U.S. Department of Transportation

**Federal Aviation Administration**

# Advisory Circular

**Subject: Means of Compliance with Title 14 CFR, Part 23, § 23.629, Flutter**

**Date: 9/28/04**
**Initiated By: ACE-100**

**AC No:23.629-1B**
**Change:**

1. PURPOSE. This advisory circular presents information and guidance to provide one means, but not the only means of complying with § 23.629, Flutter (including divergence, and control reversal) of part 23 of the Federal Aviation Regulations. Accordingly, this material is neither mandatory nor regulatory in nature.

2. CANCELLATION. AC 23.629-1A, Means of Compliance with Title 14 CFR part 23, § 23.629, Flutter, dated October 23, 1985, is cancelled.

3. BACKGROUND. The complexity of flutter analysis has historically prompted endeavors to find simplified methods of flutter substantiation. Although the advent of electronic computers has de-emphasized the need to make drastic assumptions previously necessary to enable mathematical treatment of the flutter phenomenon, there remains a need to simplify flutter solution as much as possible consistent with safety in order to minimize the cost and effort required to show freedom from flutter. Past experiences gained by the necessity to judiciously choose degrees of freedom, and by the need to make essential parametric studies to establish practical boundaries of the effectiveness of the various physical quantities, has resulted in a generally recognized set of good practices. These good practices form the basis for this advisory circular.

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# CHAPTER 1. METHODS OF SUBSTANTIATION

1. GROUND TESTS FOR DYNAMICALLY SIMILAR AIRCRAFT. (§ 23.629(a)) Comparison of test data may be used in lieu of a totally new analysis and flutter test, in the case of dynamically similar aircraft. Comparison would usually be based upon geometry, mass and stiffness distributions, speed regime, and more importantly, upon a comparison of the measured coupled vibration modes.

a. Ground Testing would normally include:

(1) Ground Vibration Testing

(2) Control Surfaces and Tab Mass Property Determination

(3) Stiffness Tests of Wings, Stabilizers, etc.

(4) Free Play Measurement of All Control Surfaces and Tabs

(5) Rotational Frequency for All Control Surfaces and Tabs

(6) Rotational Stiffness for Control System and Tab System.

b. Appendix 1 presents some guidelines for recommended tests and procedures.

c. The degree of similarity between aircraft that is required for flutter substantiation can vary greatly. Some of the factors, which should be considered are the amount of safety margins available, flutter speed sensitivity to certain parameters, and the thoroughness of the original analysis. There are no hard and fast rules. Each project must be evaluated using engineering judgment. However, consider the following:

- The airplanes should be similar in weight. (You can't use dynamic similarity to compare a 5,000-pound airplane with a 19,000-pound airplane).

- The airplanes should have a similar speed range (You can't use dynamic similarity to compare a 120-knot airplane to a 250-knot airplane).

- The airplanes should be geometrically similar. (You can't use dynamic similarity to compare a V-Tail configuration airplane to a Cruciform or T-Tail configuration airplane).

- The airplanes should be similar in mass and stiffness distribution. (You can't use dynamic similarity to compare an airplane with wing-mounted engines to an airplane with aft fuselage mounted engines).

- The aircraft should have similar control systems and architecture. (You can't use dynamic similarity to compare an airplane with unassisted manual mechanical controls to one with a sophisticated powered automatic flight control system).

2. RATIONAL ANALYSIS WITH FLIGHT FLUTTER TESTS. (§ 23.629(b and c))

a. Flight Flutter Tests. The latest amendment (23-48) of section § 23.629 requires certification based upon flight test, and either rational analysis (§ 23.629(c)) or the rigidity and mass balance criteria (§ 23.629(d)). Earlier amendment levels did not require both analysis/criteria and flight flutter test.

(1) The results of any of the rational analysis procedures required by § 23.629(c), could be used to provide guidance for formulating a flight flutter test plan. The rigidity and mass balance criteria specified in § 23.629(d) may be used in lieu of a rational analysis for certain airplanes (see paragraph 3) for simplicity.

(2) However, it is not recommended to use ONLY the rigidity and mass balance criteria (§ 23.629(d)) prior to flight flutter tests. Unless a rational analysis is accomplished, the critical mode is unknown, and this mode must be excited during flight flutter tests. Extensive instrumentation is required to record the vibration responses during flight. An excitation system must be available to excite all the significant modes of the airplane when a rational analysis has not been accomplished prior to the flight flutter test. Each mode, including those affected by airplane weight or fuel, would have to be excited if an analysis has not been conducted to determine the critical modes. Simple pilot induced control impulses may not be adequate. It is highly recommended that a rational analysis be accomplished for all airplanes prior to flight flutter test, even if the airplane qualifies for the use of the rigidity and mass balance criteria, and it was used for the airplane design. In all cases, as required by § 23.629(a), the natural frequencies and the mode shapes of main structural components should be determined by vibration tests or other approved methods prior to conducting any flight testing. A more thorough discussion of flight flutter testing is presented in Appendix 2.

b. Review of Past Analysis. Review of previous flutter analyses conducted upon similar aircraft can provide the engineer with useful information regarding trends, critical modes, etc. Although in general such a review is not used as a substantiation basis for a new aircraft, it can provide a useful tool in evaluating the effect of modifications to existing certified aircraft.

c. Two-Dimensional Analysis. The flutter characteristics of straight wings (or tails) of large aspect ratio can be predicted reasonably well by considering a "representative section" that has two or three degrees of freedom. Translation and pitch are always needed for main surfaces, and the third degree of freedom for analysis with control surfaces is the rotation about the hinge line.

d. Three-Dimensional Analysis. This analysis is based upon consideration of total span, rather than "representative section" discussed in paragraph 2c. The behavior is integrated over the whole structure being analyzed. Some idealization is always necessary; the most common being the division of the span into strips. Other types of modeling such as doublet lattice box methods are also used.

(1) For part 23 airplanes, the wing and empennage analyses may be conducted separately; however, this is not always adequate for unconventional configurations or airplanes capable of speeds in excess of 0.6 Mach. Both the symmetric and anti-symmetric modes require

investigation in the flutter analysis.

(2) Calculated mass and stiffness distributions are generally used to calculate uncoupled modes and frequencies of the airplane components such as wing, stabilizer, etc. These modal parameters are then used to conduct coupled vibration analysis of the whole airplane. The resulting coupled modes and frequencies are then compared with measured natural frequencies and mode shapes obtained from the ground vibration tests.

(3) The calculated stiffness-related inputs are generally adjusted until good agreement is obtained with the ground vibration test data. This analytical model is validated by the ground tests. The validated model is then used in the flutter analysis.

(4) It is suggested that one perform parametric variation of stiffness and other important parameters in the assumed input conditions to see which parameters are critical. Control surface balance conditions and control system frequencies (especially tab frequencies) are often investigated parametrically. The effect of control system tension values at the low and high ends of the tolerance range should be assessed during flight flutter tests.

(5) It may be advisable to vary certain main surface frequencies (stiffness), especially torsional frequencies and engine mode frequencies, while leaving other frequencies constant, to study the effect of variations in stiffness of the control system.

(6) Sometimes it is desirable to evaluate the effect of a slight shift in span wise node location for a very massive item where the node is located very close to or within the item. (Test data may not be sufficiently accurate for this assessment.)

(7) It is normal practice to run a density-altitude check to include near-sea-level, maximum and any other pertinent altitudes such as the knee of the airspeed-altitude envelope where the design dive speed becomes MACH-limited.

(8) It is essential to investigate aircraft coupled modes for airplanes with $V_D$ of 260 KEAS/0.6 Mach or above, as well as for airplanes with unconventional configurations or complex control systems.

(9) Flutter Analysis Evaluation. The resulting output of flutter analysis consists of a number of theoretical damping values (g) with associated airspeeds and flutter frequencies.

(10) Various cross plots of these values among themselves and versus varied input parameters allow a study of trends. Common plots are: damping versus equivalent airspeed (V-g plots), control surface balance versus flutter speed, modal frequency versus flutter speed, altitude versus flutter speed, etc. Normally only the critical items will be extensively compared.

