5.0 AEROELASTICITY

Aeroelastic phenomena have influenced airplane design since its origin. Section 5.1 describes potential static and dynamic problems associated with aeroelasticity and discusses the historical experience. Section 5.2 considers the torsional (static) divergence problem and its implications relative to the Model 35 Bonanza tail. Section 5.3 discusses the conditions for elevator flutter that might affect the V-tail Bonanza.

5.1 AEROELASTIC EFFECTS

There is a vast amount of literature available that deals with aeroelasticity and its associated dynamic, elastic and aerodynamic theories. The most comprehensive books on this subject are those by Bisplinghoff, Ashley and Halfman[63], Fung[64], Bisplinghoff and Ashley[653], Scanlan and Rosenbaum (Reference 5-4), and a manual edited by Jones[67]. A USAF report[68] also contains a wealth of information on aeroelastic effects in stability and control. There are also many surveys reviewing the field of flutter[69,70]. The most recent developments are more involved with numerical computation methods[71].

The aeroelastic problem involves the mutual interaction between aerodynamic forces, elastic forces, and possibly inertia forces, and the influences of the interaction on airplane performance. Such problems only became important during the early stages of World War II. Before that time, airplane speeds were relatively slow and aircraft structures were sufficiently rigid to preclude excessive aeroelastic interactions. As the speeds increased and the structures became more flexible, a wide variety of aeroelastic problems appeared. Such trends were vividly illustrated over the years of World War II by the increases in the wing slenderness ratio and the reduced velocity parameter[65]. The slenderness ratio (the ratio of wing semispan to wing root thickness) is a measure of wing flexibility and the reduced velocity parameter (the maximum flight speed divided by the wing chord at the three-quarter semispan and the fundamental frequency of torsional vibration) relates to the magnitude of aeroelastic effects.

The aeroelastic problem arises because the structural deformations induce a change in the aerodynamic forces which in turn alter the deformations. The interactions may reach a condition of stable equilibrium or continuous oscillation, or become divergent and destroy the aircraft. Such interactions may also change the control effectiveness of the airplane because the distribution of the air loads induced by the deflection can be significantly different from that obtained from a rigid structure[65]. In a more severe situation, the intended effects of a given maneuver can be nullified completely by the structural deformations. This condition is referred to as control system reversal.

The dynamic instability of the aeroelastic interactions which can result in oscillations of finite amplitudes or divergent oscillations destroying the aircraft is called flutter. There are many kinds of flutter. Classical flutter involves smooth flow over the elastic surfaces. The pressure on the surfaces is a function of the surface velocity. Under certain specific conditions the effects of inertia and the surface slopes with respect to the flow enable the transfer of energy from the airstream to sustain the structural oscillation. The phenomenon is now well understood, and many sophisticated methods have been developed to solve such problems. However, to predict the amplitude of flutter oscillation which actually

controls the structural failure is complex and more difficult because of the nonlinearity associated with the finite-amplitude vibration.

The nonclassical type of flutter is usually associated with separated unsteady flow and stall conditions. This is also a self-exciting phenomenon in which energy is extracted from the airstream sustaining the oscillation or leading to destruction of the structure. Due to the nonlinear nature of nonclassical flutter, it is difficult to predict analytically and, therefore, difficult to control in a new design or new configuration.

Classical flutter is an inherent instability which, when it exists, is likely to be triggered by a variety of disturbances such as turbulence in the air flow, gusts, maneuver inputs from the pilot, or even engine noises. However, nonclassical flutter may require a specific disturbance or disturbances of sufficient amplitude.

Flutter is usually, but not necessarily, associated with motions of two or more degrees of freedom. The most common flutter is that involving bending and/or twisting of wing or tail surfaces. Mass distribution and stiffness, rather than strength, are the important structural parameters affecting flutter behavior. Prevention or cure of flutter usually is accomplished by either increasing the stiffness, adjusting the mass distribution to decrease the coupling of modes, or a combination of both. For both wing and tail, the torsional stiffness is the most important stiffness parameter for flutter considerations. It is not uncommon that the flutter condition controls the selection of skin thickness, which is the primary contributer to the torsional rigidity of these components. Flutter is also the main consideration in the selection of locations of the heavy masses such as the fuel tanks and nacelles on the wing.

