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Technical Counselor Note #3
by Will Fox

Aircraft Center of Gravity Limits

You just finished your experimental Goes Like a Bat Out of Hell (GLBOH) aircraft, had it inspected, and are ready to fly it. The inspection went really well but the inspector had some confusing question about how you calculated the empty Center of Gravity (CG) for your aircraft. You didn't want to tell him that you never did understand that whole C.G. thing very well and that you found a spreadsheet on the Internet and plugged in what you thought were the right numbers. Instead you told him that you had worked with your EAA Technical Councilor and he helped you figure it out. The inspector didn't need to know that you wouldn't ask that know-it-all TC for the time of day, let alone help figuring out your CG. Well anyways, the CG has to be about in the right place because you followed the plans pretty much. In fact you made a few improvements, like putting the battery on the firewall instead of the baggage compartment so you would have shorter battery cables and save some weight. You also put in a larger engine with a constant speed propeller for better performance. Your GLBOH ought to really go. So, the time has finally come to fly and you begin your takeoff roll. The GLBOH really has some acceleration and a lot of P-factor from that big engine. You are halfway down the runway and drifting well left of the centerline when you haul back on the stick expecting the aircraft to leap into the air. It doesn't want to fly though. You look at your airspeed indicator and it shows that you have more than enough airspeed but the GLBOH just won't part the surly bonds of earth. You look back up and realize that you are almost out of runway, and going way too fast to stop. You have to get this bird flying, so you really haul back on the stick hard and the GLBOH staggers into the air just as you pass the departure end of the runway. That big engine keeps accelerating the aircraft and pretty soon you are able to relax your death grip on the stick and trim out all that back-pressure you were holding on the stick. You fly around for a while to get the feel of the airplane, but don't do any slow flight or stalls because you never liked doing that stuff and besides the GLBOH is supposed to go fast not slow. Your airspeed indicator must be a little out of calibration, because the airplane isn't flying nearly as fast as you expected. You decide to come back in for a landing and on final approach realize that you are going way too fast. You pull the power completely off and as the GLBOH starts to slow down, you start trimming like crazy to keep the nose up. You run out of trim, so you have to hold the nose up with the yoke and you are still going pretty fast, but you figure too fast is better than too slow. As you fly over the numbers on the approach end of the runway, you start your flare, but the nose just won't come up. You now have the stick all the way back and the nose is still going down and the ground is coming up way to fast. This landing is going to be a really hard one….

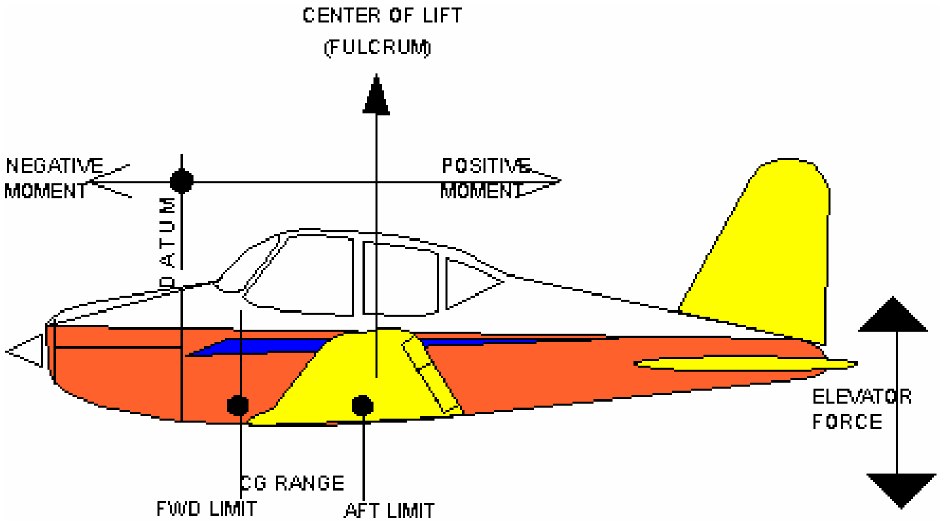

Figure 1 showing location of datum and center of gravity limits on an aircraft.

What just happened? You probably guessed it, The CG was too far forward as a result of the "improvements" the builder made. Also the builder did not really understand how to figure out where the CG was for the aircraft and as a result took off with it well forward of the forward limit. The forward CG limit of an aircraft is typically determined by making sure that, at the forward limit, the elevator has sufficient authority to allow the aircraft to achieve its design stall speed. As the aircraft is loaded forward of this point, it becomes increasing difficult to hold the nose of the aircraft up as it slows down and it may pitch nose down in an uncontrollable manner at an airspeed significantly above normal stall speed. The aircraft will also require considerable nose up trim at normal cruise speed resulting in greater trim drag and a lower cruise speed. Lets see what happens when the CG is behind the rear CG limit.