(11) Of particular importance is evaluating the crossing of a damping velocity (V-g) curve toward the unstable region, through the zero damping line. The typical critical V-g curve will first become increasingly stable with increasing speed, then the damping will decrease and finally cross the zero damping line as in curves 3 and 4 in Figure 1-1. Figure 1-1 shows some typical characteristics.

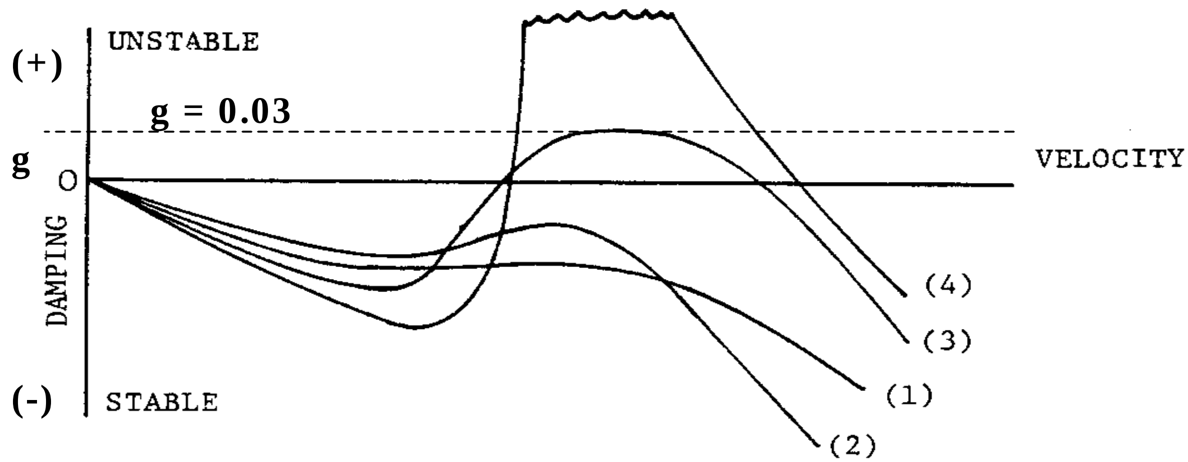


Figure 1-1. Flutter Analysis Evaluation

(12) Curves 1 and 2 show slight trends toward instability, but do not approach actual instability.

(13) Curve 3 crosses the stability axis but, depending on the inherent structural damping, may or may not actually become unstable. Curve 4 is obviously unstable and probably violent, since its slope is steep as it passes through the zero damping line. In actual flight it may be a few miles an hour or so between completely stable and extremely unstable explosive flutter. Flight tests are not advisable when this type of plot is observed inside or at the boundary of the flight envelope.

(14) Much can be learned from V-g and V-f plots. Absolute values should be viewed with some reserve as there is no perfect one-to-one correspondence of the analytical parameters and flight parameters. Equally important is the rate of approach to instability (slope of curve).

(15) The general practice is to use a damping value of g = +0.03 (as the inherent structural damping) in the V-g plots. In Figure 1, an assumed value for the inherent structural damping value of g = +0.03 would be a positive value. However, this value should be used with caution if the slope of the curve is steep (damping decreases very rapidly with an increase in airspeed) between g = 0 and +0.03. In cases where the slope is steep (generally this would be a decrease in damping of 50 percent for a 5-10 knot airspeed increase), it is suggested that the g = 0 airspeed be at least 1.2 $V_D$. Freedom from flutter should be shown to $1.2V_d/1.2M_d$.

(16) For damping curves such as (3), which peak out below 1.2 $V_D$, the predicted damping should be no more unstable than g = +0.02 unless justification is provided by other acceptable means.

(17) For a more thorough discussion of flutter analysis refer to texts listed in Appendix 3 or other basic engineering textbooks on aeroelasticity.

3. RIGIDITY AND MASS BALANCE CRITERIA. (§ 23.629(d))

a. Guidelines. Airframe and Equipment Engineering Report No. 45 is intended to serve as a guide to the airplane designer in the prevention of flutter, aileron reversal, and wing divergence. This method may only be used for airplanes that meet the criteria specified in § 23.629(d)(1),(2), and (3). The material presented relies upon:

(1) A statistical study of the geometric, inertia, and elastic properties of those airplanes, which had experienced flutter in flight, and the methods used to eliminate the flutter.

(2) Limited wind-tunnel tests conducted with semi-rigid models. These were solid models of high rigidity with motion controlled at the root by springs to simulate wing bending and torsion. Springs at the control surface were used to simulate rotation.

(3) Analytic studies based on the two-dimensional study of a representative section of an airfoil.

b. Wing and Aileron. Prevention of wing flutter is attempted through careful attention to three parameters; wing torsional flexibility, aileron balance, and aileron free play.

(1) The aileron balance criteria is obtained from the aileron product of inertia, K, about the wing fundamental bending node line and the aileron hinge line; and the aileron mass moment of inertia, I, about its hinge line. A limit of the parameter, K/I, is set as a function of $V_D$.

(2) A wing torsional flexibility factor, F, is defined and a limit established as a function of $V_D$. In order to apply the criteria, one needs to know wing twist distribution per unit applied torque wing platform, and limit dive speed.

(3) The total free play of each aileron with the other aileron clamped to the wing must not exceed the specified maximum.

c. Elevator and Rudder. Dynamic balance criteria for the elevator and rudder (similar to the K/I of the aileron) are defined and limits set as a function of limit dive speed. In order to utilize the criteria, the following information is required:

| | | |
|---|---|---|
| (1) | Geometry | Horizontal tail semichord at the midspan<br>Semispan of horizontal tail<br>Distance from fuselage torsion axis to tip of fin<br>Semichord of vertical tail measured at 70 percent span position |
| (2) | Stiffness | Fuselage vertical bending frequency<br>Fuselage torsional frequency<br>Fuselage lateral bending frequency |
| (3) | Mass | Elevator static balance about hinge line<br>Elevator mass moment of inertia about hinge line<br>Elevator product of inertia referred to stabilize centerline and elevator hinge line<br>Rudder static balance about hinge line |

Product of inertia of rudder referred to fuselage torsion axis and rudder hinge line
Rudder mass moment of inertia about hinge line.

d. Tabs. In accordance with reference 1, all reversible tabs should be 100 percent statically mass balanced about the tab hinge line. In practice, most tabs are irreversible, which means:

(1) For any position of the control surface and tab, no appreciable deflection of the tab can be produced by means of a moment applied directly to the tab when the control surface is held in a fixed position.

(2) The total free play at the tab trailing edge must be less than 2.5 percent of the tab chord aft of the hinge line, at the station where the free play is measured (this is specified in reference 1). However, since in service wear may increase the free play, we recommend the following tighter tolerances as a maximum for the initial design:

(a) If the tab span does not exceed 35 percent of the span of the supporting control surface, the total free play should not exceed two percent of the distance from the tab hinge line to the trailing edge of the tab perpendicular to the tab hinge line.

(b) If the tab span equals or exceeds 35 percent of the span of the supporting control surface, the total free play should not exceed one percent of the distance from the tab hinge line to the trailing edge of the tab perpendicular to the tab hinge line.

(3) The tab natural frequency should be equal to or should exceed the value calculated in reference 1 and expressed as a function of tab and control surface geometry and airplane dive speed.

(4) Spring loaded tabs are free to rotate and thus are not irreversible. Generally, these tabs will require dynamic as well as static balance. Extensive flutter analysis is always needed to define these requirements.