A static aeroelastic instability which involves only aerodynamic forces and elastic forces can cause structural divergence. The most common problem is torsional divergence of a wing or a tail. To illustrate the concept, consider a straight wing or tail with the center of twist of the lifting surface aft of the aerodynamic center. The aerodynamic moment twists the structure, increasing the angle of attack, and this increases the air loads further. When the increment in aerodynamic moment due to the increase of the twist angle is exactly equal to the increment in elastic restoring torque, the neutrally stable condition is reached. The aerodynamic moment is proportional to the square of the speed, whereas the elastic restoring torque is independent of speed. The speed at which the structure first reaches the neutrally stable condition is called the critical speed. When the critical speed is exceeded, the increment in the aerodynamic moment is greater than the increment in restoring torque, and the structure becomes unstable. The torsional stiffness and the offset between the elastic axis and the aerodynamic center are the most important parameters for torsional divergence considerations.

As a historical note, according to Bisplinghoff[63], the reason for the dominance of biplanes over monoplanes in the early days of airplane development was at least in part a result of the aeroelastic problem. The plane designed by S. P. Langley, which was wrecked on the Potomac due to a wing failure, was a monoplane. It is believed, in light of modern knowledge, that the incident was the result of wing torsional divergence. Shortly after, the Wright Brothers, in a biplane, made the first famous sustained flight that dawned the aviation age. The failure of the monoplane versus the success of the biplane gravitated designers' thinking toward the biplanes which dominated early aviation development for many years. It was not until the mid-

thirties that the monoplane was reborn in response to demand for high-performance military aircraft.

The biplane with its interbracing has a relatively high torsional rigidity which prevented the wing aeroelastic problems of the early airplanes. The main problem then was tail flutter. One of the first documented tail flutter incidents occurred on the Handley Page 0/400 Bomber at the beginning of World War I. The problem involved a severe vibration of the elevators, coupled with the torsional vibration of the fuselage. These two modes had low frequencies close to each other. The problem was cured by stiffening the elevator attachments.

Wing aeroelastic difficulties became widespread after monoplanes were introduced. Many of the problems were associated with wing torsional divergence because of the lack of torsional rigidity of the early monoplanes. An example was the high-performance Fokker D-8 airplane. In the first few days of service in combat, repeated wing failures occurred in high speed dives even though the plane had been proved to have adequate strength in ground tests.

The development of the cantilever monoplane stimulated research in aeroelasticity. The first theory of wing load distribution and wing divergence was published by Reissner in 1926[72]. The mechanism of classical flutter was understood sufficiently well for design application by 1935 through the works of Glaubert[73], Frazer and Duncan[74], Kussner[75], and Theodorsen[76]. However, according to Bisplinghoff et. al.[63], few designers were able to comprehend the early papers and the majority were reluctant to trust mathematicians to compute the sizes of structural members to preclude aeroelastic effects. By the early 1940's, the period during which the first Bonanza was designed, aeroelastic effects were a well recognized problem and a part of required consideration in aircraft design. However, the method for design was predominately one of trial-and-error rather than a well developed systematic procedure.

5.2 TORSIONAL DIVERGENCE CONSIDERATIONS

The structural design of the stabilizer for the original V-tail Bonanza and Models A35 and B35 can be considered conservative and torsional divergence is not a concern. As discussed in Section 4, the increase in length of the tail chord on the Model C35 by extending the nose introduced a less conservative configuration. The susceptibility to torsional divergence was further increased in Model C35 because the ribs of the stabilizer primary box were replaced by skin beads. The shape of subsequent Model 35 tail configurations has remained basically the same since Model C35, but the evolution has resulted in increased structural rigidity.

For the tails of recent models of the Bonanza, the torsional divergence speed was estimated to be about 400 mph, which is safely above V_D, the design dive speed. However, this estimate is based on linear theory which provides a good approximation only until severe skin buckling occurs. For the stabilizer with the extended nose section, the air load of Maneuver Condition J (as defined in Section 4.4) has a center of pressure located more than 3 in. forward of the main spar. Since the primary box has no ribs other than one at each end and one in the middle (on the H35 and later Models), when the skins over the primary box are severely buckled very little load can be transferred to the rear spar and consequently the main spar must carry a large portion of the bending and torque of the segment between the root rib and fuselage. The main spar is of open cross section, which has a low torsional stiffness, and is an ineffective member for carrying torque. As a result the

torsional deflection of the stabilizer can be sufficiently large so that the change in aerodynamic load due to the deformation may become significant. Based on the limited data available from tests conducted by Mike Smith Aero, Inc. (severe buckling occurred at 950 lb), the air load for torsional divergence can correspond to the load causing the severe buckling of the stabilizer primary box. The critical speed could thus be less than that estimated by the linear analysis. The torsional divergence speed for H35 for the condition of 15° yaw with the elevator neutral can be approximately 180 mph. The corresponding limit speed is obtained by dividing the torsional divergence speed by the square root of 1.5. The result is about 147 mph, which is slightly higher than the maneuver speed.

