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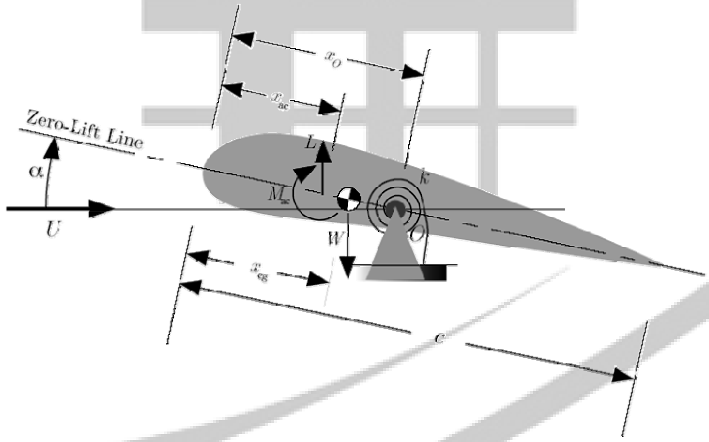
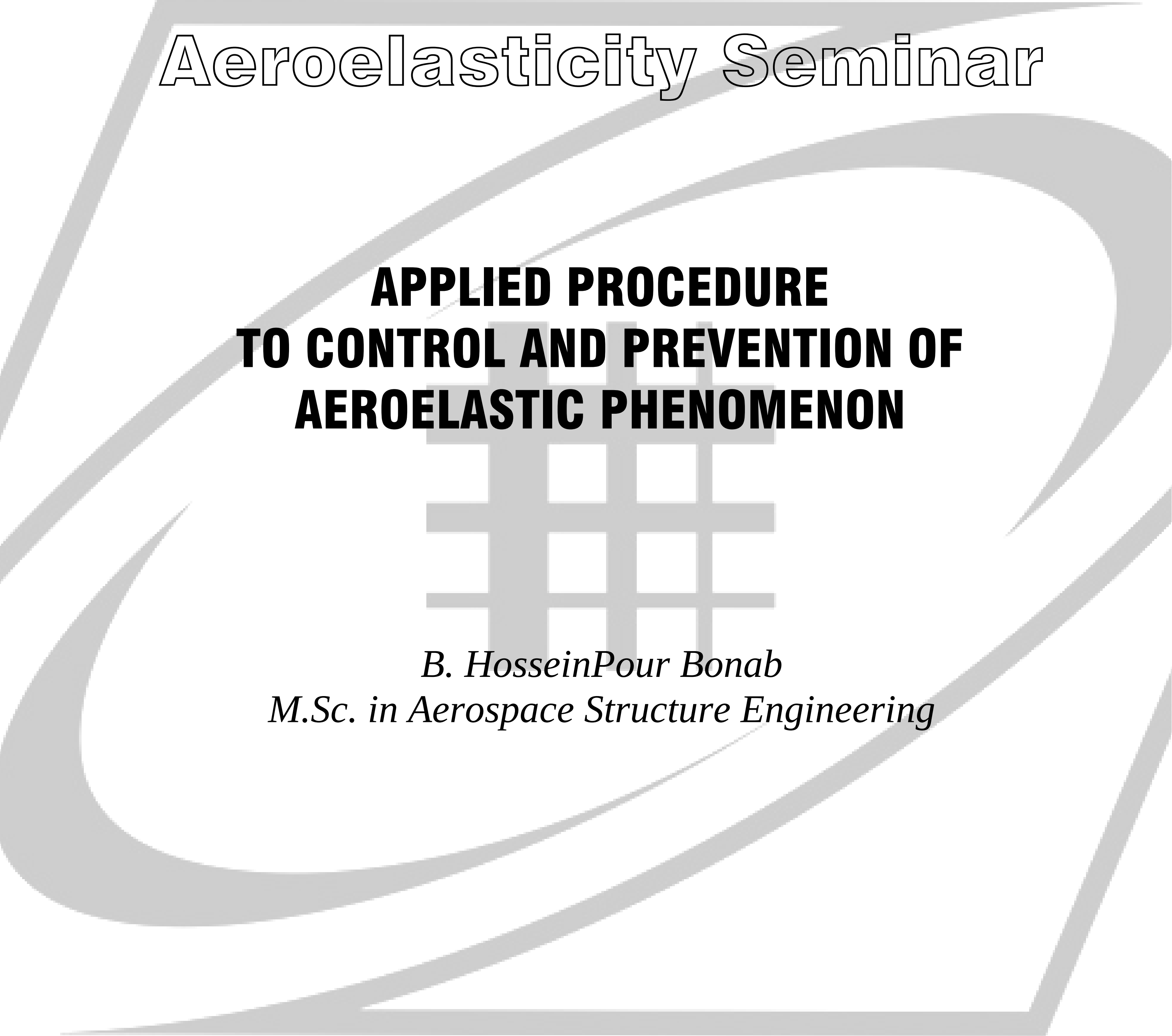
راهکارهای اجرایی
برای کنترل و جلوگیری از
پدیده های ایروالاستیسیته

APPLIED PROCEDURE TO CONTROL AND PREVENTION OF AEROELASTIC PHENOMENON

B. HosseinPour Bonab
M.Sc. in Aerospace Structure Engineering

تنظیم و گردآوری: مهندس بهروز حسین پور بناب
کارشناسی ارشد سازه مهندسی هوافضا





Aeroelasticity Seminar

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B. HosseinPour Bonab
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سمینار ایروالاستیسیته

راهکارهای اجرایی برای کنترل و جلوگیری از پدیده های ایروالاستیسیته

گردآوری و تالیف:

مهندس بهروز حسین پور بناب

APPLIED PROCEDURE TO CONTROL AND PREVENTION OF AEROELASTIC PHENOMENON

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"Some fear flutter because they do not understand it
And some fear it, because they do."
The famous aerodynamicist Theodore von Karman.

1 Introduction

The purpose of this report is introducing the applied methods and procedures of aeroelasticity theories. The applying of theory on the real airplane is always along with many problems. The introduced methods and examples in this report are real engineering technique/means for overcoming to aeroelasticity troubles.

The major Intention is the flutter evaluation of your airplane with the approved regulation before/after manufacturing. Flutter can be a problem with any aircraft design and we prefer to predict and modify the critical flutter speed of an aircraft before an incident occurs.

Flutter analysis is often called a black science

Today's Powerful engines, higher-pitch propellers and good, low-drag designs with moderately higher wing loadings all combine to produce surprisingly high-speed flight. Also, the practice of carrying armaments and auxiliary fuel on external pylons, and the vast variety of possible combinations of external loads, make flutter analysis of modern fighters especially difficult. But, we know that aeroelasticity was the first conscious integrated design effort in aeronautics because it developed in response to a requirement to keep airplanes flying faster with low weight. Aeroelasticity is a design activity concerned with the consequences of interactions between aerodynamic forces and structural deformations. Important aeroelastic phenomena include aerostructural instabilities such as flutter and divergence, load redistribution and flight control ineffectiveness at high speeds.

