or wimpy it might just be enough.

Finally, let me say that this was far from a 'rigorous' analysis. Some of you with engineering or other similar technical backgrounds may look
at a few of the statements I've made with a raised eyebrow. I admit to some over simplification at a point or two and leaving out a pre-condition here and there. But I believe the spirit of the 'analysis' doesn't violate any fundamental principles, and is sufficient in scope to help pilots improve their flares.

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POSTSCRIPT: In the years since I wrote this I have talked to some pilots who thought the approach of trying to “kick the keel” was unsafe in that you would not have your feet underneath you at a critical time. I realize I should have been clearer in the original article. “Kicking the keel” is a mental image to help you achieve the correct flare position and motion. The rotational inertia of the glider is very small compared to moving the entire mass of the pilot in an arc about the hang point - it is the glider that will do most of the moving, not the pilot.

Prior to writing this article I had spent some time on the training hill trying to perfect this technique. The first glider I tried it on was the old bowsprit Mosquito, a notoriously nose-heavy glider that I had been having a lot of difficulty landing well. I had wheels on the glider for safety and decided to just try throwing my legs back as I’ve described here. The flare ended up being so vigorous that I made a two point landing - the keel and my butt! My legs had been thrown out in front of me by the unexpected (and unaccustomed) braking force I experienced from that flare.

The only way you can throw your legs back to “kick the keel” is by having something to push forward on - that something being the control bar. But the control bar isn’t capable of resisting the force necessary to actually push your legs backwards - you just end up raising the nose sharply in exactly the way you wanted to all along. You just have to *believe*...