U.S. Department
of Transportation
Federal Aviation
Administration

Advisory Circular

Subject: Aeroelastic Stability Substantiation of Transport Category Airplanes

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Initiated By: AIR-600

AC No: 25.629-1C

This advisory circular (AC) provides general guidance for acceptable means, but not the only means, of demonstrating compliance with those provisions of Title 14, Code of Federal Regulations (14 CFR) 25.629, *Aeroelastic stability requirements*, and other part 25 regulations related to aeroelastic instabilities of flutter, divergence, and control reversal. Revision C of this AC contains guidance based on rule changes to § 25.629.

If you have suggestions for improving this AC, you may use the Advisory Circular Feedback form at the end of this AC.

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FIGURES

1 PURPOSE.

This AC provides guidance for acceptable means, but not the only means, of demonstrating compliance with 14 CFR 25.629, and other provisions of part 25 intended to preclude the aeroelastic instabilities of flutter, divergence, and control reversal. The details of all possible analytical procedures and testing techniques are beyond the scope of this AC. However, this AC includes general information for applicants to consider when demonstrating compliance with § 25.629 and related regulations. Revision C of this AC contains guidance based on rule changes to § 25.629. The contents of this document do not have the force and effect of law and are not meant to bind the public in any way. This document is intended only to provide clarity to the public regarding existing requirements under the law or agency policies.

2 APPLICABILITY.

2.1 The guidance provided in this AC is for airplane manufacturers, modifiers, foreign regulatory authorities, and Federal Aviation Administration (FAA) transport airplane type certification engineers and their designees.

2.2 Using this guidance as a means of compliance to § 25.629 is voluntary only and not using it will not affect rights and obligations under existing statutes and regulations. The FAA will consider other methods of demonstrating compliance that an applicant may elect to present. Terms such as “should,” “may,” and “must” are used only in the sense of ensuring applicability of this particular method of compliance when the acceptable method of compliance in this document is used. If the FAA becomes aware of circumstances in which following this AC would not result in compliance with the applicable regulations, the agency may require additional substantiation as the basis for finding compliance.

3 CANCELLATION.

This AC cancels AC 25.629-1B, *Aeroelastic Stability Substantiation of Transport Category Airplanes*, dated October 27, 2014.

4 RELATED 14 CFR REGULATIONS.

The following 14 CFR part 25 regulations are related to this AC. You can download the full text of these regulations from the Federal Register website at Electronic Code of Federal Regulations, jointly administered by the Office of the Federal Register (OFR) of the National Archives and Records Administration (NARA) and the U.S. Government Publishing Office (GPO). You can order a paper copy from the U.S. Superintendent of Documents, U.S. Government Publishing Office, Washington, D.C. 20401; at Government Publishing Office, by calling telephone number (202) 512-1800; or by sending a fax to (202) 512-2250.

- Section 25.251, *Vibration and buffeting*.
- Section 25.305, *Strength and deformation*.

- Section 25.335, *Design airspeeds*.
- Section 25.343, *Design fuel and oil loads*.
- Section 25.571, *Damage-tolerance and fatigue evaluation of structure*.
- Section 25.629, *Aeroelastic stability requirements*.
- Section 25.631, *Bird strike damage*.
- Section 25.671, *Control Systems—General.*
- Section 25.672, *Stability augmentation and automatic and power-operated systems*.
- Section 25.1309, *Equipment, systems, and installations*.
- Section 25.1329, *Flight guidance system*.
- Section 25.1419, *Ice protection*.
- Section 25.1420, *Supercooled large drop icing conditions*.

5 BACKGROUND.

5.1 Flutter and other aeroelastic instability phenomena have had a significant influence on airplane development and the airworthiness criteria governing the design of civil airplanes. The initial requirement for consideration of flutter was brief in the 1931 *Airworthiness Requirements of Air Commercial Regulations for Aircraft*, Bulletin No. 7-A. The airplane flutter requirement specified that “no surface shall show any signs of flutter or appreciable vibration in any attitude or condition of flight.” In 1934, the U.S. Civil Aeronautics Board (CAB) revised Bulletin No. 7-A in view of service experience, providing advice and good practice techniques for the early airplane designer regarding flutter prevention measures. This revision also required all airplane designs to have interconnected elevators, statically-balanced ailerons, irreversible or balanced tabs, and, in some cases, a ground vibration test (GVT).

5.2 The CAB introduced regulations on flutter, deformation, and vibration on transport category airplanes in the mid-1940s, through various provisions of part 04 of the Civil Air Regulations (CAR). The design criteria related the solution of the flutter problem to frequency ratios that were based on model tests conducted by the Army Air Corps. Also, based on the Army Air Corps’ research, part 04 imposed a safety factor of 1.2 on the required equivalent airspeed, to provide a stiffness margin for the airframe. Since aircraft technology was rapidly changing, part 04 also referenced publications containing flutter theory.

5.3 The flutter requirement of part 04 evolved into CAR 4b.308, while developing fail-safe engineering philosophy continued to change the scope of flutter substantiation. Fail-safe design is one in which a single failure would not adversely affect safety of flight. Among these developments was a revision to CAR 4b.320 in 1956 to require fail-safe tabs, and a revision to CAR 4b.308 in 1959 to require fail-safe flutter damper installations. The FAA extensively revised the flutter requirement in 1964 to require that the entire airplane comply with the single-failure criteria, and to add special provisions for turboprop airplanes.

5.4 Service experience indicated that single failure criteria related to flutter stability were not sufficiently objective and comprehensive to cover modern, complex, transport airplanes equipped with highly redundant systems. Therefore, the FAA amended part 25, the successor to part 04b of the CAR, to require that, unless an applicant could show that combinations of failures were extremely improbable, the applicant must consider such combinations when designing the airplane to be free from flutter and divergence.

5.5 The development of speed and attitude limiting systems created the need for a minimum speed margin for fail-safe aeroelastic stability substantiation. Part 25, as amended by amendment 25-77, incorporated this minimum fail-safe speed boundary, revised the safety margins for aeroelastic stability, and expanded the list of failures, malfunctions, and adverse conditions that needed to be addressed.