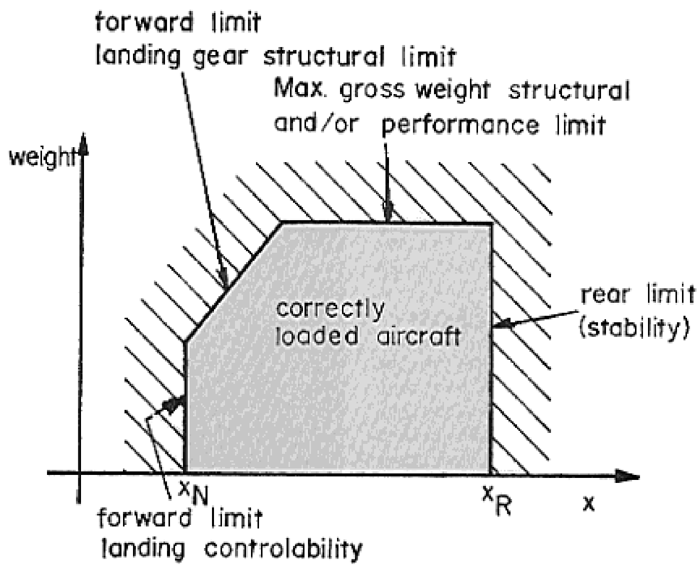

Figure 13

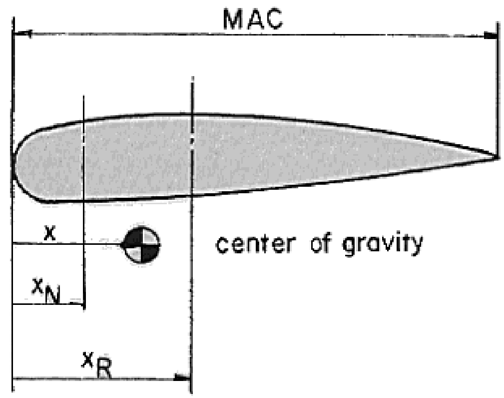

Figure 2 is a diagram showing the center of gravity envelope and what its limits are.

It is a beautiful day and you decide to fly a few of your friends up to Denver for a weekend trip in your V-tail Bonanza. You were planning on your wife and another couple going along, only to find out that they want to bring their kids along as well. You wonder a bit about the CG but then figure that those Beech engineers wouldn't have put six seats in the plane if it couldn't carry six people. As you taxi out for takeoff, you notice that the nose wheel steering is a bit sensitive, but attribute it to the fact that the front strut nose wheel strut is fully extended. You begin your takeoff roll, and as you approach rotation speed the aircraft suddenly leaps of the ground into the air at a much lower speed than normal. The stall horn blares at you and you push the nose over and notice that the controls seem lighter than normal and a bit sensitive. As soon as you can get some altitude, you turn the plane over to the autopilot because it seems to fly the plane much better than you can. A couple of hours later you begin a descent into Denver and turn off the autopilot since it has developed a gentle oscillation in pitch. The aircraft begins to pitch up and as you push forward on the yoke, the aircraft pitches down so aggressively that your wife's purse floats towards the ceiling. You pull back on the yoke and the controls are so sensitive that the aircraft pitches nose up and you feel yourself sinking into the seat from the g forces. This is getting out of hand way too quickly. You fight for control of the aircraft, but you are not sure who is going to win. Every movement you make on the yoke seems to be an overcorrection and you are chasing the airplane instead of flying it. As you start to panic, you try pulling the power and dropping the gear in the hopes that that will help. This seems to improve things a bit, at least enough that you can get control of the aircraft back. You call Denver and tell them that something is wrong with your plane an that you need to land immediately. They clear you to land on any runway and somehow you manage to get the aircraft on the ground in one piece. As you exit the plane and look at your wife and friends, you realize just how close you came to not finishing this flight in one piece. What the heck happened?

The Bonanza was loaded outside the rear CG limit. This is easy to do on many Bonanzas. The six seats in later model V-tail Bonanzas were more of a marketing ploy than a real capability. Because of the passengers in the rear seats, the aircraft was very close to its neutral pitch stability point during the takeoff, and that made it sensitive in pitch. During the flight to Denver, as the fuel was consumed the CG moved even farther back. In the Bonanza the fuel is carried in front of the spar, resulting in a rearward shift in CG as the fuel is consumed. This caused the aircraft to develop a slightly negative pitch stability. This did not become apparent to the pilot until he turned off the autopilot. Negative pitch stability resulted in the aircraft wanting to diverge from the trimmed condition, rather than to return to it when flown hands off. Reducing power and dropping the gear helped to slow the aircraft and decrease the sensitivity of the controls in this case, allowing the pilot to regain sufficient control of the aircraft that he could land it. The rear CG limit is often set based on where the neutral stability point is for the aircraft. Aircraft designers want to make sure that the aircraft maintains positive static and dynamic stability with the rear most CG so the rear CG limit is set so that it is well forward of the neutral stability point. This is one of the criteria used to set the rear CG limit, another one must also be considered as illustrated by the following story.

