Balance

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On the internet, in the hangar and in the pilot lounge frequently there is talk about the lift on the tail. Specifically, is the lift on the tail positive, i.e., in the same direction as the lift generated by the wing, or negative, i.e., opposite to the direction of the lift of the wing? The typical wisdom says that a downforce on the tail is required to make the aircraft stable. That is not the case. An aircraft can always be made stable by simply moving the center of gravity far enough forward. Unfortunately, moving the center of gravity forward has other effects, most of which are undesirable, e.g., high stick forces. What is stability anyway? Formally:

> A system (aircraft) is stable if, when slightly disturbed from an equilibrium state, the system tends to return to and ultimately remain in the original equilibrium state.

The equilibrium states that we as pilots are most familiar with are steady level cruise, a steady climb, or a steady descent.

If the lift on the tail is not associated with the stability of the aircraft, then what is it associated with? The lift on the tail of a conventionally configured aircraft such as the Bonanza results from the requirement for the aircraft to be *balanced*. An aircraft is balanced when the sum of the moments about the center of gravity is zero. What does this mean?

A simple example is a teeter-totter or seesaw. If you want to ride a teeter-totter with your granddaughter who weighs 90 lbs and you weigh 175 lbs, then you must adjust the rotational center of the teeter-totter. Specifically the distance from the center of rotation, i.e., the moment arm, must be larger on your granddaughters side than on your side. When you 'balance' the teeter-totter you are making the sum of the moments about the center of rotation zero.

Possible Aircraft Configurations

First a bit of background. In Fig. 1 the notation ac refers to the aerodynamic center. The aerodynamic center is that location on the wing about which the pitching moment coefficient does *not* vary with angle of attack. Consequently, using the aerodynamic center simplifies consideration of the moments on the wing.

Now consider a straight untapered wing of constant airfoil section (flying wing) with a positively cambered airfoil as shown in Fig. 1. The Bonanza uses a positively cambered airfoil—the NACA 230 series airfoil. At zero absolute angle of attack and hence zero lift coefficient the pitching moment about the aerodynamic center is nose down. Notice that there is no counter balancing moment, hence the wing/aircraft simply rotates nose down. Thus, balanced flight is not possible at zero absolute angle of attack or any positive angle of attack or lift coefficient. As a result, a surface is required to provide a balancing moment. Because of drag considerations it is desirable to use a small surface. Hence, a long moment arm is required.

Typically, two aircraft configurations are used; either the conventional configuration with the tail aft, i.e., behind the wing, or the canard configuration with the tail forward, i.e., in front of the wing. Because the Bonanza uses a conventional aircraft configuration we ignore the canard configuration. The balancing surface in the conventional configuration is typically called a tail or, more properly, a horizontal stabilizer. The conventional configuration is shown schematically in Fig. 2.

In the conventional configuration the lift on the horizontal stabilizer can be either positive, i.e., upward, or negative, i.e., downward. If either the lift on the wing is zero or the aerodynamic center of the wing and the center of gravity of the aircraft are coincident as shown in Fig. 2a, then the

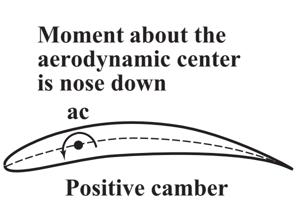

Figure 1. A wing at zero lift.