5.6 The effect of flight control systems, autopilots, stability augmentation systems, load alleviation systems, and other systems that can affect aeroelastic and aeroservoelastic stability under nominal conditions is addressed in terms of gain and phase margins that characterize feedback control systems. In addition, clarifications were added about assessing the effect of high load factors on aeroelastic stability.

6 DISCUSSION OF REQUIREMENTS.

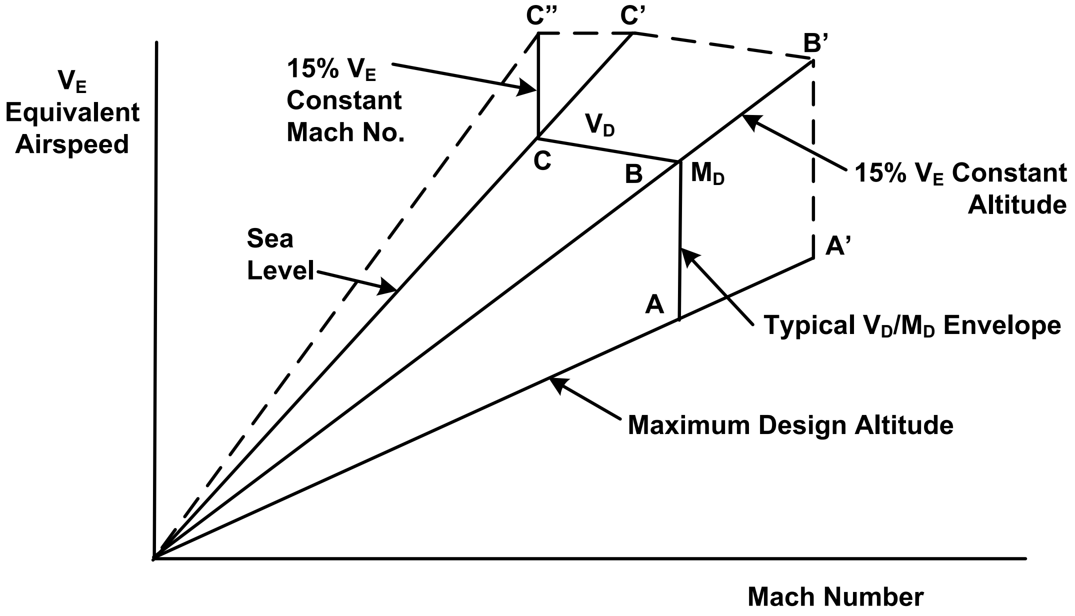
The general requirement for demonstrating freedom from aeroelastic instability is in § 25.629, which also requires investigation of these aeroelastic phenomena for various airplane configurations and flight conditions. Additionally, to assure safe flight, the applicant must investigate other conditions for aeroelastic stability, as required by the part 25 sections listed in paragraph 4 of this AC. Many of the conditions for which this AC provides guidance pertain only to certain amendments of part 25. Type design changes to airplanes certified to an earlier part 25 amendment must meet the certification basis established for the modified airplane.

6.1 Aeroelastic Stability Envelope.

6.1.1 Nominal Conditions.

For nominal conditions without failures, malfunctions, or adverse conditions, the applicant must, per § 25.629, show freedom from aeroelastic instability for all combinations of airspeed and altitude encompassed by the design dive speed (V_D) and design dive Mach number (M_D) versus altitude envelope enlarged at all points by an increase of 15 percent in equivalent airspeed at both constant Mach number and constant altitude. Figure 1 of this AC represents a typical design envelope expanded to the required aeroelastic stability envelope. Note that some required Mach number and airspeed combinations correspond to altitudes below standard sea level.

Figure 1. Minimum Required Aeroelastic Stability Margin



6.1.2 Maximum Mach Number.

The applicant may limit the aeroelastic stability envelope to a maximum Mach number of 1.0 when M_D is less than 1.0 and when there is no large and rapid reduction in damping as M_D is approached.

6.1.3 Configurations.

Some configurations and conditions that § 25.629 and other part 25 regulations require to be investigated are failures, malfunctions, or adverse conditions.

6.1.3.1 Aeroelastic stability investigations of these fail-safe conditions need to be carried out for all approved altitudes to the greater airspeed defined by—

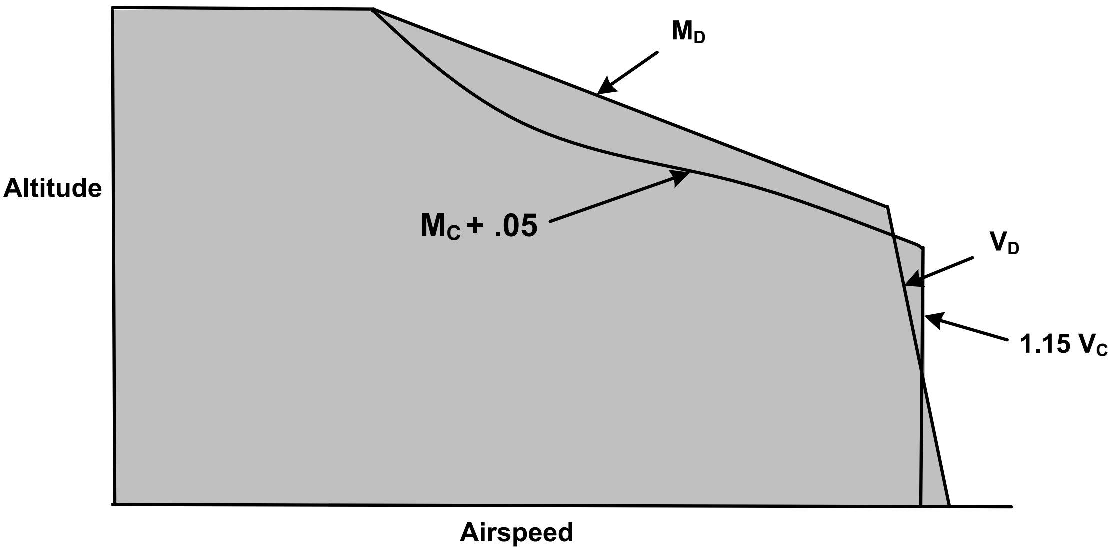
6.1.3.1.1 The V_D/M_D envelope determined by § 25.335(b); or