Flutter has always been aviation's dirty little secret. Seldom reported and little understood, it occupies one of those dimly lit and unsafe places that decent people prefer not to visit.

Flutter is all about stiffness, not strength; even the strongest structure may fail if it flutters. In general, structures that are light and stiff vibrate more rapidly; they are said to have higher natural frequencies. Structures more massive or less stiff have lower frequencies. The usual treatment for a flutter problem is to raise the natural frequency of one structure by stiffening it, but sometimes the opposite approach is used: lowering a frequency by the careful placement of damping weights. The essential thing is to eliminate coincident frequencies in structures that can feed energy to one another. A wing that is very stiff in bending should be made "softer" in torsion, and vice versa.

The terms flutter and aeroelasticity are often used synonymously, although this is not correct

Flutter is not resonance: Flutter is different. The incoming flow itself is steady, but when the system is perturbed, forces and moments created by the system motion itself occur in such a way as to draw energy from the airstream and transform it into structural kinetic energy and strain energy. For flutter, the amplitude of the oscillatory motion increases exponentially with time, not linearly. Thus, flutter has an explosive character once it starts.

Sources of aeroelastic system coupling features are many and varied. The removal of coupling by changing the location of external stores (fuel tanks and bombs or missiles) or internal components can prevent flutter (or cause it). Similarly, adding stiffness to change the coupling can also increase the flutter speed. Finally, we should select one way about flutter, control or prevention.

2 Aeroelastic Phenomenon in Air Vehicle

2.1 Introductions

Air vehicle is always subjected to aeroelastic phenomenon. Many items/parameters like as large aspect ratio, thin airfoil section, high speed, and unusual shape cause special aeroelastic effects. Flutter isn't only for wing, but the similar sections like as empennage, aileron, flapron and spoiler are subject to flutter too.

Flutter isn't only excessive oscillating of wing or empennage. But also the coupling of bending or torsion frequencies between wing and body or body and H-tail can cause flutter. One of the main criteria for prevention of flutter is proper gap between components frequencies. The proper space is obtained and recorded after very experiments, tests and calculations.

2.2 Air Vehicle Phenomenon

Aeroservoelastic Instability: Aeroservoelastic instability in which configurations that were flutter stable without their flight control systems become unstable at certain regimes with the control systems engaged.

Control Surface Buzz: Three types of control surface buzz were considered, the first being the shock wave boundary layer interaction problem which occurs at a speed slightly higher than the wing or fin critical Mach number. An oscillatory condition arises when the shock waves move rapidly back and forth across the control surface hinge line, influenced by the trailing edge shape of the control surface, and the particular flight maneuver being made.

Wing-Aileron Flutter: Following World War I, aircraft airspeeds increased and monoplane designs again reappeared, this time as low drag, very stiff, semi-monocoque designs. A new type of aeroelastic instability, called wing-aileron flutter plagued the aircraft design effort. This involved dynamic self-excited interaction between the aileron rotation and wing bending. Just as the wing warping type of control had led to wing divergence, the new aileron control led to dynamic aeroelastic failures. As depicted in Figure-1, wing-aileron flutter occurs when the lift generated by the oscillation of an aileron drives the wing bending deformation. The oscillation frequency depends on the airspeed because the aileron acts like a weathervane whose rotational stiffness increases as airspeed increases. The accelerations of the aileron, as well as the airloads transmitted to the wing will force oscillation of the wing and create a coupled vibration which when begun, will rapidly increase in amplitude.

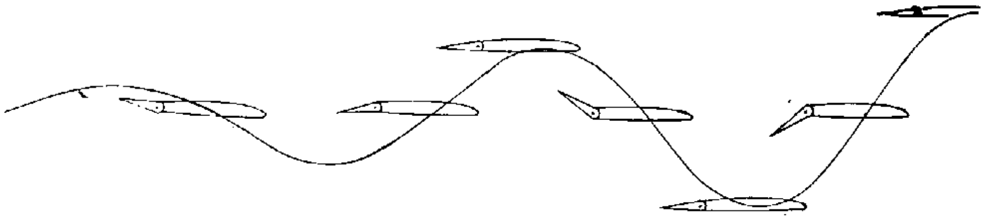


Figure-1: Wing-Aileron Flutter

If the surface is swept, the ineffectiveness is exacerbated by the fact that bending also reduces the effective angle of attack. While this does not create reversal, it reduces ineffectiveness.

Forward Swept Wing(FSW) Body-Freedom Flutter X-29 (S-37 Too): As divergence approaches, the reduced stiffness creates a situation where, at the theoretical divergence speed, the natural frequency tends to zero; exceeding the divergence airspeed results in the unstable periodic motion in which a small perturbation grows exponentially.

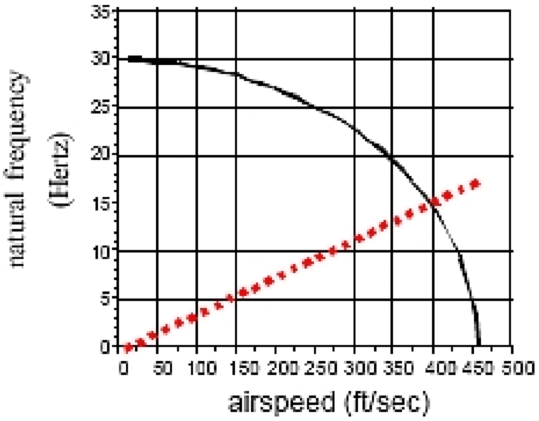


Figure-2: Typical Wing divergence example

Figure-2 illustrates this situation for a typical theoretical wing divergence example. The downward curved line represents the behavior of a normal mode the airspeed increases. The other line shown in Figure-2 originates at the origin. This line (which has curvature, but is drawn straight here) represents the natural frequency of a flight mechanics mode, such as a short period mode of the airplane, as the airspeed increases. Note that the two plots cross before the divergence speed is reached.

This frequency merging indicates that interaction between the flexible mode and the flight mechanics mode can occur, much like the interaction between and aileron and a wing. Our NASA sponsored studies clearly identified the coupling mechanism.

Accurate FSW analysis demands consideration of wing-fuselage dynamic interaction. For the forward swept wing the coupling occurs between the wing bending mode as its frequency decreases due to increased airspeed. The aircraft pitch mode frequency increases and creates a coupled rigid body pitch, wing bending mode. The result is that the coupled mode can extract energy from the air moving past the airplane.