4. WHIRL MODE. (23.629(e)) Beginning with amendment 23-7, paragraph 23.629(e) required an investigation of the whirl mode phenomena for multiengine turbopropeller airplanes only. The basis being these airplanes characteristically have wing-mounted engines wherein the stability of a flexibly mounted engine/propeller on an elastic wing is of major concern. Amendment 23-31 of § 23.629(e) now requires an investigation of the whirl mode phenomena for both single and multiengine turbopropeller airplanes. Although airframe influence may be negligible for fuselage mounted single engine tractor configurations, the potential for propeller whirl flutter still exists. For pusher configurations, empennage motion may be significantly affected by engine/propeller forces. Stability of either installation is dictated, in part, by engine mount stiffness, damping, mass properties, motion axes, propeller geometry and propeller advance ratio. Therefore, to assure freedom from whirl mode flutter, all turbopropeller installation investigations should include, in addition to the appropriate airframe degrees of freedom:

a. Whirl mode degree of freedom, which takes into account the stability of the plane of rotation of the propeller and significant elastic, inertial, and aerodynamic forces.

b. Propeller, engine, engine mount, and airplane structure stiffness and damping variations appropriate to the particular configuration; e.g., deterioration of engine isolators, large cantilevered engine installations) etc.

In addition, references 9, 10, 11, 12 and 13 of Appendix 3 contain technical information for an acceptable means of demonstrating whirl mode stability.

## CHAPTER 2. MODIFICATIONS TO AIRCRAFT ALREADY CERTIFICATED

5. RE-EVALUATION. Considerable judgment is often required to determine the degree of re-evaluation necessary. If the mass, mass distribution, or the stiffness distribution are affected sufficiently to result in possible significant changes in resonant frequencies of major modes, mode shapes, or mass coupling terms in the flutter equations, then some re-evaluation, such as pre-mod and post-mod Ground Vibration Test (GVT) data comparison, or analysis may be required. Some examples of significant changes are:

a. Engine (Propeller). A change in mass or mass moment of inertia of the powerplant or in its mounting system (bushings, etc.) or a Center of Gravity (cg.) shift should be investigated. On single-engine airplanes, such changes will most likely affect fuselage and empennage frequencies and mode shapes. For engines mounted on the wings, the entire airplane may be affected.

For changes in existing designs which entail significant increases in engine power, special assessments of the effect on primary and secondary control systems should be made.

If,

(1) Tabs are exposed to the propeller slip stream,
And;
(2) the certification basis of the change is to amendment level 23 or later, or;
(3) the changed product rule is applied in order to bring the original certification basis for the change up to amendment level 23 or later,

then,

the fail-safe criterion described and discussed in Chapter 3 applies.

b. Structural Cutouts. Severing or bridging across major structural members, such as fuselage bulkheads and ribs or stringers of aerodynamic surfaces, may produce discontinuities in stiffness parameters that significantly alter the vibratory response of the structure.

The significance of a change may be ascertained by flutter analysis.

c. Change in the Mass. Adding of concentrated masses such as a tip tank or an external pod to a lifting surface could have a profound influence on the flutter speeds. This influence needs to be investigated by analysis and/or flight testing.

# CHAPTER 3. CONTROL SURFACES AND TABS

6. RESPONSE. The aerodynamic force on an airfoil is very sensitive to control surface displacement, which in turn is responsive to both control motions and aerodynamic forces from tab displacement. Control surface displacement may result from deflection of the control system, deflection of the control surface attachment, or structural deflection of the control surface itself under forces from control application, aerodynamic force due to position or rate of position change, and inertia force.

7. BALANCE. Control surfaces and tabs are mass balanced to prevent rotation about their hinges resulting from inertial response to motion of the main (primary) surface, in any flutter mode. When the flutter mode consists of motion about some axis perpendicular to the control surface hinge axis, a concentrated ballast is most efficiently used. Caution should be used to assure that its location is in a high response area of the mode, which is difficult to determine when the mode is complex. Caution should also be used to assure that its attachment is secure to resist the inertia loads. Because the attachment is subjected to oscillatory loads, which cause fatigue failures and because a distributed ballast achieves balance against all flutter modes, it is conservative to distribute the ballast in accordance with the spanwise weight distribution of the surfaces. If less than static balance is provided, the effect of variations in the amount of balance should be evaluated. To guard against unintended balance changes in service, sealing and proper drain holes should be provided to minimize the risk of water, ice, or dirt accumulation in a control surface or tab. Excessive accumulation of these substances could alter the static and/or dynamic balance of the control sufficiently to adversely affect flutter characteristics.

8. VIBRATORY MODES. Control surface rotation about its hinge line is affected by various constraints. Control system stiffness, moment of inertia about the hinge line, and the rigidity of interconnection between control surfaces determine the control surface rotational modes. Both symmetric and anti-symmetric modes should be considered in the vibration analysis. Vibration mode changes resulting from modifications to the control system such as the addition of a bob weight must be assessed for their effect on flutter. Secondary rotations may result from flexure of the attaching structure or bending of the control surface. This is a major consideration for long short-chord tabs and may affect their effective irreversible characteristics. When it is necessary to raise a tab frequency by redesign, consideration should be given to the contributions of: hinge bending perpendicular to the surface especially near the horn-actuator station, horn length, axial stiffness of the push-pull rod or link, mounting flexibility, and lateral stability at push-rod attachment of the tab actuating mechanism.

9. ANALYSES. In most cases involving control surfaces, the flutter speeds are largely governed by the mass balance weights and their distributions. It is wise for the flutter analyst to cover a range of balance values and distributions to determine the most satisfactory ones. It is common to find that a change, which improves one mode degrades another. When conducting a multi-degree-of-freedom analysis, it is advisable to investigate the effect of control system frequency from zero to about 1-1/2 times the system frequency measured in test. Due to friction, etc., it may be difficult to excite and measure control system frequency accurately. The stiffness can be measured at the surface with the control column or rudder pedal locked in the cockpit and, using the inertia of the end items, the system frequency can be calculated.

Theoretical values of tab and control surface aerodynamic derivatives have, for some configurations, produced higher flutter speeds than flutter model testing. Analytically derived tab and control surface aerodynamic coefficients based on strip theory have for some configurations produced higher flutter speeds than wind tunnel tests. Therefore, flutter speed sensitivity to variations in the theoretical coefficients should be evaluated in all control surface/tab investigations.

10. FAIL SAFE REQUIREMENTS. Amendment 23-23 of § 23.629(f) requires flutter free operation after failure, malfunction, or disconnect of any single tab element. This fail-safe requirement is extended to include a failure, malfunction, or disconnect of any element in the primary flight control system or flutter damper on airplanes that do not meet the criteria specified in §§ 23.629(d)(1) through (d)(3).

a. Potential failures that require investigation include, but are not limited to, tab or primary control trim actuating system, primary control actuating system (both of which includes bellcranks, pulleys, brackets, and their attachments), and control cables or push rods.

b. Possible means of compliance to actuating system failures (i.e., actuators, cables, rods) may be achieved by incorporating dual systems, mass balancing the controls to counter the rotation of a disconnected or free surface, or by incorporating a combination of the above two. Proper mass balancing, particularly for tabs, requires considerable care and knowledge of the flutter mechanism to assure adequacy of the design in suppressing flutter. Dual load path designs should include an assessment of residual strength with a single failure to assure that the remaining path will not fail before the single failure is detected during appropriate specified inspection intervals.

c. The question has arisen whether the hinges attaching to the control surfaces of the primary flight controls and tabs are part of the control system. Further, are the hinge fasteners and local portions of the fixed-surface structure to which the hinge attaches considered to be part of the control system and therefore to be considered in the failure, malfunction or disconnection of any single element? It could be argued that from a literal or traditional definition, the control system ends at the control horn. On the other hand, if a single element failure of a control surface or tab hinge can cause the surface to flutter, then it may be argued that the objective of the § 23.629(f) rule has not been met.

(1) These questions were investigated thoroughly in the early 1980s, shortly after the rule change (amendment 23-23) was adopted. The following is a summary of that investigation and the resulting current policy on the matter.

- Interpretation of § 23.651 indicated that the hinges are considered part of the "control surface" rather than the "system".

- The number of other rules pertaining to hinges and fitting factors that must be applied, generally dictate robust hinge designs.

- A review of service difficulty reports (SDRs) accomplished at that time did not indicate a significant number of failures of control surface or tab hinges.

- Generally, the class of airplanes considered under § 23.629(f)(2), have three or more control surface hinges.

- Tab hinges are often the piano hinge type, which are inherently redundant.