6.1.3.1.2 An altitude-airspeed envelope defined by a 15 percent increase in equivalent airspeed above V_C at constant altitude, from sea level up to the altitude of the intersection of 1.15 V_C with the extension of the constant cruise Mach number line, M_C, then a linear variation in equivalent airspeed to $M_C + 0.05$ at the altitude of the lowest V_C/M_C intersection; then at higher altitudes, up to the maximum flight altitude, the boundary defined by a 0.05 Mach increase in M_C at constant altitude.

6.1.3.2 Figure 2 of this AC shows the minimum aeroelastic stability envelope for fail-safe conditions. This envelope is a composite of the highest speed at each altitude from either the V_D envelope or the constructed altitude-airspeed envelope based on the defined V_C and M_C.

6.1.3.3 Fail-safe design speeds, other than the ones defined above, may be used for certain system failure conditions when specifically authorized by other rules or special conditions prescribed in the certification basis of the airplane.

Figure 2. Minimum Fail-Safe Clearance Envelope



6.2 Configurations and Conditions.

The following paragraphs summarize the configurations and conditions that applicants should investigate in demonstrating compliance with part 25. If aeroelastic stability is sensitive to load conditions of operation within the airplane's maneuvering envelope, the applicant should show the airplane's freedom from aeroelastic instability for any condition of operation allowed by the maneuvering envelope, using rational analyses, parameter variations, or an appropriate test. Specific design configurations may warrant additional considerations not discussed in this AC.

6.2.1 Nominal Configurations and Conditions.

Nominal configurations and conditions of the airplane are those that are likely to exist during normal operation. The applicant should show the airplane's freedom from aeroelastic instability throughout the expanded clearance envelope described in paragraph 6.1.1 of this AC for the following:

6.2.1.1 The range of fuel and payload combinations, including zero fuel, for which certification is requested.

6.2.1.2 Configurations with ice mass accumulations on unprotected surfaces for airplanes approved for operation in icing conditions. See paragraph 7.1.4.5 of this AC.

6.2.1.3 All normal combinations of autopilot, yaw damper, or other automatic flight control systems.

6.2.1.4 All possible engine settings and combinations of settings from idle power to maximum available thrust including the conditions of one engine stopped and windmilling, to address the influence of gyroscopic loads and thrust on aeroelastic stability.

6.2.2 Sensitivity to Load Conditions.

Sensitivity of aeroelastic stability to load conditions can be determined by varying aerodynamic coefficients and conducting other parametric studies to assess the effect of redistribution of air loads due to structural and control surface deflections. Special configurations may require additional studies.

6.2.3 Failures, Malfunctions, and Adverse Conditions.

The applicant should investigate the following conditions for aeroelastic instability within the fail-safe envelope defined in paragraph 6.1.3 of this AC.

6.2.3.1 Any critical fuel loading conditions, not shown to be extremely improbable, which may result from mismanagement of fuel.

6.2.3.2 Any single failure in any flutter control system.

6.2.3.3 For airplanes not approved for operation in icing conditions, ice accumulation expected as a result of an inadvertent encounter. For airplanes approved for operation in icing conditions, the ice accumulation expected as the result of any single failure in the de-icing system, or any combination of failures not shown to be extremely improbable. See paragraph 7.1.4.5 of this AC.

6.2.3.4 Failure of any single element of the structure supporting any engine, independently mounted propeller shaft, large auxiliary power unit, or large externally mounted aerodynamic body (such as an external fuel tank).

6.2.3.5 For airplanes with engines that have propellers or large rotating devices capable of significant dynamic forces, any single failure of the engine structure that would reduce the rigidity of the rotational axis.

6.2.3.6 The absence of aerodynamic or gyroscopic forces resulting from the most adverse combination of feathered propellers or other rotating devices capable of significant dynamic forces. In addition, the effect of a single feathered propeller or rotating device must be coupled with the failures in paragraphs 6.2.2.4 and 6.2.2.5 of this AC.

6.2.3.7 Any single propeller or rotating device capable of significant dynamic forces rotating at the highest likely overspeed.

6.2.3.8 Any damage or failure condition required or selected for investigation by § 25.571. The applicant need not consider the single structural failures described in paragraphs 6.2.2.4 and 6.2.2.5 of this AC in showing compliance with this paragraph if—

6.2.3.8.1 The structural element could not fail due to discrete source damage resulting from the conditions described in § 25.571(e); and

6.2.3.8.2 A damage tolerance investigation in accordance with § 25.571(b) shows that the maximum extent of damage assumed for the purpose of residual strength evaluation does not involve complete failure of the structural element.

6.2.3.9 The following flight control system failure combinations where aeroelastic stability relies on flight control system stiffness, damping or both:

(i) any dual hydraulic system failure;

(ii) any dual electrical system failure; and

(iii) any single failure in combination with any probable hydraulic system or electrical system failure.

6.2.3.10 Any damage, failure, or malfunction, considered under §§ 25.631, 25.671, 25.672, and 25.1309. This includes the condition of two or more engines stopped or windmilling for the design range of fuel and payload combinations, including zero fuel.

6.2.3.11 Any other combination of failures, malfunctions, or adverse conditions not shown to be extremely improbable.

6.3 Detail Design Requirements.

6.3.1 Main Surfaces.

Applicants should design main surfaces, such as wings and stabilizers, to meet the aeroelastic stability criteria for nominal conditions, and investigate those surfaces for meeting fail-safe criteria by considering stiffness changes due to discrete damage or by reasonable parametric variations of design values.