The Oblique Wing: Figure-3 shows an oblique wing aircraft concept. This configuration was first suggested by Robert T. Jones in the early 1970s as a creative design for supersonic transports so that L/D remained high and the sonic boom would be reduced, compared to conventional designs. Initially this design was criticized by some aeroelasticians (including the present author) on the grounds that its swept forward wing would be divergence prone and thus heavy.

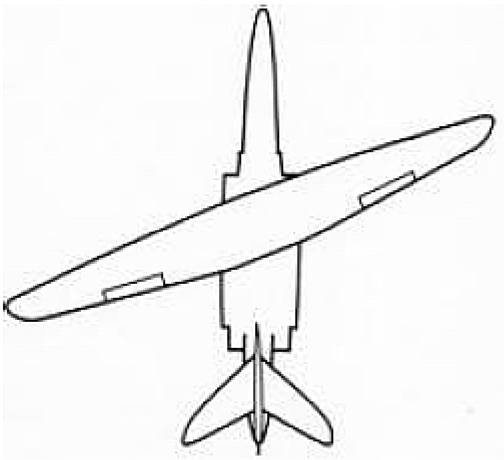


Figure-3: Airplane with the Oblique Wing

The reduced drag would then be squandered on increased weight requirements. Concern over this sweptforward wing was valid, but the separation between conventional aeroelasticity and flight mechanics, as practiced in the 1970s led to the wrong answer.

The oblique wing aircraft is unusual since it develops an asymmetrical lift distribution in flight. This type of distribution is shown in the notional diagram shown in Figure-4. The tendency of the forward swept wing to load up and the aft swept wing to unload due to aeroelastic effects is evident. Two actions are necessary to trim the oblique wing. First of all we need to reduce the angle of attack as airspeed increases and second, we need to provide lateral (roll) trim. Lateral trim can be done to some extent by building in twist along the wing, but aeroelastic effects will always require aileron input to keep equilibrium.

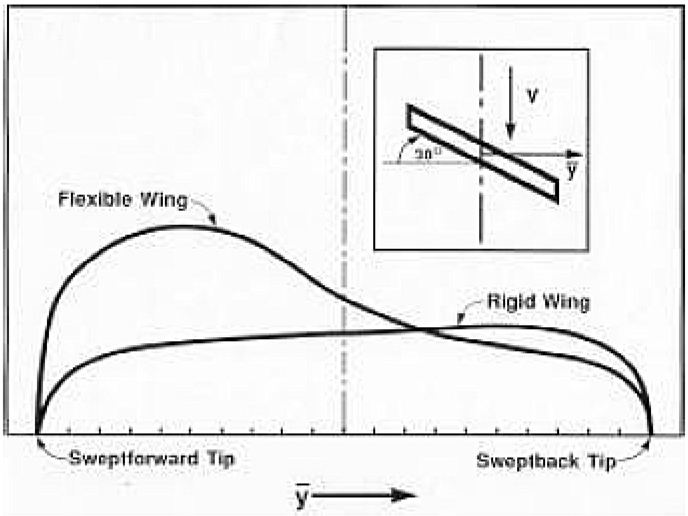


Figure-4: Load Distribution on the Oblique Wing

The oblique wing aeroelastic instability mode is unusual. Unsymmetrical wing bending vibration induces fuselage roll. At a speed slightly above the wing divergence speed, the unsymmetrical rolling mode couples with fuselage roll to produce a violent dynamic instability. Aeroelastic tailoring can reduce the severity of this problem.

HALE: High altitude and long endurance airplane have wing with large aspect ratio. Because of structure lightening for fuel saving prevention of flutter is very difficulties so flutter of this type of wing must be controlled.

Human Power: Another example of special effects is human power airplane. The weight of it is very low and components are made of composite fibers, so are very light. Low speed (near to stall speed) and very large aspect ratio cause high sensitivity at the time of turn and bank. Control of static aeroelastic phenomenon is preferable to prevention.

Rotor Blade: In the helicopter, rotor blade has the highest complex aerodynamic flow. Also rotating of wings with inertia effects added dynamics problems more complex than usual wing. In this report no discussion is about rotor blade.

Turbofan Compressors Blade: In turbofan compressors there are two principal types of aerodynamically excited instability which are of practical consequence. These are:

(a) Stall Flutter: This occurs over a band of speed just below, but usually not extending to, design speed itself. It is commonest among (although not confined to) fan or front stage compressor aerofoils of the cantilever bladed or unclappered type. On a compressor test rig it can be observed as a blade instability which is excited when the exit throttle is closed at constant speed, and may prevent a true surge point from being attained. It is associated with a critical combination of local aerofoil stalling and blade frequency parameter.

(b) Supersonic Unsteady Flutter: This type of excitation presents a stress boundary in the high speed regime of the compressor, where the blade inlet relative velocities are well supersonic over the outer section, and where blade incidences are well away from stalling values. It is usually associated with high tip speed, high aspect ratio fans, with part-span shrouds or clappers on the blades, where the whole rotor is caused to vibrate as an integral assembly when the critical speed is reached. This is a result of work transfer from air to blade, instead of vice-versa; an associated change in overall performance is not discernible, however, at the maximum safe operating stress level.

The Joined Wing Configuration: During the past 20 years the joined wing design has been presented as an aircraft with high lift to drag and stiff wings. Few, if any, comprehensive aeroelastic studies have been done on this aircraft. Figures-5 show manned aircraft designs proposed for the joined wing design. The shape of the proposed Navy aircraft supposedly makes it more suitable for antenna arrays carried in the design.

Figure-5: Lockheed-Martin box-wing freighter design

The presence of a large forward swept aft tail on the joined wing makes some (but not all) joined wing aircraft prone to body freedom flutter instability where the aircraft pitch mode couples together with the wing bending mode. This instability depends on the location of the aircraft center of gravity.

Almost Flying Wings: The airplane in Figure-6 (Lockheed Darkstar) is another unmanned high altitude surveillance aircraft. Because this aircraft must fly at high altitude, this design has few external appendages. The wings are large and flexible and have low natural frequencies because of large amounts of fuel that must be stored. This airplane is typical of HALE that must shed wetted area to loiter for long times. If the aircraft were scaled to be large enough, aeroelastic response would eventually be a concern.

Figure-6: Lockheed Darkstar

Coupling between Modes (Example): During World War I, the British Handley Page 0-400 bi-plane experienced severe tailplane vibration at high speed. Investigations in 1916 revealed that tail flutter was the culprit. This was the result of a interaction between the fuselage twisting motion and the antisymmetrical pitch rotations of the independently actuated right and left elevators. The phenomenon was the first recognized instance of flutter, a self excited, vibratory instability. This aircraft had an unusual coupling between the gyroscopic moments created by the powerful turboprop and wing bending and torsion. This coupling was only dangerous if the engine mounting between engine nacelle and wing was relatively flexible. Two accidents occurred with substantial loss of life after the aircraft wing was torn off during a propeller whirl flutter incident.