For the stabilizer without the extended nose section, which corresponds to the early Model 35 and all Models 33 and 36, the center of pressure for Maneuver Condition J lies between the two spars (about 1 in. behind the main spar and 12 in. forward of the rear spar). The torque about the root shear center is much smaller than for the extended chord configuration (2.5 vs 6.5 in.-lb. per unit net load). Even after severe buckling of the primary box, the moment and torque will be shared by both spars. Therefore, the potential failure mechanism (severe skin buckling causing the torque shift to the front spar resulting in a large torsional deformation and air load increase) cannot occur with the short nose stabilizer.* The possibility of this occurring for the stabilizer with the extended nose should be reduced if there is a leading edge support. The leading edge support can reduce the load in the main spar after skin buckling begins. In this way, the torque on the main spar will not become as high. The torsion of the stabilizer will remain small and redistribution of air load due to the deformation will be less significant.

In summary, the linear analysis indicates that the critical speed for torsional divergence is about 400 mph, which is well outside the flight envelope. However, for the stabilizer with the extended nose section, this estimate may not be conservative. For the Maneuver Conditions J or G1, or for a severe gust, the air loads can produce a significant torque on the tail that can cause the skin to buckle, thus reducing its torsional rigidity. Even though the weakened stabilizer can still sustain higher static loads, the redistribution of the air load caused by the twisting deflection resulting from the reduction in rigidity can lead to torsional divergence at speeds below that estimated by a linear analysis.

5.3 FLUTTER ASSESSMENT

The possibility of flutter contributing to Bonanza in-flight structural failures has been raised on several occasions throughout the history of the aircraft. Flutter was considered in the original design, and Beech Aircraft Corporation has conducted both analyses and tests investigating the phenomena. "The Aviation Consumer" cited a flutter analysis by Beech which indicated that the tail could flutter at speeds between 70 and 80 mph[77,78]. This early analysis was apparently in error because no test has ever demonstrated, nor flight ever experienced, flutter in this speed range. Beech later conducted two series of flight tests, several additional analyses, and wind tunnel tests as recently as 1974 to investigate a possible flutter problem of the Model 35 tail.

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* Failure caused by bending loads can result in tail deformations that look similar to those caused by torsion.

The first series of flight tests was conducted in 1946 as a part of the certification requirement. A motor-driven vibrator was mounted in one of the tails to excite flutter vibrations during flight. Tests up to a flight speed of 225 mph were performed. Most of the records were taken with power off and at an altitude of 8200 ft. but no flutter was found. The CAA considered this series of tests inconclusive because they felt that the excitation and resulting deflections of the tail were too small to excite any likely flutter instability[79]. As a consequence, Beech conducted a second series of flight tests in 1947 using an original Model 35[61]. The test was conducted at speeds at 70, 115, 145, 150, 175, 195 and 202 mph. Measurements of the transient motion of the ruddevator were made after a "snap kick" of the ruddevator pedals. This was repeated for elevator action at 145, 150 and 175 mph. The measurements included the ruddevator angle and stabilizer tip motion. Test results for 145 and 175 mph at altitudes of 6660 and 9800 ft., respectively, show that the ruddevator was critically damped, whereas the stabilizer tip oscillated continually with an amplitude about 0.1 in. during the tests. The disturbance, resulting from the "snap kick" lasting for about three cycles, was superimposed on the continuous oscillations. The reason the disturbance did not damp out in one cycle can be explained by the fact that the ruddevator input from the "snap kick" lasted about three cycles of the stabilizer tip motion (Reference 5-28). One test plane, remotely controlled, was flown close to 300 mph and no evidence of flutter was found[80].