6.3.2 Control Surfaces.

Control surfaces, including tabs, should be investigated for nominal conditions, and for failure modes that include single structural failures (such as actuator disconnects, hinge failures, or, in the case of aerodynamic balance panels, failed seals), single and dual hydraulic system failures and any other combination of failures not shown to be extremely improbable. Where other structural components contribute to the aeroelastic stability of the system, the applicant should consider failures of those components possible adverse effects.

6.3.3 Reliance on Control System Stiffness.

Where aeroelastic stability relies on control system stiffness and/or damping, the applicant must consider additional conditions in accordance with § 25.629(d). This includes that—

6.3.3.1 The actuation system continuously provides, at least, the minimum stiffness or damping required for showing aeroelastic stability for the following conditions—

6.3.3.1.1 More than one engine stopped or windmilling;

6.3.3.1.2 Any discrete single failure resulting in a change of the structural modes of vibration (for example, a disconnect or failure of a mechanical element, or a structural failure of a hydraulic element such as a hydraulic line, an actuator, a spool housing, or a valve); and

6.3.3.1.3 Any damage or failure conditions considered under §§ 25.571, 25.631, 25.671, and 25.1309.

6.3.3.2 The actuation system minimum requirements must also be continuously met after any combination of failures not shown to be extremely improbable (occurrence less than 10^{-9} per flight hour). As required by §§ 25.629(d) and 25.1309, applicants must conduct a qualitative assessment in addition to the quantitative assessment. Applicants must also consider the latent failure criteria of § 25.1309(b)(4) and (5). In accordance with § 25.629(d)(9), certain combinations of failures, such as dual electric or dual hydraulic system failures (including loss of hydraulic fluid), or any single failure in combination with any probable electric or hydraulic system failure (including loss of fluid), are assumed to occur regardless of probability calculations and must be evaluated. The reliability assessment should be part of the substantiation documentation. In practice, meeting the above conditions may involve design concepts such as the use of check valves and accumulators, computerized pre-flight system checks, and shortened inspection intervals to protect against undetected failures.

6.3.4 Freeplay.

Applicants may incorporate consideration of freeplay as a variation in stiffness to assure adequate limits are established for wear of components such as control surface actuators, hinge bearings, and engine mounts in order to maintain aeroelastic stability margins.

6.3.5 Balance Weights.

If a proposed design uses balance weights on control surfaces, the applicant should substantiate the effectiveness and strength of those weights and their support structure.

6.3.6 Automatic Flight Control System.

The automatic flight control system should not interact with the airframe to produce aeroelastic instability, in this case known as aeroservoelastic instability. To meet the requirements of § 25.629, in the nominal condition, the structural modes must have adequate aeroservoelastic gain and phase stability margins for any single control system feedback loop at speeds up to V_D/M_D, or for control laws with limited operating envelopes, the control law design speed may be used in place of V_D/M_D. When analyses indicate possible adverse coupling, the applicant should perform tests to determine the dynamic characteristics of actuation systems such as servo-boost, fully powered servo-control systems, closed-loop airplane flight control systems, stability augmentation systems, and other related powered-control systems.

7 COMPLIANCE.

Applicants may demonstrate compliance with aeroelastic stability requirements for an airplane configuration by analyses, tests, or combination thereof. In most instances, analyses will be necessary to determine aeroelastic stability margins for normal operations, as well as for possible failure conditions. Applicants may use wind tunnel flutter model tests, where applicable, to supplement flutter analyses. Ground testing may be used to collect stiffness or modal data for the airplane or components. Flight testing may be used to demonstrate compliance of the airplane design throughout the design speed envelope.

7.1 Analytical Investigations.

Analyses should normally be used to investigate the aeroelastic stability of the airplane throughout its design flight envelope and as expanded by the required speed margins. Analyses are used to evaluate aeroelastic stability sensitive parameters such as aerodynamic coefficients, stiffness and mass distributions, control surface balance requirements, fuel management schedules, engine/store locations, and control system characteristics. The sensitivity of most critical parameters may be determined analytically by varying the parameters from nominal. These investigations are an effective way to account for the operating conditions and possible failure modes that may have an effect on aeroelastic stability margins, and to account for uncertainties in the values of parameters and expected variations due to in-service wear or failure conditions.

7.1.1 Analytical Modeling.

The following sections discuss acceptable, but not the only, methods and forms of modeling airplane configurations and/or components for purposes of aeroelastic stability analysis. The types of investigations generally encountered during airplane aeroelastic stability substantiation are also discussed. The basic elements to be modeled in aeroelastic stability analyses are the elastic, inertial, and aerodynamic characteristics of the system. The degree of complexity required in the modeling, and the degree to which other characteristics need to be included in the modeling, depend upon the system complexity.

7.1.1.1 **Structural Modeling.**

Most forms of structural modeling can be classified into two main categories: (1) modeling using a lumped mass beam and (2) finite element modeling. Regardless of the approach taken for structural modeling, a minimum acceptable level of sophistication, as described below, consistent with configuration complexity, will be necessary to satisfactorily represent the critical modes of deformation of the primary structure and control surfaces. The model should reflect the support structure for the attachment of control surface actuators, flutter dampers, and any other elements for which stiffness is important in prevention of aeroelastic instability. Wing-pylon mounted engines are often significant to aeroelastic stability and warrant particular attention in the modeling of the pylon, and pylon-engine and pylon-wing interfaces. The model should include the effects of cut-outs, doors, and other structural features that may tend to affect the resulting structural effectiveness. Reduced stiffness should be considered in the modeling of airplane structural components that may exhibit some change in stiffness under limit design flight conditions. Structural models include mass distributions as well as representations of stiffness and possibly damping characteristics. Results from the models should be compared to test data, such as that obtained from GVTs, to determine the accuracy of the model and its applicability to the aeroelastic stability investigation.