Aileron Reversal (Example): Control effectiveness is a significant problem for high-speed aircraft. The Japanese A6M5 “Zero” shown in Figure-7 provides an excellent example of the effect of aeroelasticity on airplane performance and fighter tactics.

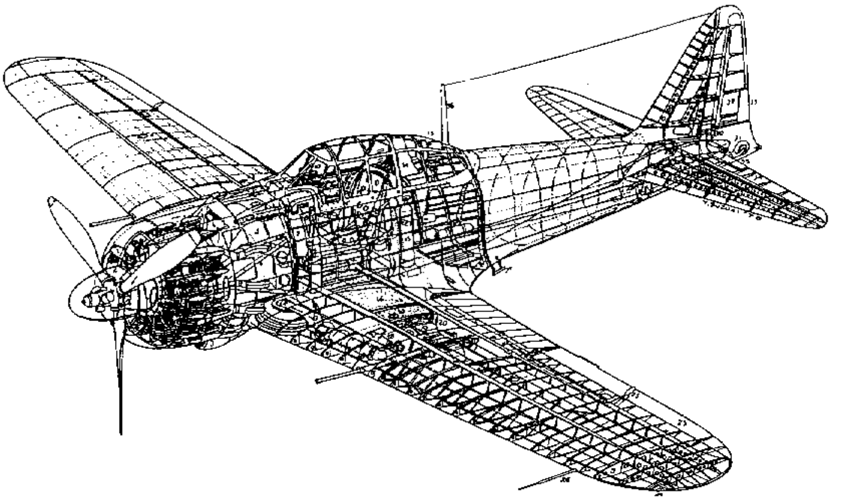


Figure-7: Japanese A6M5 Zero, lightweight and lethal

The Japanese Zero was a lightweight fighter designed by a young and talented design team in the 1930’s. The chief designer had trained at a seaplane design facility in Denmark after the First World War. This facility was staffed by many German designers who were prohibited by the Treaty of Versailles from building powered German aircraft. The Zero was highly maneuverable at low speeds associated with dogfighting. It was lethal. Because it was so lightweight and structurally efficient it suffered from control ineffectiveness at higher speeds. U.S. Navy aircraft, outmatched at first, used a tactic where one aircraft would draw the Zero into a dive while the second aircraft followed. At high speeds the Navy plane would quickly turn (their planes were built by Grumman and were “iron birds”). The Zero could not turn with the first airplane because it was near reversal. The second Navy airplane would then pounce on the Zero. This was a dangerous tactic, but was made possible by the poor aeroelastic performance of the Zero.

> **Even with the wind tunnel and extremely sophisticated software, however, some flutter modes are elusive: "You can't predict them, until they happen."   Keller quips**

The speed at which flutter will occur depends on many factors: hinge friction, weight and size of the control surface; location of its CG relative to the hinge line; and stiffness of the control linkage. When the speed is sufficient to excite the frequency of the oscillations, flutter can occur. The aircraft's flutter speed appeared dependent on the fuselage bending and torsional stiffness, with the wing torsional stiffness playing a secondary role.

3 Flutter Predication/Control/Prevention

3.1 Introduction

There are several stages in engineering development. The first stage is observation that involves simple experimentation and understanding of the phenomenon involved. The second stage is analysis in which important parameters are selected and identified and then combined to develop a theory that predicts the phenomenon. The third stage is control and exploitation. In this stage we control or perhaps prevent the phenomenon or use it to create some beneficial effect. These three stages are sequential.

The tendency to flutter does not usually rise instantly to a maximum when one parameter or another say, airplane speed reaches a critical value. It normally ramps up gradually enough for speed increments of one or two mph to give the pilot warning of impending trouble.

In this section, we review predication, control and prevention of static/dynamic aeroelastic phenomenon.

3.2 Predication–theoretical method

Progress in understanding and predicting flutter depended on theories to predict the aerodynamics of lifting surfaces, particularly the unsteady airloads on these surfaces as they oscillate in a moving airstream.

In England, during the 1920’s, Frazer and Duncan developed the first theoretical formulation to the flutter problem and used wind tunnel measurements for the necessary aerodynamic derivatives. Their work at the Royal Aeronautical Establishment (RAE) began activities that established RAE as a leader in this area for several decades. Frazer and Duncan’s report “The Flutter of Aeroplane Wings,” known popularly as the “Flutter Bible,” became an established reference for many years.

There are two classes of design problems that are encountered in this area. The first and most common to all flight vehicles is the effect of elastic deformation on the airloads associated with normal operating conditions. These effects can have a profound influence on the performance, handling qualities, flight stability, structural load distribution, and control effectiveness/reversal phenomena. The second class of problems involves the potential for static instability of the structure that will result in a catastrophic failure. This instability is often termed “divergence” and can impose a limit on the flight envelope.

Divergence: **C**onsider a rigid, spanwise-uniform model of a wing that is mounted to the side walls of a wind tunnel in such a way as to allow the wing to pitch about the support axis, as illustrated in Figure-8. The support is flexible in torsion, which means that it restricts the pitch rotation of the wing in the same way as a rotational spring would.

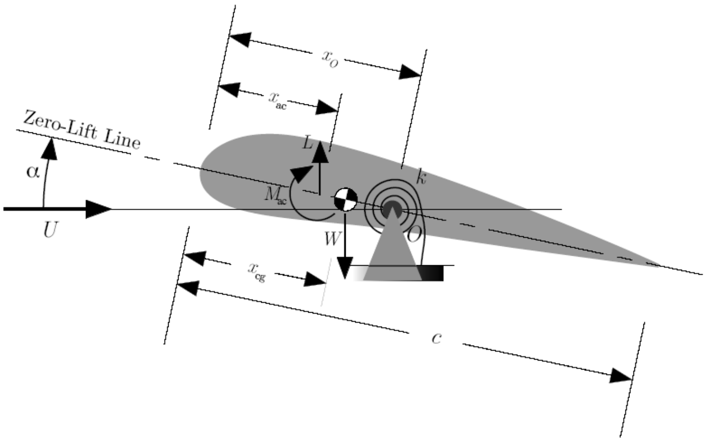


Figure-8: Rigid, Spanwise-uniform Model

Equilibrium equation about elastic axis is:

$$M_{ac} + L\left(x_O - x_{ac}\right) - W\left(x_O - x_{cg}\right) - k\theta = 0$$

After substantiation expression of each parameter, we obtain the resultant angle due to aeroelastic:

$$\theta = \frac{qScC_{M_{ac}} + qSC_{L_\alpha}\alpha_r\left(x_O - x_{ac}\right) - W\left(x_O - x_{cg}\right)}{k - qSC_{L_\alpha}\left(x_O - x_{ac}\right)}$$

When the support point O is aft of the aerodynamic center, so that xO > xac, the denominator can vanish, which implies that θ blows up. This behavior is a static aeroelastic instability called "divergence."