The flutter analysis results indicate that the aft fuselage torsion coupled with asymmetrical elevator oscillation is the most critical mode with the flutter frequency in the range or 11 to 12 Hertz[58]. The most important parameters affecting tail flutter are tail "heaviness", structural damping, tab cable and stabilizer stiffness. The tail heavy or imbalance condition is defined as the weight of the elevator and trim tab times the distance from the center of the mass to the hinge. Increase of the damping and stiffness, or decrease in tail heaviness tends to increase the flutter speed. The maximum allowable tail heaviness, 100 percent as specified by Beech for models prior to S35, is 19.84 in.-lb. As shown in Figure 5-1, with a structural damping of 3 percent of critical damping and a tail heaviness of 20.6 in.-lb. (about 104 percent of the maximum specified) the critical flutter speed is about 170 mph at sea level; there is no flutter if the tail heaviness is below 104 percent. In the same analysis, Beech also found the possibility of asymmetric instability in the air speed range above 250 mph if the balance was less than 14.5 in.-lb. Beech stated that a properly maintained plane is likely to have more than 3 percent effective damping because of the friction in the cables, pulleys and various control mechanisms. Based on the analysis there should not be any flutter within the range of operating speeds if the plane is maintained within specifications.

The flutter problem can be more critical at higher altitudes. Using the conversion of

$$v_i=(1-v_c^2/\,a^2)^{\frac{1}{2}} \qquad (5\text{-}1)$$

where v_i and v_c are, respectively, the velocities in an incompressible and compressible flow, and a is the sonic speed at sea level, Beech's analysis indicates that flutter can occur at higher altitudes for tail heaviness of 100 percent or less[59]. For example, the flutter speed is about 120 mph (140 mph EAS based on a given temperature) at 17,000 ft. for 100 percent tail heavy, and in the range of 120-180 mph at 25,000 ft. and 90 percent tail heavy. As a result of this analysis, Beech recommended changing the tail heavy limit from 19.86 to 17.4 in.-lb. for the Model S35 and later models. The results for the higher altitudes are based on an

extrapolation from the incompressible flow analysis. This reduction of the maximum allowable tail heaviness is a matter of precaution.

The analytical results at low altitudes have been verified by wind tunnel tests[81]. The wind tunnel tests were conducted in 1974 at a Lockheed Georgia wind tunnel using a full-scale Model C35. The test conditions were equivalent to an altitude of 2,000 ft., the region where the incompressible flow assumption is valid. The results showed that the flutter was always triggered by the wind tunnel turbulence, but could not be excited by a "jerk-wire" outside the flutter boundary. Flutter occurred at 176.6 mph EAS with an aft ruddevator balance of 25.97 in.-lbs. (130 percent of maximum allowable) and with the normal control system. With the ruddevators disconnected from the control system at the horns, flutter was found at 167.6 mph EAS with a ruddevator unbalance of 22.6 in.-lb. The flutter frequencies were between 12 and 14 Hertz. With the tab cables disconnected, the tab started to flutter at 105 mph at a frequency of 7.5 Hertz, and the motion became divergent at 106 mph.

Even though both analyses and wind tunnel tests indicated that no flutter is possible if the plane is properly maintained and has the parameters kept within specification, there are still concerns of potential aeroelastic problems. The concerns are summarized in the following paragraphs.

Classical flutter analyses indicate that the Bonanza is marginally susceptible to flutter instability, especially in an antisymmetric mode (fuselage torsion coupled with ruddevator oscillation). The analysis indicated that, if there were no structural damping, at 10,000 ft. altitude and 100 percent tail heaviness the flutter speed would lie between 140 and 180 mph. For an older, poorly maintained airplane in cold upper air, the structural damping may drop to a value below 3 percent, resulting in aeroelastic instability. An average paint job adds about 2.0 to 2.8 in.-lb. tail-heavy static imbalance, which is sufficient to place the elevator balance outside the limit. Even though specified procedure requires rebalancing after painting the ruddevators, it may be neglected in some instances. Such incidents have resulted in in-flight flutter in the past[80]. According to Beech, there have been no cases involving flutter for the Model A35 and newer V-tail configurations.

The Model 35 V-g diagram shown in Figure 5-1 indicates that the flutter characteristic at a tail heaviness of 100 percent or more is a hump mode type, i.e., if the structural damping is above the hump, there is no flutter at any speed. The critical structural damping at the hump of 100 percent tail heaviness is about 0.014 at about 180 mph (IAS). However, the analysis based on the V-g diagram cannot provide the information on how much effective damping (a combination of structural and aerodynamic damping) the plane will have at a given flight condition if the structural damping itself exceeds 0.014. There is the possibility that the plane has no flutter instability in the classical sense, i.e., the structural damping is above the hump but its effective value is very small and the structure is susceptible to external excitation such as turbulence. The continuous lightly damped oscillation could distract the pilot and reduce pilot alertness, especially in bad weather conditions.

There is another condition that can reduce the flutter speed allowing it to occur within the operating speed range. Fuselage damage near the tail attachment bulkhead, which could lower the asymmetrical vibration frequencies of the empennage, is known to have caused flutter in flight[80].