- A review of the regulatory history including the preamble, NPRM, and the 1974-1975 Airworthiness Review discussions, does not show anything addressing whether the hinges should be included as part of the flight control or tab control system in evaluating § 23.629(f). The implication is that it was not the intent of the rule to include the hinges and supporting structure.

(2) It is, therefore, concluded that the control surface hinges and tab hinges, their attachments, and local portions of structure should not be included as part of the flight control system or tab control system in determining compliance with the flutter requirements of § 23.629(f). The control surface hinges, tab hinges, their attachments, and local portions of structure are not considered part of the control “system”, regardless of whether the system is fail-safe or not.

(3) In conjunction with this policy, special emphasis should be given to ensure that the rules applying specifically to hinges (§§ 23.393, 23.415, 23.623, 23.625, 23.657, 23.659) are fully evaluated and documented. In addition, hinges should also be evaluated for good design practices with respect to number of hinges, redundancy of fasteners, adequacy of structure adjacent to hinges, methods of providing hinge pin retention if the nut backs off, etc. Similarly, control surface or tab balance weights, their attachments, and local portions of the supporting structure are part of the control surface. They should not be included as part of the primary flight control system or tab control system in determining compliance with the flutter requirements of § 23.629(f).

## CHAPTER 4. DIVERGENCE AND CONTROL REVERSAL

11. GENERAL. Static aeroelastic instabilities of lifting surfaces are avoided by providing adequate torsional rigidity. Methods to determine the adequacy of torsional rigidity are outlined in references 2 and 3 of Appendix 3.

12. DIVERGENCE. Divergence occurs when the aerodynamic torque exceeds the torque resisting capability of the wing. Because the aerodynamic torque is a function of speed as well as deflection, whereas the resisting torque depends on the torsional rigidity of the lifting surface which is a constant, there exists a limiting divergence speed. Divergence may occur with no warning.

13. CONTROL REVERSAL. Control reversal will often be preceded by pilot comments of "heavy" or "sluggish" ailerons. A limiting reversal speed is reached when the change in lift due to control surface rotation is nullified by the change in lift due to twist of the lifting surface.

# APPENDIX 1. GROUND TESTING

1. INTRODUCTION. The adequacy of the methods used to show compliance with § 23.629, as discussed in the main body of this document, is dependent upon the availability of reliable ground test data to verify the analytical data used and/or to serve as a basis for flutter substantiation per the simplified criteria of reference 1. This appendix, therefore, presents guidelines in conducting the more significant tests required to accomplish this objective. However, in keeping with the general purpose of this advisory circular, the information provided is not intended to be mandatory, nor is it to be considered an exhaustive treatment of the subject.

2. CONTROL SURFACE AND TAB MASS PROPERTIES. The experimental mass properties of control surfaces and tabs (weight, static moments, moments of inertia, and c.g.) are important ingredients in flutter substantiation. These properties form a basis for verification of the analytical data used in the rational analysis and provide the necessary parameters for use in the simplified criteria. Reference 1 presents a detailed procedure for the experimental determination of these properties.

3. TAB FREE PLAY. Free play tests provide the necessary data for determining the effectiveness of a tab in fulfilling the requirements for irreversibility as specified in the main body of this document. In addition to demonstrating the maximum free play available, these tests provide the stiffness of the actuating system for use in computing tab rotational frequency.

a. Free play and stiffness may best be measured by a simple static test wherein "upward" and "downward" (or "leftward" and "rightward") point forces are applied near the trailing edge of the tab at the spanwise attachment of the actuator (so as not to twist the tab). The control surface should be blocked to its main surface. Rotational deflection readings are then taken near the tab trailing edge using an appropriate measuring device, such as a dial gauge. Several stepwise load and deflection readings should be taken using loads first applied in one direction, then in the opposite.

b. A plot of these load deflections typically appears as shown in Figure A-1.

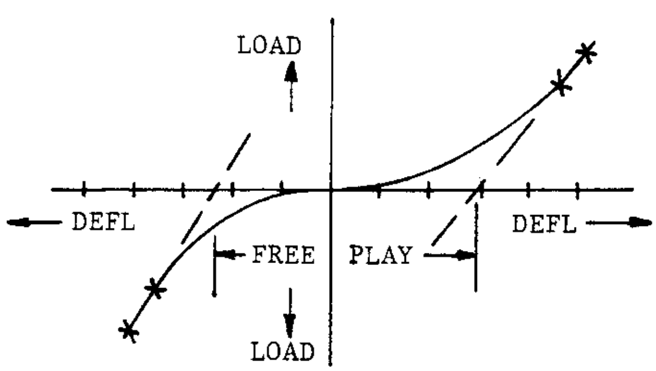


Figure A-1. Load Deflections Plot

c. Free play is then defined by extending the best straight lines through zero. System stiffness may then be obtained from the slopes of the curves away from the zero point.

4. INFLUENCE COEFFICIENT TESTS. Bending and/or torsion influence coefficient test results form the basis for the definition of component stiffness distributions. The extent of the tests depends on the intended use of the data. A full scale test program, wherein the coefficients of each spanwise mass strip are defined, may be desired if experimental data is the primary source for defining component stiffness. In contrast, calculated influence coefficients, based on analytical bending (EI) and torsion (GJ) stiffness distributions, may be adjusted reliably with considerably less test data. A method is outlined below for determining influence coefficients for conventional structure, i.e., aspect ratio greater than four and unswept elastic axis.

a. The test article, wing, tailplane, or fin, is generally mounted at its root, without control surfaces, in a rigid test fixture for these tests. However, wing stiffness tests, particularly torsion as required for simplified criteria, may be successfully conducted with the wing mounted on the fuselage restrained in a cradle. This type of setup requires duplicate loading fixtures for right and left wing to balance the aircraft under load and thus minimize "jig rotation" effects.

b. The chordwise location of the elastic axis is determined by applying a torque load at selected stations and plotting the deflection versus chord shear center or elastic axis at that station.

c. Torsional influence coefficients (radians twist about the elastic axis per unit torque load) are obtained by applying a pure torque load about the elastic axis at the tip and measuring the resulting spanwise twist. The twist per unit torque applied at intermediate inboard stations will be the same inboard of the load point. Thus, it is necessary to load only one additional inboard station, say 75 percent span, to check for data repeatability only. To insure that the load applied is a pure torque load, the deflections of the elastic axis should be monitored during the loading process. Zero deflections should result.

d. Bending influence coefficients (deflections per unit shear load) are obtained by applying shear load on the elastic axis at a selected station and measuring the resulting deflections at a sufficient number of spanwise locations to define the influence line for that load point. The procedure is repeated for each load station. To insure that the shear load is applied on the elastic axis, no appreciable chordwise variation in the measured deflections should be evident.

e. The experimental determination of fuselage stiffness properties can be accomplished essentially the same way as for the aerodynamic surfaces. In this test the fuselage is treated as two beams, forward and aft fuselage, each cantilevered from the wing-root attachment. It is extremely important that the fixture at this attachment be very rigid; and, any displacement of the test jig during loading must be monitored, regardless of how small, throughout the test for inclusion in the data analysis. Small displacements can be quite influential in a rather complex data reduction procedure, and if improperly done, can lead to erroneous and troublesome conclusions. On this basis it is often the practice to compute fuselage stiffness properties for the fuselage, then use ground vibration test results to tune calculated modes and, in turn, stiffness as required.

f. Thin-skinned structure may buckle at a very low load, reducing actual stiffness in flight considerably from that determined by the above procedure and the analyst is cautioned to investigate such conditions.

5. GROUND VIBRATION TESTS. Ground vibration testing has as its fundamental objective the definition of vibration mode frequencies, mode shapes, and damping characteristics of an aircraft. These data then become the basis for the analytical development of a mathematical vibration model of the airplane or serve as a check on such a model once it is developed. The results ultimately become the basis for rational flutter analyses. If the simplified flutter prevention criteria of reference 1, discussed in the main body of this advisory circular, is used, then the results from these tests are used directly to establish a predicted flutter speed of the airplane.