It was a good day to spin a new aircraft. The air was cool and calm. No cloud decks to worry about and visibility was excellent. Even so, the test pilot was a bit nervous. She always was, when it came to spin testing a new aircraft. As good as the engineers were, they still had trouble predicting spin behavior in new designs. Today, the spin testing would explore the recovery characteristics of the aircraft at rear CG locations. The goal was to find the rear CG limit with acceptable spin recovery characteristics. The FAA certification requirement was that after a one turn spin in either direction, the aircraft must be recoverable in less than one and one half additional turns. The engineers had rigged a gizmo behind the pilot seat that allowed the test pilot to adjust the CG of the aircraft while she was flying it. Basically it was a motorized trolley on rails with a weight on it. The trolley could be motored fore and aft on the rails to change the CG location. The pilot had a switch on the yoke, similar to a trim switch, that she could use to run the trolley back and forth.

The plane had climbed to 12,000 AGL, and the pilot was cleared to begin the first spin test. She flipped the diagnostics switch that would turn on the data recorder and moved the trolley aft, to the first test position. She could feel a change in the pitch stability of the aircraft, but it still had good positive pitch stability. She cleared the area around her and below her, checked her altitude and heading, reduced power, and then executed a spin entry. After one turn she executed the recommended recovery technique with full rudder against the spin and centered the yoke. The rotation began to slow and then stopped in about half a turn with the nose pitched down. After the aircraft gained speed, the pilot pulled the nose up into level flight. She had lost about a thousand feet in the spin. She climbed back up to try another spin. The testing continued with the pilot gradually moving the trolley farther and farther back after each spin and recovery. The pitch stability of the aircraft remained positive, even though it was becoming less so, and the spin recovery was taking a bit longer each time. She finally moved the trolley to the rear limit that the engineers wanted to test. This would be the rear CG limit for the aircraft if it had acceptable stability and spin recovery characteristics. The pilot executed another spin entry and noticed that the nose did not drop as much as in the other spin entries. After one turn, the pilot executed the normal recovery technique. The rotation began to slow but did not stop in the required one and a half turns, in fact it did not stop at all. The nose began to rise as the aircraft continued past two turns. The test pilot neutralized the controls and tried the recommended recovery technique again. Once again the spin rate slowed, but did not stop. As the spin went through 3 turns the test pilot then tried an alternate recovery technique that involved pushing the stick full forward with full opposite rudder. Once again, the aircraft slowed, but did not stop spinning. The pilot glanced at the altimeter and noted that she had now lost 3000 feet. It was time to recover the aircraft before it entered a fully developed spin. The pilot activated the trolley and ran it forward to its stop. As she did so the nose of the aircraft began to drop and the spin rate began to accelerate. She then executed the recommended spin recovery technique and the aircraft rotation slowed to a stop. The pilot pulled out of the dive and leveled off. She noticed that her pulse rate had increased and beads of sweat had formed on her forehead. She reminded herself that had the change in CG not worked, she could have deployed the spin chute, and if that had not worked she could have bailed out. Never the less, being a test pilot could certainly be exciting at times. As she returned for landing, she thought to herself that the engineers would not be happy about having to move the rear CG limit farther forward then they had planned, but it was either that, or redesign the empennage for greater rudder effectiveness.

The story illustrates the effect of a rearward CG on spin recovery. An aircraft may have positive pitch stability behind the specified rear CG limit, but it may not have acceptable spin recovery characteristics.

CHAPTER FOUR

During flight tests in 1994, the cabin interior of the prototype 777 was filled with what at first glance looked like aluminum beer kegs. In fact, these 55-gallon barrels contained water. The contents of two dozen barrels in the forward cabin and a like number of barrels in the aft section were pumped back and forth to simulate shifts in center of gravity that would result from passengers moving about. The top photo shows the cabin as it is when the 777 is delivered.

Figure 3 shows pictures of a B777 during testing where water stored in barrels replaces normal seats and is pumped fore and aft to simulate center of gravity shifts.

These stories are based on actual experiences that pilots have had. I hope they are helpful in letting you understand the implications of flying your aircraft outside of the recommended CG limits and encourage you to develop a better understanding of why it is important to know where the center of gravity is for your aircraft.