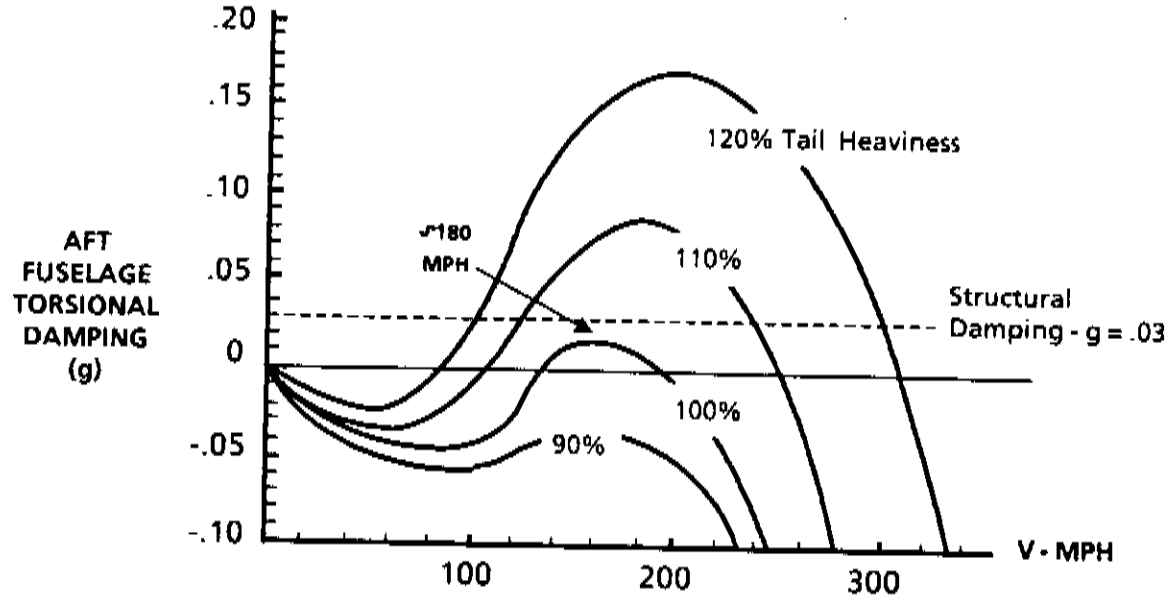

FIGURE 5-1. V-g DIAGRAM FOR THE S35 MODEL FOR VARIOUS DEGREES OF TAIL HEAVINESS (%)

The cable tension in flight could be less than what was measured on the ground. It has been suggested that the reduction of cable tension might reduce the flutter speed. Stearman has shown in a test[82] that the tension in the trim tab cables could be reduced under loads. In fact, tail flutter is affected by the cable stiffness or spring constant which is a function of the cable cross-sectional area. Cable tension variation should have no influence on the flutter speed unless the cables are completely loose or broken.

There have also been FIFAF accidents in which the ruddevator counterweight was ripped off and found miles away from the rest of the wreckage. Since it is estimated that an acceleration of more than 100 g is required to rip off the counterweight, the presence of flutter is suggested. However, further analysis shows that the flutter frequency is about 12 Hertz, and in order for the balance weight to reach 100 g acceleration, the flutter amplitude at the counterweight location would have to exceed 6.75 in. which is much larger than the travel limit of the elevator will allow. Therefore, the counterweight separation could not have been caused directly by the flutter oscillation.

As stated by Beech, for flutter to cause an in-flight airframe failure (IFAF) accident, there would be evidence of stress reversal on the failed spars, internal stringers, ribs, fasteners, etc., and skin of the failed surfaces, and damage at the elevator stops. Such evidence was generally not found in the wreckages.

Both analysis and testing have demonstrated that no flutter exists within the flight envelope if the plane is properly maintained. Since flutter is an inherent instability phenomenon, it can be excited by either natural disturbances or maneuvering. With the millions of hours flown by the V-tail Bonanza, if flutter were a problem, there would be an avalanche of flutter incidents. Also, 90 percent of the flight hours are in clear sky while only 10 percent are in bad weather. Accident data showed that 90 percent of the accidents occurred in bad weather. If flutter were the cause of the accidents, a much higher accident rate in clear weather would be expected.

From the above considerations, the task force concluded that there is no flutter problem for the Model 35 within the flight envelope, provided the airplane is maintained within specifications. However, inadequate maintenance and/or damage to structural components may leave the plane vulnerable to flutter.