7.1.1.2 **Aerodynamic Modeling.**

7.1.1.2.1 Aerodynamic modeling for aeroelastic stability requires the use of unsteady, two-dimensional strip or three-dimensional panel theory methods for incompressible or compressible flow. The choice of the appropriate technique depends on the complexity of the dynamic structural motion of the surfaces under investigation and the flight speed envelope of the airplane. Aerodynamic modeling should be supported by tests or previous experience with applications to similar configurations.

7.1.1.2.2 Main and control surface aerodynamic data are commonly adjusted by weighting factors in the aeroelastic stability solutions. The weighting factors for steady flow (k=0) are usually obtained by comparing wind tunnel test results with theoretical data. Special attention should be given to control surface aerodynamics because viscous and other effects may require more extensive adjustments to theoretical coefficients. Main surface aerodynamic loading due to control surface deflection should be considered.

7.1.2 Types of Analyses.

7.1.2.1 Oscillatory (flutter) and non-oscillatory (divergence and control reversal) aeroelastic instabilities should be analyzed to show compliance with § 25.629.

7.1.2.2 The flutter analysis methods most extensively used involve the modal analysis with unsteady aerodynamic forces derived from various two- and three-dimensional theories. These methods are generally for linear systems. Analyses involving control system characteristics should include equations describing system control laws in addition to the equations describing the structural modes.

7.1.2.3 Airplane lifting surface divergence analyses should include all appropriate rigid body mode degrees-of-freedom since divergence may occur for a structural mode or the short period mode.

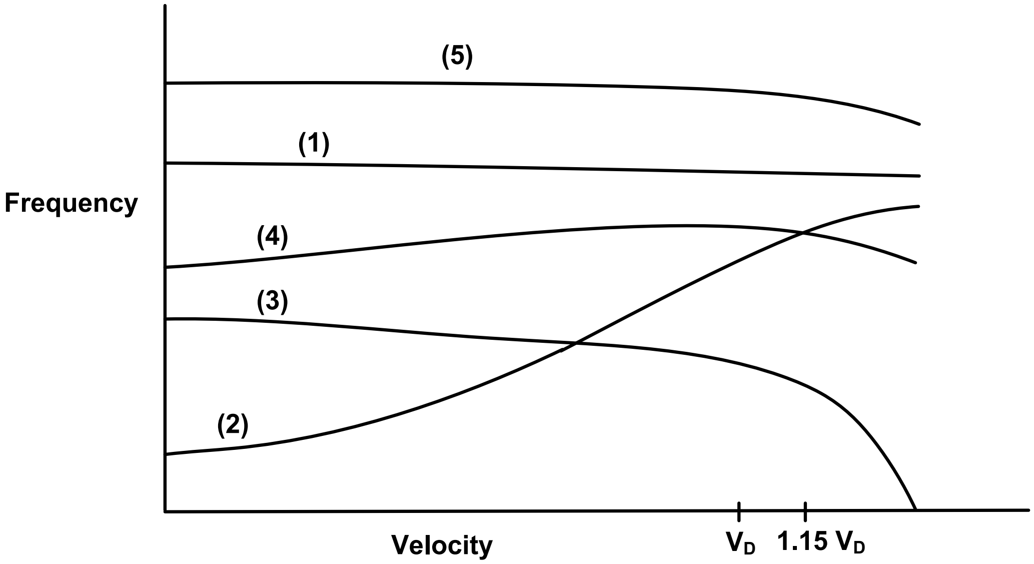
7.1.2.4 Loss of control effectiveness (control reversal) due to the effects of elastic deformations should be investigated. Analyses should include the inertial, elastic, and aerodynamic forces resulting from a control surface deflection.

7.1.3 Damping Requirements.

7.1.3.1 There is no intent in this AC to define a flight test level of acceptable minimum damping.

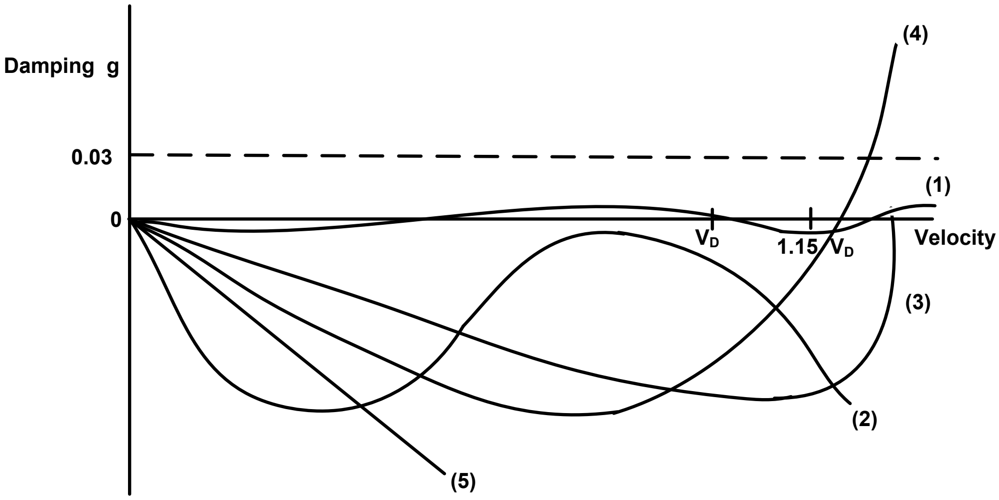
7.1.3.2 Flutter analyses results are usually presented graphically in the form of frequency versus velocity (V-f, figure 3) and damping versus velocity (V-g, figure 4 and figure 5) curves for each root of the flutter solution.