So for an engineer, it is necessary checks his plane for initial estimation or prevention of this instability. Aerodynamic parameter from initial performance calculation and stiffens of wing from F.E. software, a people can check the denominator of above equation.

Aileron reversal: **w**e here consider the problem of aileron reversal (figure-9). It is known that wing torsional flexibility causes certain primary flight control devices, such as ailerons, to function in a manner that is completely at odds with their intended purpose.

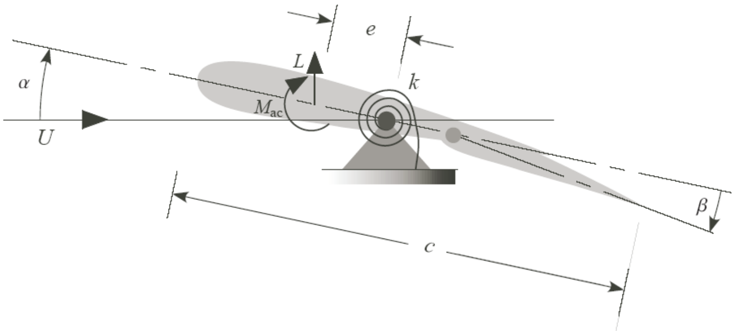


Figure-9: Wing Model for Aileron Reversal

Consider the airfoil section of a flapped two-dimensional wing. Similar to the model, the wing is pivoted and restrained by a rotational spring with spring constant k. Moment equilibrium for this system about the pivot requires that

$$M_{\mathrm{ac}} + eL = k\theta$$

We substitute necessary equations and determine θ. We know that because of the torsional flexibility (represented here by the rotational spring), θ is a function of β. Substituting one obtains an expression for the aeroelastic lift

$$L = \frac{qS\left[C_{L_\alpha}\alpha_{\mathrm{r}} + C_{L_\beta}\left(1 + \frac{cqSC_{L_\alpha}C_{M_\beta}}{kC_{L_\beta}}\right)\beta\right]}{1 - \frac{eqSC_{L_\alpha}}{k}}$$

However, as dynamic pressure increases, the aeroelastic effect becomes stronger; and there is a point at which the net rate of change of lift with respect to β vanishes so that

$$\frac{\partial L}{\partial \beta} = 0 = \frac{qSC_{L_\beta}\left(1 + \frac{cqSC_{L_\alpha}C_{M_\beta}}{kC_{L_\beta}}\right)}{1 - \frac{eqSC_{L_\alpha}}{k}}$$

Thus, one finds that the rotational spring constant k at which the reversal occurs is

$$k = -\frac{q_R cSC_{L_\alpha}C_{M_\beta}}{C_{L_\beta}}$$

Notice that since $C_{M\beta} < 0$, K > 0.

Torsional stiffens is function of aerodynamic and flight dynamic parameter, so we can obtain it and compare with the stiffens from F.E. calculation.

3.3 Predication–Research

In this section we collected some of researches about applied aeroelastic of different projects.

CF-105 Structure: The structure of the CF-105 is relatively conventional, but the thin low aspect ratio delta configuration and the two engines buried in the fuselage have introduced a number of interesting structural problems. In the WING Vibration modes were calculated by a matrix iteration method from a 60-point matrix. A number of methods of calculating flutter were tried, and we came to the conclusion that a conventional strip theory analysis using two-dimensional derivates was inadequate for highly swept wings, and that a form of lifting surface theory was required. The aircraft's flutter speed appeared to be dependent on the fuselage bending and torsional stiffness, with the wing torsional stiffness playing a secondary role. In the FIN and RUDDER the results showed that flutter should be no problem on the fin, providing the rudder frequency was kept to twice the fundamental bending frequency. A steam-wise strip method was used for the supersonic analysis.

Aeroelastic aspects for the assessment of F-16 fatigue life consumption: This work is aimed at the analysis of aerodynamic characteristics relevant to aeroelastic aspects and limit loads for the assessment of F-16 fatigue life consumption. As part of the ongoing military AESIM (Aeroelastic Simulator) investigation towards the understanding and modeling of non-linearaeroelastic phenomena, such as transonic dip and limit cycle oscillation, various time-accurateviscous flow simulations have been carried out Using the ENFLOW system. Further analysis of simulation results has led to the conclusion that the phase difference between the aerodynamic pressures and the structural motion is a key issue in assessing the amount of energy that is being transferred from the flow to the F-16 aircraft structure.

Aeroelasticity, Aerothermoelasticity and Aeroelastic Scaling of Hypersonic Vehicles: This final report describes the work during the period of the grant. Three separate hypersonic aeroelastic stability problems were considered: (a) a typical cross section having a double wedge airfoil, (b) the stability of a low aspect ratio wing, also with a double wedge airfoil, and (c) the behavior of a complete generic hypersonic vehicle. For problems (a) the unsteady airloads were computed using third order piston theory, as well a CFD based Euler and Navier- Stokes loads. For case (b) piston theory, Euler and Navier-Stokes based airloads were used, and case (c) both piston theory and Euler airloads were used. For the three-dimensional wing the treatment of thermal effect was also considered by solving the heat transfer problem using the Navier Stokes equations to determine the temperature distribution over the vehicle and conducting an aeroelastic analysis that accounts for the effect of thermal stresses and material degradation on the mode shapes. These mode shapes were used in an aeroelastic analysis based on 3rd order piston theory. This comprehensive treatment of the aerothermoelastic problem, the first of its kind in the literature, produces large reductions in aeroelastic stability margins. The results indicate that the flutter boundaries for third order piston theory can differ by 35% from those based on Euler unsteady loads. Solutions based on the loads obtained from the solution of the Navier-Stokes equation indicate further changes in aeroelastic stability margins. Important conclusions for the design of such vehicles are summarized in the body of the report.

Flutter Control of an Adaptive Laminated Composite Panel with Piezoelectric Layers: A new finite element formulation of an adaptive composite laminated panel with piezoelectric sensors and actuators is presented. Classical laminated theory with electromechanical induced actuation and variational principles are used to formulate the equations of motion. The finite element model based on the bilinear Mindlin plate theory with 24 structural degrees of freedom and one electrical degree of freedom per piezoelectric layer is much simpler and computationally more efficient than models based on solid element formulations with a significant decrease in the number of degrees of freedom. The numerical results from simulations agree well with data reported in the literature. Next, the effectiveness of using the adaptive composite panel to control panel flutter is examined. First order piston theory is used to model the supersonic flow. The piezoelectric actuators are used passively to induce inplane forces to alter the panel stiffness characteristics. The results show that piezoelectric devices can significantly increase panel flutter velocities. However, it was found that the added mass to stiffness ratio and the piezoelectric patch configuration are two factors affecting actuator performance.