The degree of sophistication required to conduct a resonance test (techniques, recording equipment, suspension system, etc.) depends upon the complexity of the structure being tested. Since it is impossible to cover all test situations that may arise, the discussions presented in this section are fundamental in nature, dealing specifically with sinusodial methods of excitations. They are intended as guidelines for those persons concerned with general type aircraft, which have only the basic test facilities. Other procedures employing random or impulse excitations are being used more frequently. However, these methods are considered beyond the scope of this advisory circular.

a. Test Article and Suspension System. The airplane should be supported in a level attitude such that the rigid body frequencies of the airplane on its support are less than one-half the frequencies of the lowest elastic wing or fuselage mode to be excited.

One of the following methods of support can generally be used:

(1) Support the airplane on its landing gear with the tires deflated sufficiently to achieve the above result. Fifty percent normal tire pressure usually achieves good results. It may be necessary to block the landing gear struts to eliminate damping in the oleos.

(2) Suspend the airplane on springs.

(3) Support the airplane on its landing gear resting on spring platforms.

(4) Support the airplane fuselage and wings on large air-filled flotation bags.

(a) The airplane should be equipped with all items having appreciable mass such as engines and tip tanks. The weight and c.g. of the test article should be determined to enable proper correlation with the analytical model. Where fuel is located in the outboard 50 percent of the wing semispan, it may be desirable to test a full fuel condition in addition to the empty condition in order to provide additional data for math model correlation.

(b) It is generally advantageous to lock the control surfaces in their neutral position when obtaining airframe modes.

b. Equipment. Various types of shakers are available, i.e., inertia, elastic, airjet, electromagnetic, etc. Electromagnetic exciters are generally preferred and most commonly used. This type consists of a coil that is attached to the structure with a fixed drive rod, as opposed to a flexible shaft or spring for inertia or elastic type shakers. The coil is surrounded by a magnetic field and is set in motion by an alternating current. Electronic oscillators and amplifiers are used to control this type of system.

(1) Vibration amplitude may be obtained by using either velocity pickups or accelerometers so long as transducer mass is insignificant. Most modern accelerometers weigh only a few ounces. Typically that is insignificant when installed on the fuselage, wings, or vertical and horizontal stabilizers. When used on control surfaces, this same accelerometer may affect the flutter characteristics. Care should be exercised to select a small, light-weight accelerometer when mounting on control surfaces like tabs. The output can be observed using a cathode ray oscilloscope and digital voltmeter. Phase relationship between two transducers can be noted with sufficient accuracy, and by exercising extra care, using an oscilloscope equipped with a grid screen.

(2) Data systems are available that provide the coincident, in-phase or real term, and the quadrature, the imaginary term, responses of the total response frequency (the product of the force and reference signal). Graphical representation of these terms is presented, providing a very accurate identification technique for resonant frequencies and phase relationships. Structural damping is also readily available from these data.

(3) Whatever data system is used, uniformity is recommended. Piecemeal systems, using velocity pickups and accelerometers, or filters with different characteristics, etc., can give erroneous data and should not be used without careful regard to their calibrations and performance characteristics and limitations.

c. General Procedures for Airframe Modes. It is usually sufficient to apply a harmonic excitation force to the structure provided the force is not applied in the proximity of a node line. For this reason vibrators are usually attached at an extremity such as the nose and/or rear of the fuselage or near the tips of the wing or empennage surfaces where nodes are not likely to occur.

(1) The node line lies along the elastic axis of the structure (fuselage, wing, stabilizer, etc.). The axis passes through the loci of the shear centers of the cross-sections along the span of the structure. This theoretical location is typically determined mathematically when the dynamic computer model is created, and may be tweaked during the ground vibration tests. It can also be determined during the vibration tests, since an excitation force that is applied in the proximity of a node line will produce a near zero structural response. The point of application of the excitation force can then be moved away from that point and tried again.

(2) With the shaker(s) and a reference pickup mounted at a selected location, frequency is varied upward through the range usually encountered in aircraft structures. With small increments of frequency, the response of the structure is recorded and the resulting plot of amplitude of response versus forcing frequency is used to determine the resonant frequencies of the system. A typical sweep is shown in Figure A-2.

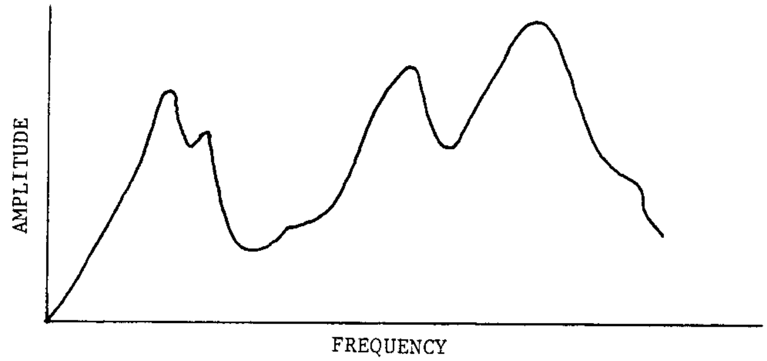


Figure A-2. Typical Sweep

(3) Although duplication of peak responses will result, it is advantageous to obtain frequency response records with a reference pickup positioned on each of the main surfaces and fuselage at a specific shaker location. This will reduce the chances of overlooking modes.

(4) There are several criteria for establishing that the excited response approximates a normal mode of vibration. The most commonly accepted approach requires that all of the criteria below be met:

(a) A relative maximum response per unit input exists. A normal mode of vibration occurs at a resonant frequency. At resonant frequency, the response is at its maximum. One needs to "tune" the excitation frequency very carefully until the maximum response is reached. The frequency at which the maximum response is observed, gives the resonant frequency. If the excitation frequency is slightly off of that frequency, the response will fall well below the maximum response.

(b) Accelerations at all points in the structure are either exactly in phase or 180 degrees out of phase with each other. The accelerations measured at all points on the structure during resonance will be either in phase or out of phase with a reference location but will be at a ± 90 degree phase angle with the force, for small values of damping.

(c) A decay record exhibits a single-frequency, non-beating, low-damped characteristic.

(5) Having established the resonant frequencies, a survey of the aircraft is conducted with the shakers tuned to each frequency in-turn. A roving transducer is used to sense amplitude and phase angle relative to the reference pickup at each airplane location. An adequate number of points should be surveyed along the span and chord (typically on the spars) of each surface and along the fuselage to define the airplane modal displacements, and the associated node lines. The number of survey points depends on the nature and span of the surface and the number of modes to be surveyed. If one is interested in obtaining a number of modes, (like third bending or fourth bending modes) more accelerometers are needed span-wise. Usually 8 to 10 accelerometers are sufficient for a small airplane. To obtain proper phase relationship additional excitation may be necessary.

(6) It may not be necessary to survey identical peak frequency responses although they occur at different locations. In all probability, the mode will be the same. This can be determined by checking only a few stations or simply by visually observing the motion of the aircraft.

(7) Care should be exercised in defining component node lines for each mode. This is particularly important in evaluating the effectiveness of balance weight locations.

d. Aircraft Structural Modes Usually Encountered. The modes excited during ground vibration depend on the type of configuration being tested. The vibration modes of an airplane that carries heavy mass on the wing, such as engines, tip tanks, etc., or has the stabilizer located high on the fin will be highly coupled and generally cannot be described except by diagrams that show the relative shape and phase of each part of the airplane.

Airplanes that do not have these design characteristics usually have relatively uncoupled modes, which can be described by naming the type of motion that is predominant. In general, the following predominant modes should be obtained insofar as is practicable.

(1) Wing Group Modes.

(a) For wings without engines, tip tanks, or heavy external or internal stores: Wing vertical bending and wing torsion, fundamental and higher modes, symmetric and anti-symmetric.

(b) For wings carrying heavy masses outboard of the fuselage: Wing bending coupled with wing torsion and flexible store (engines) modes, fundamental and higher modes, symmetric and anti-symmetric.

(2) Fuselage - Empennage Group Nodes.

(a) Fuselage Torsion (coupled with stabilizer anti-symmetric bending).

(b) Fuselage lateral bending and fin bending, fundamental and higher order consisting of two fundamental modes in which the fin tip and aft fuselage are in phase in one mode, and out of phase in the other.