Figure 3. Frequency versus Velocity



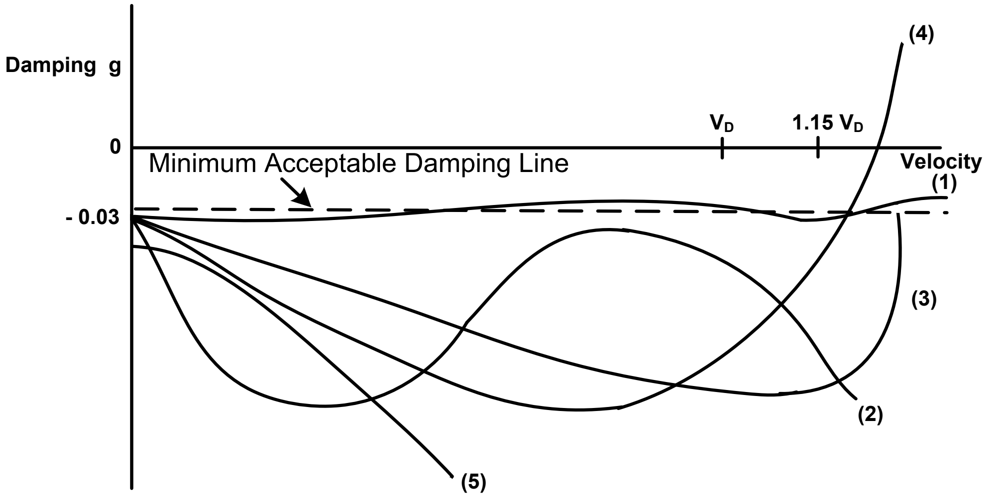
7.1.3.3 Figure 4 details one common method for showing compliance with the requirement for a proper margin of damping. It assumes that the structural damping available is 0.03 (1.5 percent critical viscous damping) and is the same for all modes as depicted by the V-g curves shown in figure 4. No significant mode, such as curves (2) or (4), should cross the g=0 line below V_D or the g=0.03 line below 1.15 V_D. An exception may be a mode exhibiting damping characteristics similar to curve (1) in figure 4, which is not critical for flutter. A divergence mode, as illustrated by curve (3) where the frequency approaches zero, should have a divergence velocity not less than 1.15 V_D.

Figure 4. Damping versus Velocity—Method 1



7.1.3.4 Figure 5 shows another common method of presenting the flutter analysis results and defining the structural damping requirements. An appropriate amount of structural damping for each mode is entered into the analysis prior to the flutter solution. The amount of structural damping used should be supported by measurements taken during full scale tests. This results in modes offset from the g=0 line at zero airspeed and, in some cases, flutter solutions different from those obtained with no structural damping. The similarity in the curves of figure 4 and figure 5 are only for simplifying this example. The minimum acceptable damping line applied to the analytical results as shown in figure 5 corresponds to 0.03 or the modal damping available at zero airspeed for the particular mode of interest, whichever is less, but in no case less than 0.02. No significant mode should cross this line below V_D or the g=0 line below 1.15 V_D.

Figure 5. Damping versus Velocity—Method 2



7.1.3.5 For analysis of failures, malfunctions or adverse conditions being investigated, the minimum acceptable damping level obtained analytically would be determined by use of either method above, but with a substitution of V_C for V_D and the fail-safe envelope speed at the analysis altitude as determined by paragraph 6.1.3 of this AC.

7.1.4 Analysis Considerations.

Airframe aeroelastic stability analyses may be used to verify the design with respect to the structural stiffness, mass, fuel (including in-flight fuel management), automatic flight control system characteristics, altitude, and Mach number variations within the design flight envelope. The complete airplane should be considered as composed of lifting surfaces and bodies, including all primary control surfaces that can interact with the lifting surfaces to affect flutter stability. Control surface flutter can occur in any speed regime and has historically been the most common form of flutter. Lifting surface flutter is more likely to occur at high dynamic pressure and at high subsonic and transonic Mach numbers. Analyses are necessary to establish the mass balance and/or stiffness and redundancy requirements for the control surfaces and supporting structure and to determine the basic surface flutter trends. The analyses may be used to determine the sensitivity of the nominal airplane design to aerodynamic, mass, and stiffness variations. Sources of stiffness variation may include the effects of skin buckling at limit load factor, air entrapment in hydraulic actuators, expected levels of in-service freeplay, and control system components that may include elements with nonlinear stiffness. Mass variations include the effects of fuel density and distribution, control surface repairs and painting, and water and ice accumulation.

7.1.4.1 **Control Surfaces.**

Control surface aeroelastic stability analyses should include control surface rotation, tab rotation (if applicable), significant modes of the airplane, control surface torsional degrees-of-freedom, and control surface bending (if applicable). Analyses of airplanes with tabs should include tab rotation that is both independent and related to the parent control surface. Control surface rotation frequencies should be varied about nominal values as appropriate for the condition. The control surfaces should be analyzed as completely free in rotation unless it can be shown that this condition is extremely improbable. All conditions between stick-free and stick-fixed should be investigated. Freeplay effects should be incorporated to account for any influence of in-service wear on flutter margins. The aerodynamic coefficients of the control surface and tab used in the aeroelastic stability analysis should be adjusted to match experimental values at zero frequency. Once the analysis has been conducted with the nominal, experimentally adjusted values of hinge moment coefficients, the analysis should be conducted with parametric variations of these coefficients and other parameters subject to variability. If aeroelastic stability margins are found to be sensitive to these parameters, then additional verification in the form of model or flight tests may be required.

7.1.4.2 Mass Balance.

7.1.4.2.1 Applicants may evaluate the magnitude and spanwise location of control surface balance weights by analysis and/or wind tunnel flutter model tests. If the control surface torsional degrees of freedom are not included in the analysis, then adequate separation needs to be maintained between the frequency of the control surface first torsion mode and the flutter mode.

7.1.4.2.2 Control surface unbalance tolerances should be specified to provide for repair and painting. The accumulation of water, ice, and/or dirt in or near the trailing edge of a control surface should be avoided. Freeplay between the balance weight, the support arm, and the control surface should not be allowed. Control surface mass properties (weight and static unbalance) should be confirmed by measurement before conducting a GVT.