Flutter control of incompressible flow turbomachine blade rows by splitter blades: Splitter blades as a passive flutter control technique are investigated by developing a mathematical model to predict the stability of an aerodynamically loaded splittered-rotor operating in an incompressible flow field. The splitter blades, positioned circumferentially in the flow passage between two principal blades, introduce aerodynamic and/or combined aerodynamic-structural detuning into the rotor.

And some other contents …

Controller Design for Unstable Aeroelastic Systems
Authors: Hitay Ozbay; OHIO STATE UNIV COLUMBUS DEPT OF ELECTRICAL ENGINEERING

Development of Preliminary Design Models for Active Aeroelastic Wing Application
Authors: Frank Eastep; CSA ENGINEERING INC PALO ALTO CA

Flutter Control of Wing Boxes Using Piezoelectric Actuators
Authors: Edwin E. Forster; PURDUE UNIV LAFAYETTE IN SCHOOL OF AERONAUTICS AND ASTRONAUTICS

Supersonic Flow Past Two Oscillating Airfoils
Authors: Georgios Alexandris; NAVAL POSTGRADUATE SCHOOL MONTEREY CA

Supersonic Flutter of Simply Supported Isotropic Sandwich Panels
Authors: Larry L. Erickson; Melvin S. Anderson; NATIONAL AERONAUTICS AND SPACE ADMINISTRATION HAMPTON VA LANGLEY RESEARCH CEN TER

The Aeroelastic Effects of Transverse Shear Deformation on Composite Wings in Various Speed Flow Regimes
Authors: Michael Oliver; NAVAL ACADEMY ANNAPOLIS MD DEPT OF AEROSPACE ENGINEERING

Flutter Prevention Handbook: A Preliminary Collection
Authors: D. D. Liu; Sarhaddi; F.M. Piolence; L.S. Wasserman; W. Roberts; ZONA TECHNOLOGY INC MESA AZ

3.4 Predication–Finite Element Programs

Subsonic Aerodynamic Flutter (SAF): This program can accurately predict flutter speed with the **EMRC-NISA** finite element analysis program and SAF flutter computer program which run on Windows 95/98/2000/XP.

A flutter analysis is performed by setting up a very detailed finite element analysis (fea) model of the structure to find the eigenvalues and mode shapes. The control surface weights and control stiffness of the fea model are matched to those of the actual aircraft.

The mode shapes from the fea are input into our **Subsonic Aerodynamic Flutter** (SAF) program to determine the critical flutter speeds. Balanced control surfaces, altitude and fuel load are some of the parameters that influence flutter speeds. We have made flutter analysis affordable. Be safe and fly safe.

This is the animated fuselage bending mode of the original BD10 Jet which crashed. The fuselage bending occurs at a frequency of 27.3 Hz and couples with horizontal tail twisting (figure-10). The flutter analysis predicted the exact critical flutter speed. ADI increased the critical flutter speed by rigidly fixing the horizontal tail and stiffening the tail and fuselage structures.

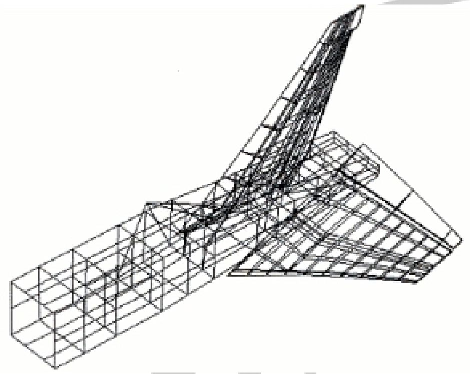


Figure-10: Horizontal Tail Twisting Mode Couple with Fuselage Bending Mode

This is the finite element model for the Lancair 360 with the large tail. The back of the fuselage required stiffening to increase the critical flutter speed (figure-11). Some builder have opted not to make this very simple modification. There is an old saying, "You can lead a horse to water but you cannot make him drink!"

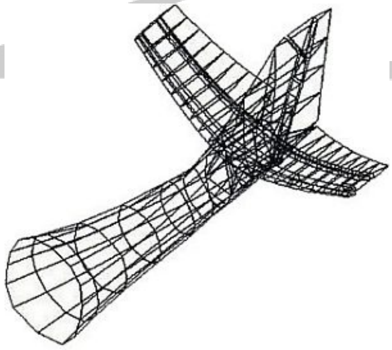


Figure-11: Fuselage Bending Mode

MSC/NASTRAN AEROELASTIC ANALYSIS USER'S GUIDE, VERSION 68(book):

By William P. Rodden and Erwin H. Johnson

CHAPTER 5 - OUTPUT FEATURES AND INTERPRETATION
CHAPTER 6 - AEROELASTIC SOLUTION SEQUENCES
CHAPTER 7 - STATIC AEROELASTIC ANALYSIS SAMPLE PROBLEMS
CHAPTER 8 - FLUTTER ANALYSIS SAMPLE PROBLEMS
CHAPTER 9 - DYNAMIC AEROELASTIC RESPONSE ANALYSIS
CHAPTER 10 - AEROELASTIC DESIGN SENSITIVITIES AND OPTIMIZATION

3.5 Control

Aeroelastic interaction can be controlled to suppress the interactions or to use the interaction to improve performance. Control of aeroelasticity depends on the continued development of new materials, sensors and actuators, integrated analytical tools and, most importantly, the same human inquisitiveness and creativity that has driven aircraft design for over a century.

Wright Brothers incorporated pilot-controlled airload-wing: The Wright Brothers incorporated pilot-controlled airload-wing twist interaction into the design of their 1903 Wright Flyer to control lateral (roll) attitude. Today designers provide this control with ailerons. However, torsional flexibility was intentionally designed into the outer wing bays to allow a control cradle, operated by the prone pilot's hip movements, to transmit loads to move cables attached to the wings. Movement of these cables created differential wing twist or "warping" of the biplane wings to create an aircraft rolling moment.

The Bleriot XI braced monoplane: In 1909 Bleriot flew across the English Channel from France at a speed of about 60-mph. The Bleriot XI was an externally braced monoplane with wing warping control (Figures-12).

Figure-12: Bleriot XI Monoplane

As engine power and airspeed increased this low stiffness created aeroelastic problems that led to wing failures since the wings were easier to twist at high speeds than at low speeds. The torsionally flexible wings allowed pilot to twist the wing tips easily at high speeds and accidentally overload the wing.