(c) Fin bending - symmetric and anti-symmetric for multi-tail airplanes.

(c) Fin torsion (generally highly coupled with stabilizer yawing if stabilizer is located at the outer span stations of the fin).

(e) Rudder bending and torsion.

(f) Fuselage vertical bending and stabilizer bending, fundamental and higher order consisting of two fundamental modes in which the aft fuselage and stabilizer tips are in phase in one mode, and out of phase in the other.

(g) Stabilizer torsion - symmetric and anti-symmetric.

(h) Stabilizer yawing for surface located at the outer span stations of the fin.

(i) All movable horizontal tail - rotation coupled with bending, torsion.

(3) Engine or External Store Modes. For multiengine aircraft or aircraft carrying "large" pylon-mounted stores (the weight and the cg location with respect to the elastic axis of lifting surface are the significant factors in this instance), the pitch, roll, yaw, and lateral and vertical translation modes should be defined. These modes should also be determined for all turbo propeller engine installations. It may be necessary to excite the engine fore and aft on the propeller blade to obtain the most critical pitch and yaw modes. If this method is used, consideration should be given to possible modal distortion due to propeller blade flexibility. Also, caution should be exercised and the engine manufacturer's instructions followed concerning possible damage to bearings when exciting the engine.

e. General Procedures for Control System Modes. The experimental determination of control surface and tab rotation modes about their hinge lines may be difficult due to inherent friction within the system or the masking of these modes by structural interaction.

(1) On this basis, extra care is required for proper identification of the system's characteristics.

(2) For conventional aileron or elevator systems, the rotation modes may be successfully measured by applying a single excitation force to either the right hand or left hand surface. However, multiple shakers are preferred, particularly if the right and left surfaces are operated from separate control systems. Likely shaker positions are on the trailing edge at midspan or on the horn leading edge. Tab rotation may be determined from the control surface excitation but usually a direct excitation on the tab surface is required with the control surface (aileron, elevator, or rudder) blocked to its main surface.

(3) A transducer placed on the control being excited is used to monitor the response and determine peak frequencies by the same technique described for airframe modes. To define the modes excited, it is generally necessary to follow any or all of the following procedures:

(a) Monitor the phase between the right and left surface, the control column, or the attaching structure.

(b) Conduct a detailed survey of the surface, spanwise and chordwise, to define any structural modes. If the surface has a very long span or wide chord, these modes, bending and torsion, are likely to be dominant.

(c) Visually monitor the surface under excitation.

(d) Simple rationalization to distinguish the excited modes from previously defined airframe modes.

(4) In the performance of these tests, the shakers and/or transducers may contribute sufficient weight to the surface being tested to significantly affect the frequency of the surface. This is particularly true for tabs with very small mass and rotational inertias. Dunkerly's equation, presented in Appendix 3, reference 8, provides an acceptable method for correcting the measured frequency to the true surface frequency.

(5) A check on experimentally determined modes may be facilitated by calculating rotational frequencies from measured inertias and system stiffness properties obtained from static tests.

(6) For extremely light-weight structures, another method that may be used to eliminate the shaker influence is to use an air shaker or other device which does not directly attach to the control surface or tab.

f. Control Surface Rotation. Symmetric aileron rotation, the normal opposed operational mode, with control stick fixed or free, is defined as the peak frequency at which both ailerons are rotating in phase. Anti-symmetric rotation, the normal operation mode, generally has zero or very low stiffness.

(1) Rudder rotation in the normal operation mode with pedals free occurs when the rudder and pedals are out of phase.

(2) Elevator and all movable tail plane rotation modes should be determined with the pilot's controls fixed and free. Elevator rotation with the stick fixed is defined as the peak frequency at which both elevators are in phase for symmetric rotation, and out of phase for anti-symmetric rotation. For all moving tailplanes or elevators with stability augmentation systems (control column bob weights and down springs), normal opposed operation with stick free will occur when the control stick and elevator are responding out of phase.

(3) The effect of variations in control cable tension should be investigated. Typically a nominal value is specified for the cable tension along with certain tolerances. During the tests, the control surface cable can be, rigged to nominal tension, minimum tension, and maximum tension, and the tests repeated for each case. The variation, if any, can then be observed.

g. Tab Rotation. Rotational modes for irreversible trim and servo tabs are determined experimentally to supplement the calculated frequency obtained from measured stiffness in the free play tests. Tab rotation frequency will usually vary with angular deflection and is determined at maximum trailing edge up, neutral, and maximum trailing edge down positions to determine the range of tab frequencies. For geared tabs, the rotation frequency is usually determined with the control surface at maximum deflections and at neutral.

(1) Large tabs, either wide chord or very long with a single actuator, often tend to be difficult to measure in a resonance test. Wide chord tabs often become significantly involved with "plate modes" of their carrying surfaces, while long narrow tabs may have their lowest frequency in a torsional mode rather than rotation. On this basis, it may be

necessary to survey each response frequency rather extensively to properly define each mode.

(2) Test requirements for spring tabs are dependent upon the tab control system design. In general, the following tests should be conducted to provide the required data for a mathematical representation of a spring tab system. (These tests are similar to those discussed in the previous paragraph for all moving tailplane systems.)

(a) For a preloading spring, tests should be performed for several amplitudes including complete removal of the preload, if practical.

(b) Frequency of the control surface, with tab locked to surface and pilots control column blocked, against the elastic restraint of the control system, a stick fixed mode.

(c) Frequency of the control column with the control surface locked to its main surface, against the elastic restraint of the control system, a stick free mode.

(d) Frequency of the tab, with the control system cables disconnected and the control surface blocked to its supporting structure, against the elastic restraint of the springs in the tab system.

(3) Spring loaded tabs are non-linear systems, which are usually quite sensitive to small parameter changes making the design of these systems to preclude flutter most difficult. It is advisable to avoid their use unless extensive flutter analyses, including detail parameter evaluations, are conducted.

h. Structural Damping Measurements.

(1) Structural damping of each significant mode surveyed should be measured. The most commonly used procedure is based on the measurement of the rate of decay of oscillation. This is best expressed in terms of logarithmic decrement, the natural logarithm of the ratio of two successive amplitudes. Records of the response of a reference transducer, while driving the structure at a specific frequency and obtained immediately before and after power to the shaker is cut off, provide the amplitude relationships required as shown in Figure A-3.

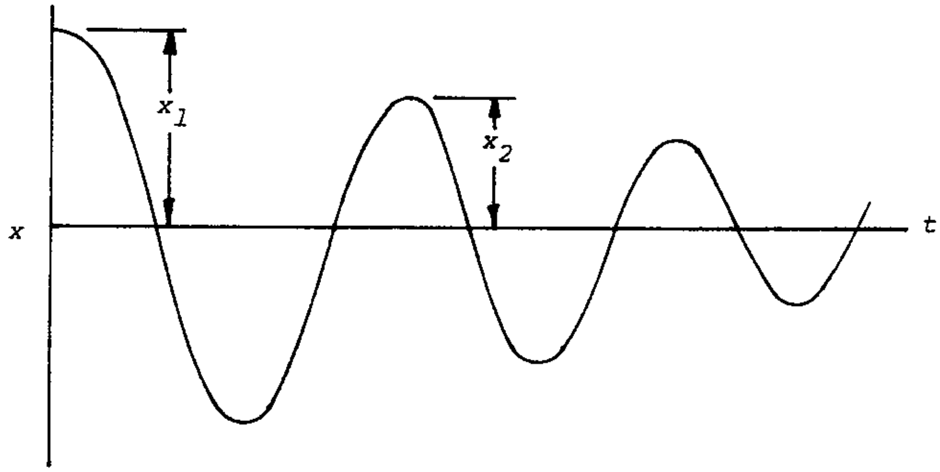


Figure A-3. Structural Damping Measurements
(X = Displacement, t = time)

The log decrement, $\delta$, is then equal to ln $(X_1/X_2)$; or as $\frac{0.693}{n}$
Where n=no. of cycles to ½ amplitude; i.e.: $X_1/X_2 = 2$.