7.1.4.2.3 The balance weights and their supporting structure should be substantiated for the extreme load factors expected throughout the design flight envelope. In the absence of a rational investigation, the following limit accelerations, applied through the balance weight center of gravity, should be used:

- 100g normal to the plane of the surface.
- 30g parallel to the hinge line.
- 30g parallel to the plane of the surface and perpendicular to the hinge line.

7.1.4.3 Passive Flutter Dampers.

Control surface passive flutter dampers may be used to prevent flutter in the event of failure of some element of the control surface actuation system or to prevent control surface buzz. Flutter analyses and/or flutter model wind tunnel tests may be used to verify adequate damping. Damper support structure flexibility should be included in the determination of adequacy of damping at the flutter frequencies. Any single damper failure should be considered. Combinations of multiple damper failures should be examined when not shown to be extremely improbable. The combined freeplay of the damper and supporting elements between the control surface and fixed surfaces should be considered. Provisions for in-service checks of damper integrity should be considered. See paragraph 6.3.3 of this AC for conditions to consider where a control surface actuator is switched to the role of an active or passive damping element of the flight control system.

7.1.4.4 **Intersecting Lifting Surfaces.**

Intersecting lifting surface aeroelastic stability characteristics are more difficult to predict accurately than the characteristics of planar surfaces such as wings. This is due to difficulties both in correctly predicting vibration modal characteristics and in assessing those aerodynamic effects that may be of second order importance on planar surfaces but are significant for intersecting surfaces. Proper representation of modal deflections and unsteady aerodynamic coupling terms between surfaces is essential in assessing the aeroelastic stability characteristics. The in-plane forces and motions of one or the other of the intersecting surfaces may have a strong effect on aeroelastic stability; therefore, the analysis should include the effects of steady flight forces and elastic deformations on the in-plane effects.

7.1.4.5 **Ice Accumulation.**

Aeroelastic stability analyses should use the mass distributions derived from ice accumulation up to and including those that can accrete in the applicable icing conditions in 14 CFR part 25, Appendices C and O. This includes any accretions that could develop on control surfaces. The analyses need not consider the aerodynamic effects of ice shapes. For airplanes proposed to be approved for operation in icing conditions, all the part 25, Appendix C icing conditions and the Appendix O icing conditions for which certification is sought are applicable. For airplanes excluded from § 25.1420, no evaluation of appendix O icing conditions is required. For airplanes not approved for operation in icing conditions, all the icing conditions in Appendices C and O are applicable since the inadvertent encounter discussed in paragraph 6.2.2.3 of this AC can occur in any icing condition. For all airplanes, the ice accumulation determination should take into account the ability to detect the ice and, if appropriate, the time required to leave the icing condition.

7.1.4.6 Whirl Flutter.

7.1.4.6.1 The applicant's evaluation of the aeroelastic stability should include investigations of any significant elastic, inertial, and aerodynamic forces, including those associated with rotations and displacements in the plane of any turbofan or propeller, including propeller or fan blade aerodynamics, powerplant flexibilities, powerplant mounting characteristics, and gyroscopic coupling.

7.1.4.6.2 Failure conditions are usually significant for whirl instabilities. Engine mount, engine gear box support, or shaft failures that result in a node line shift for propeller hub pitching or yawing motion are especially significant.

7.1.4.6.3 A wind tunnel test with a component flutter model, representing the engine/propeller system and its support system along with correlative vibration and flutter analyses of the flutter model, may be used to demonstrate adequate stability of the nominal design and failed conditions.

7.1.4.7 Automatic Control Systems.

The interactions of the airplane's automatic control systems coupling with the structural modes must be controlled to prevent the occurrence of any aeroelastic instability (§ 25.629), which includes prevention of aeroservoelastic instability. These control systems could include flight control systems, autopilots, yaw damper systems, modal suppression systems, or any other feedback system that could interact with the airplane's structural modes. Aeroelastic stability analyses of the basic configuration should include simulation of any control system for which interaction may exist between the sensing elements and the structural modes. Where structural/control system feedback is a potential problem, the effects of servo-actuator characteristics and the effects of local deformation of the servo mount on the feedback sensor output should be included in the analysis. The effect of control system failures on the airplane aeroelastic stability characteristics should be investigated. Failures that significantly affect the system gain and/or phase and are not shown to be extremely improbable should be analyzed to ensure stability. For nominal conditions, the structural modes should have the analytical stability margins specified below for any single control system feedback loop at speeds up to V_D/M_D and may linearly decrease to zero margins (stable at nominal gain and phase) at the envelope described in § 25.629(b)(1). For control laws with limited operating envelopes, the control law design speed may be used in place of V_D/M_D, and these margins may linearly decrease to zero (stable at nominal gain and phase) at the design speed plus 25 ft/sec equivalent airspeed increment, expanded by 15% in equivalent airspeed at both constant Mach number and constant altitude. If these margins are not used, then a technical justification should be provided for the use and acceptance of alternative criteria.

7.1.4.7.1 A gain margin of at least 6 dB and, separately,

7.1.4.7.2 A phase margin of at least ±60°.

7.2 **Testing.**

The aeroelastic stability certification test program may consist of ground tests, flutter model tests, and flight flutter tests. Ground tests may be used for assessment of component stiffness and for determining the vibration modal characteristics of airplane components and the complete airframe. Flutter model testing may be used to establish flutter trends and validate aeroelastic stability boundaries in areas where unsteady aerodynamic calculations require confirmation. Full-scale flight flutter testing provides final verification of aeroelastic stability. The results of any of these tests may be used to provide substantiation data, to verify and improve analytical modeling procedures and data, and to identify potential or previously undefined problem areas.

7.2.1 Structural Component Tests.

Stiffness tests or GVTs of structural components are desirable to confirm analytically predicted characteristics and are necessary where stiffness calculations cannot accurately predict these characteristics. Components should be mounted so that the mounting characteristics are well defined or readily measurable.

7.2.2 Control System Component Tests.

When reliance is placed on stiffness or damping to prevent aeroelastic instability, the following control system tests should be conducted. If the applicant performs the tests off the airplane, the test fixtures should reflect local attachment flexibility.