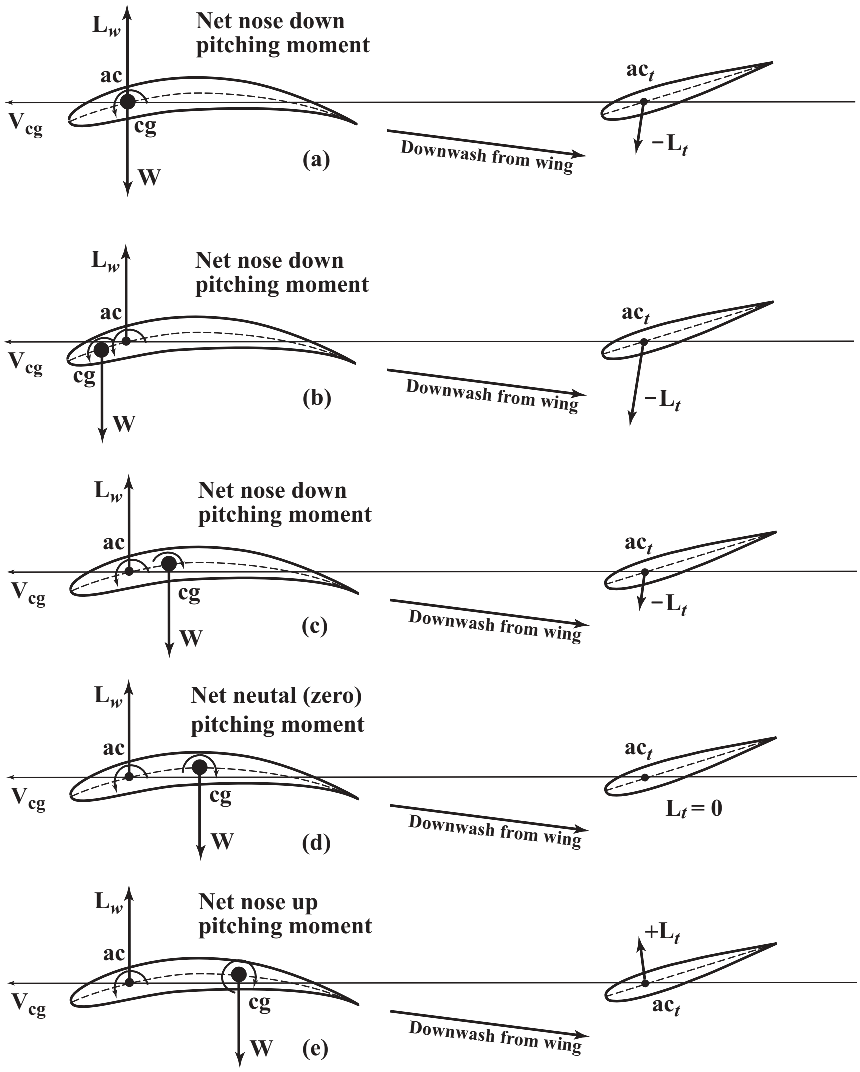

Figure 2. Effect of center of gravity location on horizontal stabilizer lift.

wing pitching moment is equal to the pitching moment about the wing aerodynamic center which is nose down as shown by the counterclockwise arc in Fig. 2a. The counteracting balancing moment generated by the horizontal stabilizer must then be nose up. Hence, a negative lift on the horizontal stabilizer is required as shown by the down arrow representing the lift on the horizontal stabilizer in Fig. 2a. This is essentially the same as the situation shown in Fig. 1 and discussed above.

If the center of gravity of the aircraft is ahead of the aerodynamic center of the wing as shown in Fig. 2b, then the pitching moment caused by the couple formed by the lift on the wing, L_w, acting though the aerodynamic center and the weight, W, acting through the center of gravity is nose down as shown by the counterclockwise arc around the center of gravity in Fig. 2b. The pitching moment about the aerodynamic center is also nose down, again as shown by the counterclockwise arc in Fig. 2b. The total pitching moment of the wing is the sum of these two nose down pitching moments. Hence, again, a negative lift on the horizontal stabilizer is required to generate a larger counteracting nose up balancing moment, as shown in Fig. 2b by the longer down arrow at the aerodynamic center of the horizontal stabilizer.

If the center of gravity of the aircraft is behind the aerodynamic center of the wing, then the pitching moment caused by the couple formed by the lift on the wing, L_w, acting through the aerodynamic center and the weight, W, acting through the center of gravity, is nose up. Depending on the magnitudes of the lift and weight and the distance between the aerodynamic center and the center of gravity, the resulting moment may be less than, as shown in Fig. 2c, equal to, as shown in Fig. 2d, or greater than, as shown in Fig. 2e, that generated by the pitching moment about the aerodynamic center. Consequently, the resulting moment about the center of gravity due to the wing may be nose down, as shown in Fig. 2c, zero, as shown in Fig. 2d or nose up, as shown in Fig. 2e. As a result, the required balancing moment due to the horizontal stabilizer may be nose up (downward horizontal stabilizer lift), zero (zero lift) or nose down (upward horizontal stabilizer lift).

The total lift on the aircraft is the sum of the lift on the horizontal stabilizer and on the wing. Downward lift on the horizontal stabilizer requires that, in steady level flight, the wing produce additional lift. Hence, additional induced drag is produced by the wing *and* the horizontal stabilizer. Although upward lift on the horizontal stabilizer reduces the required lift and the induced drag of the wing, because the horizontal stabilizer usually is of lower aspect ratio and has a symmetrical airfoil section, the additional induced drag on the horizontal stabilizer is usually greater than the reduction in induced drag on the wing. The result is an increase in aircraft drag and a reduction in aircraft performance.

What does this have to do with the Bonanza?

The Bonanza was designed for high speed cruise. For a late Model 33 the design speed is 157 KTAS. The design center of gravity is 84.4 inches aft of the datum or approximately 2 inches aft of the quarter chord of the wing spar. The aft center of gravity location is at 86.7 inches aft of the datum. Above 2800 lbs gross weight the permissable center of gravity range is 4.6 inches, i.e, from 82.1 in to 86.7 in. Thus, the design center of gravity is in the center of the permissible center of gravity range. The horizontal stabilizer incidence is 2 degrees leading edge down with respect to the aircraft zero lift line or approximately 3.5 degrees leading edge down. Wing downwash effectively increases the angle of attack of the horizontal stabilizer and the negative lift. Consequently, in order to achieve positive lift on the horizontal stabilizer the true airspeed needs to be well above the design speed and the center of gravity near the aft center of gravity range—possible but unlikely.

Summary

If the center of gravity is placed far enough forward, then it is always possible to make the aircraft stable. Hence, it is not the stability requirement that determines an acceptable aircraft configuration. Rather, it is the requirement that the aircraft be both stable and *balanced* that dictates the configuration. Depending on the location of the center of gravity, the lift on the horizontal stabilizer may be downward, zero or upward. For a late Model 33 Bonanza it is unlikely that the horizontal stabilizer achieves positive (upward) lift for reasonble operating conditions.