For small values of damping, the damping factor, or $\gamma C/C_o$, can be Estimated as $\delta/2\pi$ and the structural damping $g= \delta/\pi$ (Appendix 1, references 2 and 8).

(2) Multiple Input and Multiple Output (MIMO's) Methods. MIMO's have become more or less common in recent times. These methods input random excitation in the structure and samples several outputs simultaneously. These methods enable completion of the ground vibration tests much faster, and several cases can be considered during ground tests.

i. Balance Weight Attachment. For control surfaces with balance weights mounted at one end of a cantilevered moment arm, the resonant frequency of the balance weight attachment arm should be at least 50 percent greater than the highest frequency of the fixed surface with which the control surface may couple. The control surface should be mounted in a jig and the vibrator attached to the balance weight. The input frequency is varied upward and the response of a reference transducer mounted on the balance weight is monitored to define the peak response.

All balance weight supporting structures should be designed for a limit static load of not less than 24g normal to a plane containing the hinge and the weight, and not less than 12g within that plane parallel with the hinge. The balance weight loads should be able to be carried by the control surface and by the fittings and their attachments on both sides of the hinge. Proof of these criteria can be accomplished by relatively simple static tests of the control surface mounted in a jig.

# APPENDIX 2. FLIGHT FLUTTER TESTING

1. INTRODUCTION. This appendix presents a general discussion of acceptable procedures for conducting flight flutter tests intended as final validation of flutter free operation within the flight envelope for new or modified airplanes. The methods described herein do not represent a comprehensive survey of existing techniques, but rather represent methods, which have been proven to be particularly adaptable to general aviation aircraft.

a. It is recommended that these tests be conducted only after appropriate analyses, defining the critical conditions and severity of flutter onset, have been performed. Both the risk and scope of testing required to substantiate the total airplane is significantly increased without the benefit of reference analyses.

b. In-flight excitation of only the critical mode(s) is generally, all that is necessary for final demonstration of flutter free operation if preceded by rational flutter analyses. However, without these studies, all modes of the airplane, or those modes affected by the modification of an altered airplane, must be excited in flight. All test airplanes should include proper instrumentation for recording airplane response.

2. DETERMINATION OF VIBRATION CHARACTERISTICS. Section 23.629(a) requires a determination of the natural frequencies of main structural components by vibration tests or other approved methods. This must be done regardless of the flutter substantiation method selected; i.e., (a) rational analysis plus flight flutter tests, or (b) simplified criteria plus flight flutter tests. This determination must be made for all new airplanes and for existing airplanes, before and after any major modification to assess the effects of these structural changes. Engineering judgment should be exercised in determining whether the effects of the modification on aerodynamics, stiffness, or mass are sufficient to warrant flutter reinvestigation. The effects of variations in fuel loading, airplane weight, and center of gravity should also be assessed. It is recommended that mode shapes, as well as frequency, be determined by either ground vibration tests or analytical methods, if adequately supported by test.

For modified airplanes with no available analyses, the degree of frequency change requiring flight investigation is dependent upon, in part, the nature of the modification, the relative change of bending-torsion frequency ratios, and the relationship of the structural modes to control surface modes. Shifts in node lines may also dictate flight checks.

3. AIRCRAFT EXCITATION METHODS. The airframe modes and frequencies can be excited in flight by any number of techniques. The important criteria for technique selection is that the modes and frequencies of interest must be adequately excited to allow for proper modal response. During the tests, flutter critical modes are to be excited. If an 11-Hz. mode is critical, the method of excitation must be positively able to excite that mode. The flight test data should be able show that mode at that frequency and it should be distinct in the frequency-amplitude plot. Methods like stick raps will not excite frequencies higher than 7 to 8 Hz. In such cases, eccentric mass excitation or other methods must be used. To illustrate, most general aviation aircraft use cable or push rod control systems,

which have high levels of coulomb damping. The coulomb damping will cause a non-linear control response. At low amplitudes the damping will be high and the system stable; whereas, at higher amplitudes, the coulomb damping will be reduced and the control system could be unstable. A proper level of modal excitation will, therefore, produce lower system damping and an earlier indication of a developing flutter mechanism. Consequently, without proper excitation, the test engineer may have very little warning of developing flutter.

Consideration should also be given to the possible influence of the excitation system on the flutter characteristics of the airplane. Excitation methods presently being used for general aviation airplanes are discussed briefly in the following paragraphs.

a. Pilot Induced Control Surface Impulses. Pulsing the controls may be used to excite modes, generally, below 8 Hz, and is not recommended above 8 Hz. The effectiveness of the method is usually limited by either the ability of the pilot to impart a pulse of proper duration or the ability of the control to transmit the pulse to the primary surface. Three degrees of control rotation are normally sufficient if the duration is short enough to encompass all harmonics of interest.

b. Sinusoidal Excitation Using Rotation Masses. This technique has been used successfully for exciting airplane modes between 10 and 50 Hz. Rotating eccentric mass shakers mounted in the wing tips and/or the tail section of the fuselage will usually produce wing and empennage modes of concern. Although shakers in each wing tip and both vertical and lateral mounted fuselage shakers may be required to excite both symmetric and anti-symmetric modes, single shakers have been used successfully for both symmetries where adequate frequency separation exists. The eccentric mass should be large enough to excite the 10 Hz modes and the shaker supporting structure strong enough to withstand the shaker force at 50 Hz. Shaker forces of up to 300 pounds at 50 Hz have been used and produced very good results. In general, the larger the exciting forces the safer the test since the non-linearity will be minimized. The shaker force should be adequate to assure that modal response is easily distinguishable from random or buffet excitation. In other words, the response should be well above the noise levels of the data. This can only be determined during the test. If the response is not distinct, the shaker force is to be increased suitably. Several samplings of data will eliminate the random and buffet responses.

A simple inertial shaker system can be constructed using off-the-shelf shop components. The system consists of a container of compressed nitrogen, pressure regulator, line gate valve, air hose and shop drill motor. The RPM of the drill motor is controlled by varying the line pressure and can be monitored by a tach generator attached to the drill motor shaft. The only parts requiring design and fabrication are the eccentric mass and appropriate mounting brackets.

c. Excitation Using Autopilot And Other Methods. Sinusoidal excitation using the autopilot will produce modal responses similar to the inertial system but has the advantage of supplying a stronger input to the fundamental modes. A restriction is its ability to transmit energy into the control surfaces at the higher frequencies due to control system flexibility.

Other methods such as flutter vanes and rocket impulse units may be used. Regardless of the method used, the same principles of frequency response and mode identification apply; i.e., adequate response of the modes and frequencies will produce the desired indication of any developing flutter mechanism.

4. AIRCRAFT INSTRUMENTATION. The aircraft instrumentation required to adequately monitor vibration characteristics will vary greatly depending on the extent of the test (number of modes being investigated) and the special design characteristics. As a minimum, transducers that measure acceleration or velocity should be installed on the tips of the aerodynamic surfaces of concern; i.e., for wing and horizontal stabilizers, front and rear spars on one side for bending and torsion response and on one spar of the opposite side as an indicator of symmetry. The frequency response characteristics of the installed transducer should be checked to assure adequate sensitivity throughout the test frequency range. Strain gages or accelerometers should also be installed on each control surface. Care should be taken to assure control balance is not disturbed by the instrumentation. This may be accomplished by choosing light-weight accelerometers, and avoiding placement of the accelerometers at the leading or trailing edge of the control surface.

a. Unless workload makes it prohibitive, it is preferred that the in-flight data recorder and exciters be operable by the pilot to eliminate any need for additional personnel on board the airplane during the test. This is particularly desirable if testing is performed without supporting analysis.

b. Although various telemetry systems exist for recording and transmitting data to the ground, an on-board oscillograph or magnetic tape recorder are more commonly used. A magnetic tape recorder is advantageous over an oscillograph if filtering, sensitivity change, and speed variations are available on playback to aid in determining frequency and damping. An oscilloscope, or other means to monitor input frequency in real time, should also be available to the crew.

c. The complete excitation and data recording system should be thoroughly checked and calibrated, on the ground and as mounted in the airplane, to assure excitation of the desired modes and in turn to establish baseline amplitude and damping data. The response to engine noise and aerodynamic buffeting can seriously distort the data and, as a general rule, the signal-to-noise ratio should be at least 4 to 1. The unwanted signals can be filtered or minimized by increasing the exciter force. However, the maximum level of excitation should be limited to prevent structural damage from dynamic overload.