AEROELASTIC TAILORING (Aeroelastic Passive Control): Aeroelastic tailoring is the design of wings using the directional properties of composite materials to optimize aeroelastic performance. The concept of aeroelastic tailoring is relatively new and came into the forefront during the design of forward-swept wings in the 1980s. The low divergence speed was a major hurdle in the design of wings with forward sweep. As will be seen in this section, use of composite materials can help remove the disadvantages of forward sweep. Presently, aeroelastic tailoring is an integral part of composite wing designs and can be used to provide optimum performance. Composite materials are anisotropic, which implies different material characteristics (such as stiffness) in different directions.

Tailoring concepts build on the original Wright Flyer pilot controlled wing warping concept, but differ in that the pilot control is the feedback mechanism for load deformation interaction, while tailoring uses a passive, built-in aero/structure feedback that naturally occurs when flight loads are applied. Modern tailoring depends on advanced composite materials and the ability of a designer to control ply orientation during the design of the aircraft so that requirements other than strength can be addressed.

A recent study found that, over a broad range of airspeeds, wing induced drag can be reduced with either passive wing aeroelastic tailoring or active control actuators. When used in combination, induced drag can be minimized with minimal actuator input if the structure is tailored properly. Thus, a combination of structural tailoring and control surface design can actively reduce drag if aeroelastic features are exploited.

There is a strong relationship between the energy required to operate trailing edge controllers and the direction of primary laminate plies. Because of the favorable effects of tailoring on aileron effectiveness, it is better to operate near the divergence airspeed for the wing. These concepts depend on the development of nontraditional actuators. The use of so-called smart actuators in wing surfaces for distortion control has been investigated for about 10 years. Advanced actuators, including piezoelectric devices with "smart" structures have been proposed for small airplane control. These materials and devices are experimental and have been developed in isolation. The development of such devices and the innovative employment on air vehicles is an important development for the future.

Favorable propeller performance: In another example, Professor Max Munk, then at the Catholic University of America in Washington, D.C., used aeroelastic deformation to provide favorable propeller performance. This design, shown in Figure-13, was patented in 1949. Munk proposed directionally laminated plywood with a wood grain directionally oriented to provide spanwise anisotropy. Bending due to lift and centrifugal effects caused the propeller to twist nose-down so that lift, in this case propeller thrust was decreased at high speeds. As a result there was an automatic, passive, favorable propeller pitch change without a mechanical device needed. Wind tunnel tests verified increased propeller performance predictions for the tailored grain orientation.

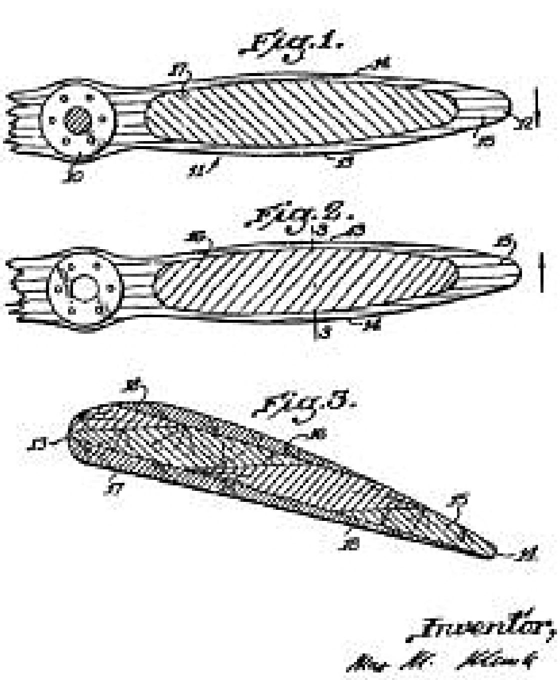


Figure-13: Max Munk Propeller

Orienting the skin laminate: The initial ideas for tailored advanced composite lifting surfaces originated at the Fort Worth Division of General Dynamics Corporation. The General Dynamics group included people such as Charlie Rogers, Max Waddoups, Arnie McCullers, Mike Love and Bill Rogers, to name only a few.

They recognized that coupling between bending and torsion deformation could be introduced by orienting the skin laminate in certain beneficial directions, as indicated in Figure-14.

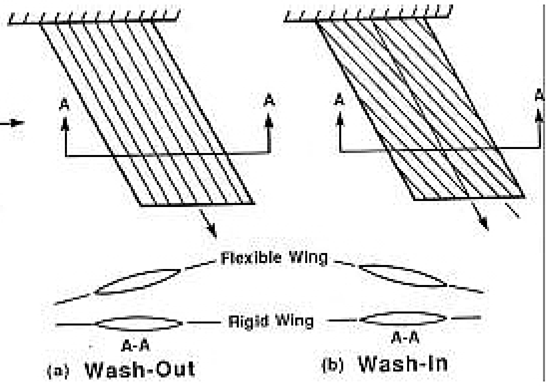


Figure-14: Wing Layer Tailoring

In Fig (a) the primary stiffness of the wing is oriented along the wing's swept axis. Air loads induce mostly bending, which in turn create a geometric nose down twist with respect to the freestream. This is called *wash-out*. Laminates oriented as indicated in Figure-14(b), introduce coupling between bending and torsion so that the wing bends upward and also must twist in the nose-up direction. This creates *wash-in*. In Figure-14(a) we reduce the airload when the wing bends, while in Figure-14(b) we the add part of the airload back because twist accompanies wing bending. The stiffness orientations required to obtain benefits are summarized in Figure-15.

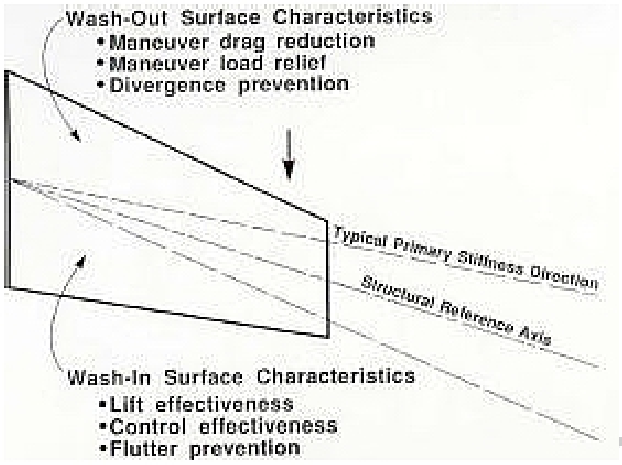


Figure-15: Stiffness Orientations of Wing

The Forward Swept Wing Project: An excellent example of successful innovation with advanced composites and integrated design was the development of the X-29 forward swept wing aircraft shown in Figure-16. The result was an unstable aircraft.