7.2.2.1 Actuators for primary flight control surfaces and flutter dampers should be tested with their supporting structure. These tests are to determine the actuator/support structure stiffness for nominal design and failure conditions considered in the fail-safe analysis.

7.2.2.2 Flutter damper tests should be conducted to verify the impedance of damper and support structure. Satisfactory installed damper effectiveness at the potential flutter frequencies should be assured. The results of these tests can be used to determine a suitable, in-service maintenance schedule and replacement life of the damper. The effects of allowable in-service freeplay should be measured.

7.2.3 Ground Vibration Tests.

7.2.3.1 Ground vibration tests or modal response tests are normally conducted on the complete conforming airplane. A GVT may be used to check the mathematical structural model. Alternatively, the use of measured modal data alone in aeroelastic stability analyses, instead of analytical modal data modified to match test data, may be acceptable provided that the accuracy and completeness of the measured modal data is established. Whenever structural modifications or inertia changes are made to a previously certified design or a GVT-validated model of the basic airplane, a GVT may not be necessary if these changes are shown not to affect the aeroelastic stability characteristics.

7.2.3.2 The airplane is best supported such that the suspended airplane rigid body modes are effectively uncoupled from the elastic modes of the airplane. Alternatively, a suspension method may be used that couples with the elastic airplane, provided that the suspension can be analytically de-coupled from the airplane structure in the vibration analysis. The former suspension criterion is preferred for all GVTs and is necessary in the absence of vibration analysis.

7.2.3.3 The excitation method needs to have sufficient force output and frequency range to adequately excite all significant resonant modes. The effective mass and stiffness of the exciter and attachment hardware should not distort modal response. More than one exciter or exciter location may be necessary to ensure that all significant modes are identified. Multiple exciter input may be necessary on structures with significant internal damping to avoid low response levels and phase shifts at points on the structure distant from the point of excitation. Excitation may be sinusoidal, random, pseudo-random, transient, or other short duration, non-stationary means. For small surfaces, the effect of test sensor mass on response frequency should be taken into consideration when analyzing the test results.

7.2.3.4 The minimum modal response measurement should consist of acceleration (or velocity) measurements and relative phasing at a sufficient number of points on the airplane structure to describe accurately the response or mode shapes of all significant structural modes. In addition, the structural damping of each mode should be determined.

7.2.4 Flutter Model Tests.

7.2.4.1 Dynamically similar flutter models may be tested in the wind tunnel to augment the flutter analysis. Flutter model testing can substantiate the flutter margins directly or indirectly by validating analysis data or methods. Some aspects of flutter analysis may require more extensive validation than others, for example, control surface aerodynamics, T-tails, and other configurations with aerodynamic interaction and compressibility effects. Flutter testing may additionally be useful to test configurations that are impractical to verify in flight test, such as fail-safe conditions or extensive store configurations. In any such testing, the mounting of the model and the associated analysis should be appropriate and consistent with the study being performed.

7.2.4.2 Direct substantiation of the flutter margin (clearance testing) implies a high degree of dynamic similitude. Such a test may be used to augment an analysis and show a configuration flutter free throughout the expanded design envelope. All the physical parameters that have been determined to be significant for flutter response should be appropriately scaled. These will include elastic and inertia properties, geometric properties, and dynamic pressure. If transonic effects are important, the Mach number should be maintained.

7.2.4.3 Validation of analysis methods is another appropriate use of wind tunnel flutter testing. When the validity of a method is uncertain, correlation of wind tunnel flutter testing results with a corresponding analysis may increase confidence in the use of the analytical tool for certification analysis. A methods validation test should simulate conditions, scaling, and geometry appropriate for the intended use of the analytical method.

7.2.4.4 Trend studies are an important use of wind tunnel flutter testing. Parametric studies can be used to establish trends for control system balance and stiffness, fuel and payload variations, structural compliances, and configuration variations. The set of physical parameters requiring similitude may not be as extensive to study parametric trends as is necessary for clearance testing. For example, an exact match of the Mach number may not be needed to track the effects of payload variations on a transonic airplane.

7.2.5 Flight Flutter Tests.

7.2.5.1 Full-scale flight flutter testing of an airplane configuration to V_{DF}/M_{DF} is a necessary part of the flutter substantiation. An exception may be made when aerodynamic, mass, or stiffness changes to a certified airplane are minor, and analysis or ground tests show a negligible effect on flutter or vibration characteristics. If a failure, malfunction, or adverse condition is simulated during a flight test, the maximum speed investigated need not exceed V_{FC}/M_{FC} if it is shown, by correlation of the flight test data with other test data or analyses, that the requirements of § 25.629(b)(2) are met.

7.2.5.2 Airplane configurations and control system configurations should be selected for flight test based on analyses and, when available, model test results. Sufficient test conditions should be performed to demonstrate aeroelastic stability throughout the entire flight envelope for the selected configurations.

7.2.5.3 To achieve adequate test results, flight flutter testing requires excitation sufficient to excite the modes shown by analysis to be the most likely to couple for flutter. Excitation methods may include control surface motions or internal moving mass or external aerodynamic exciters or flight turbulence. Use the appropriate method of excitation for the modal response frequency being investigated. The effect of the excitation system itself on the airplane flutter characteristics should be determined prior to flight testing.

7.2.5.4 Measurement of the response at selected locations on the structure should be made to determine the response amplitude, damping, and frequency in the critical modes at each test airspeed. It is desirable to monitor the response amplitude, frequency, and damping change as V_{DF}/M_{DF} is approached. In demonstrating that there is no large and rapid damping reduction as V_{DF}/M_{DF} is approached, an endeavor should be made to identify a clear trend of damping versus speed. If this is not possible, then sufficient test points should be undertaken to achieve a satisfactory level of confidence that there is no evidence of an adverse trend.

7.2.5.5 An evaluation of phenomena not presently amenable to analyses, such as shock effects, buffet response levels, vibration levels, and control surface buzz, should also be made during flight testing.

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