5. TEST CONDITIONS.

**NOTE**

> Several of the following are recommendations for safety only (noted as *Safety Recommendation*) and not required for showing compliance. The applicant is free to pursue other means of achieving a safe, flight test program.

a. Flight flutter tests should be conducted with the airplane configured to provide maximum safety to the crew. In preparing the airplane, a checklist of configuration requirements should be closely adhered to. The list should include the following.

(1) The airspeed indicating system should be calibrated.

(2) All equipment items in the cabin should be secured adequately to meet emergency landing load requirements of § 23.561. *Safety Recommendation*

(3) When certification is by § 23.629(d) (simplified criteria) and testing, control surfaces should be balanced to the most under balanced (tail heavy) condition and trim tab free play set at the maximum allowed. If certification is by analysis and testing, the analysis should dictate the appropriate settings.

(4) Control system damping should be minimized to simulate wear.

(5) The crew should be provided with parachutes. *Safety Recommendation*

(6) Each of the crew members should have easy access to an escape exit. *Safety Recommendation*

(7) Each emergency exit door should be equipped with a quick release mechanism allowing the door to separate from the airplane. The doors should be checked at various airplane yaw angles to make sure that the pressure distribution over the door will allow it to be drawn away from the airplane. *Safety Recommendation*

(8) For airplanes with large cabins, a knotted rope should be installed the length of space of the cabin. *Safety Recommendation*

b. The airplane configuration(s) to be tested (i.e., fuel loading, c.g., weight) obviously depends upon the purpose of the test, upon whether the airplane is a new type design or a modified type design, and upon the nature of the modification if the airplane is a modified type design, etc. Generally, a minimum of two-wing fuel loading conditions, representing maximum and minimum, should be checked if this parameter affects a significant change in component modes. Acceptable tolerances from the selected condition, to account for fuel usage, must be established and maintained throughout the tests. The need to explore airplane weight and c.g. variations must be based on the effect of these parameters on the airplane component(s) of concern.

c. At least two altitudes should be checked, if appropriate to the design. One representative of high dynamic pressure (approximately 9,000 feet will provide emergency egress protection) and one at approximately 75-percent service ceiling or the altitude at the $V_d/M_d$ knee, if a design limiting condition. These recommendations may not be appropriate or adequate for all airplane designs. As one example, a 9,000-foot altitude would not be safe for a Mach .72/275 kcas airplane that descends at 10,000-feet per minute to reach dive speed. Qualified individuals must make the final determination of the sufficiency of the test procedures to demonstrate compliance in a safe manner.

6. <u>FLIGHT TEST PROCEDURES</u>. Due to the potential dangers involved in conducting flight flutter tests, there is always the desire of the crew to get the tests over with and a general tendency to want to skip speed points and short cut the test. For this reason, a flight plan should be established prior to beginning the test and followed as closely as possible.

a. A chase plane should be used for all tests. It is recommended that the chase plane have videotape capabilities. This is a safety recommendation only, and is not required for showing compliance, however it is a standard practice.

b. Testing should begin at a low airspeed point to establish a database; i.e., frequency correlation with ground vibration modes. Follow-on increments should be based on the flight history of the airplane. If the airplane has previously flown to some limit speed, then enough test points should be checked to that pre-achieved speed to develop a data trend. For unexplored speeds, the increments should be smaller and no more than two-speed data points checked at any one altitude during a flight unless data trends show continuously increasing, or very high, damping with no indications of ensuing shifts in this trend. More data points may be checked per flight if telemetry and real time data analysis systems are available. Between $V_C$ and $V_D$, the number of airspeed increments should be increased.

c. Atmospheric turbulence should be avoided as much as possible during these tests to eliminate superposition of unwanted random signals on the data records and to preclude possible structural overload at speeds near $V_D$.

d. At high speeds, prior to the commencement of test points, the test pilot should establish adequate controllability of the airplane by slowly exercising each of the three control systems and ensuring the proper response is received.

e. If inertia shakers, aero vanes, or other sinusoidal exciters are used, frequency sweeps should be conducted at each speed point. It is also recommended that shaker dwells be performed at selected airspeeds as a check on the damping characteristics established from sweeps. These are conducted by tuning the shaker(s) to each peak frequency, allowing time for the airplane to stabilize, then cutting the shaker power and recording the response of each transducer. If pilot induced control impulses are used, each axis should be pulsed at least twice in each direction wherein the airplane is allowed to stabilize, with hands off controls, prior to the next impulse or speed point.

7. DATA REDUCTION AND INTERPRETATION. The methods used for analyzing flight flutter data will depend on (1) the type of excitation used, (2) the availability of electronic analysis equipment, (3) the degree of accuracy required, and (4) the time allowed for data reduction. Generally, absolute damping values are not necessary to achieve the objective of the flight tests wherein monitoring of damping versus airspeed trends is the primary concern. The approximation methods addressed briefly in this section will allow development of reliable trends provided consistent procedures are followed in reducing the response traces throughout the test.

a. When impulse excitation is used, the damping can be obtained by measuring the decay rate directly from the response traces. For cases where several frequencies are being excited by the impulse, it may be necessary to reverse the transient and play it into a tuned filter. The frequency of the tuned filter can then be varied to yield discrete modal responses (reference 7).

b. When continuously forced oscillation techniques are used to excite the structure, either the amplitude response method or the vectorial analysis method as developed by Kennedy and Pancu (reference 6) can be used to reduce the data. The amplitude response method is advantageous for general aviation applications since it provides a good approximate damping level, requires a minimum of electronic equipment, and the data can be quickly reduced. For this method it is assumed that the relative damping ratio is approximately inversely proportional to the maximum resonant amplitude of the respective modes. Therefore, if the amplitude for a given mode is increasing as the airspeeds increase, a reduction in stability will be indicated. The approximation method is briefly outlined as follows: (1) The product of response amplitude times damping will be constant for a given exciter force; i.e., $(A_g)\ (g_g) = c$

(2) If the exciter force relative to frequency remains constant, then at a given airspeed, the net structural damping will be:

$$(A_v)\ (g_v) = (A_g)\ (g_g)$$

then:

$$g_v=(A_g)\ (g_g)/A_v$$

where:

$A_g$=peak amplitude on ground
$A_v$=peak amplitude in air at test velocity
$g_g$=damping measured on ground at zero velocity
$g_v$=net structural damping at test velocity

(3) The net damping ($g_v$) can be defined as the actual structural damping measured on the ground ($g_g$) minus the analytical aerodynamic damping (g) determined from the flutter analysis with zero structural damping; i.e., $g_v=g_g-g$, where g is negative when stable.

(4) To permit use of this method, the shaker force and sweep rate must remain consistent from run to run.

c. A gradual increase in peak response ($A_v$) by a factor of 3 or a rapid increase in $A_v$ by a factor of 2 will normally require stopping the test to inspect the airplane, instrumentation, etc. For example, a gradual increase in response occurs over a large range of speed (200 to 300 knots). Therefore, an increase from 10 units response at 150 knots, to 30 units response at 350 knots may be considered a gradual increase in peak response. An example of a rapid increase may be 20 units response at 250 knots, to 40 units response at 280 knots. One must rely on engineering judgment to make this determination. It is also possible to experience a very sharp rise in damping followed by a sharp decrease leading to violent flutter, thus making it difficult to predict trends without the aid of reliable analyses.

d. It is advisable to check the effects of variation in sweep frequency on the peak response damping using techniques included in Appendix 3, reference 2. It is also advantageous to supplement continuously forced damping measurements with damping obtained from decay records. Flutter margin predictions per the techniques of Zimmerman and Weissenburger (Journal of Aircraft, 1964, Volume 1, Number 4) may be a beneficial data presentation approach to supplement the characteristic velocity versus damping plots.

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