Figure-16: X-29 Swept Forward

An engineer was working on a research grant from NASA Ames Research Center to study aeroelastic features of oblique wing, supersonic transport aircraft. The object of this project was to optimize the aluminum structure to prevent wing divergence and reduce weight. Krone's found details on the design of the German Junkers Ju-287 bomber with forward swept wings. Figure-17 summarizes the important results from Krone's thesis (the airplane was added for emphasis). It shows that the tendency of forward swept wings to diverge creates the need for increased stiffness and weight – if the material is metallic.

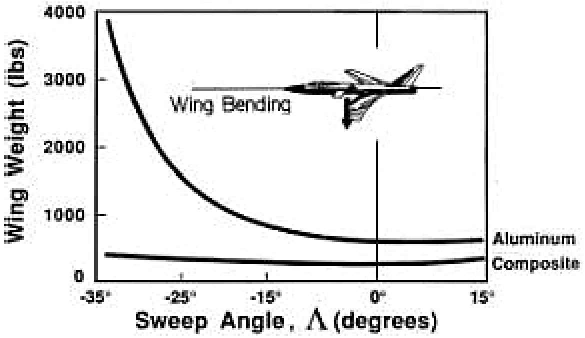


Figure-17: Summarize of Krone's Ph.D. thesis

This occurs because the wing bending creates an increased angle of attack, increased airloads and when the airspeed is high enough – an overturning moment that cannot be resisted by the structure. As indicated in Figure-17, at zero sweep the wing with composite material requires less weight since the composite material has higher allowable stress.

However, we also notice that the composite structural weight required is relatively insensitive to forward sweep angle. Krone found that the need for divergence prevention could be satisfied if the composite laminate was designed to introduce more bend twist coupling so that upward bending induced airloads were reduced by inducing nose-down twist to create wash-out. The X-29 success created an astounding amount of interest in aeroelastic tailoring and launched other tailoring studies.

(Ph.D. thesis was called "the most expensive Ph.D. thesis" ever funded by the U.S. Air Force)

On the other hand, composite structures using carefully controlled arrangements of graphite and other exotic fibers are much stiffer than aluminum or steel, and can even be made to deform under load in such a way as to reduce aerodynamic loads and therefore the chance of flutter.

wing with an inboard chordwise hinge: In his review paper "The First Fifty Years of Aeroelasticity" Collar mentions an application of bending induced load relief, normally associated with swept wings, that can be designed into an unswept wing. According to Collar, French designers before

World War II proposed an unswept, hinged wing design. This wing had an inboard chordwise hinge skewed towards the rear part of the fuselage to force the wing to bend about the hinge-line; this hinge line rotation was to be constrained by stiff springs. As a result, downward bending would cause increased lift, just as in the case of a modern swept wing. Rolling power was to be provided by an elevon control of the tail. A rolling moment applied at the tail would then produce inertia loads to create wing deformation that in turn would produce an additional flexibility induced angle of attack and roll moment on the wing. The result was an automatic structurally induced geometrical wing warping effect. During normal flight gusts would also cause the wing to relieve itself of load; landing forces would induce cushioning lift. Hinge design and spring constraint difficulties precluded actual design of the wing

Electronic flight: Increasingly, new fighter and transport designs rely on electronics for stability and control, and in some cases for flutter prevention as well. The F-16, for example, is prone to a non-destructive wing flutter when carrying certain combinations of external loads. The wings flap out of phase the left wing goes down while the right one goes up—imparting a rocking motion to the fuselage. Rather than modify the wing, researchers at the U.S. Air Force flight testing facility at Edwards Air Force Base in California programmed the fighter's electronic flight control system to sense the flutter and use the ailerons to oppose the wing's flexing. The fix, which will be incorporated in a flight control software upgrade scheduled for 2002, is indicative of what electronic flight controls can do. But they are not a panacea for flutter; the number of control surfaces available on an airplane's wings and tail falls far short of the number of possible flutter modes they can exhibit.

Reshaping the spanwise lift distribution with an internal mechanism: At about the same time, programs like the Transonic Aircraft Technology Program (TACT) had performance optimization objectives involving limit load maneuvering; this required actively reshaping the spanwise lift distribution with an internal mechanism for chordwise wing bending to force variable camber shapes. Through camber control, drag polars were reshaped to reduce drag at operational airspeeds and to reduce critical wing bending moments. The constant span drag reduction objective translates into making the spanwise lift distribution as close to elliptical as possible, as long as strength requirements are not violated. The internal mechanisms required to do this reshaping were heavy and literally "outweighed" their benefits. Recently, a procedure to control drag by aileron/flap deflection on an L-1011 aircraft was tested by NASA Dryden. This procedure used real-time performance optimization and in-flight measurements to reduce drag on an L- 1011 test aircraft. This scheme used a pair of symmetrical ailerons.

Active torque tube: The idea of controlling aerodynamic performance by active, mechanically controlled distortion of wings is not new. For instance, in 1979, Elber[25] filed a patent entitled *"Means for Controlling Aerodynamically Induced Twist."* His controller was an active torque tube located inside the wing so that it could twist the wing tip to root to control the tendency of swept wings to lose lift effectiveness. He did not claim to directly control drag.

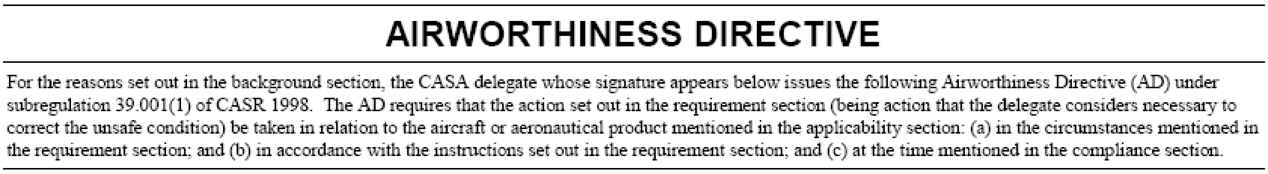
Active/passive control - active materials/adaptive actuators: Two other innovative approaches to active/passive control of aerodynamic performance are worth mentioning. The first is the use of active material and adaptive actuators for aeroelastically leveraged control. This control includes rolling and climbing, as well as control of transonic drag. Second, there has been interest in improving lateral roll authority by intentionally reducing stiffness (the Active Flexible Wing/Active Aeroelastic Wing) and then controlling the aeroelastic response. The active aeroelastic wing concept has been studied extensively for at least fifteen years. This aircraft control approach allows a wing control system to be so flexible that it will reverse and then be actively controlled. It was the subject of a patent filed by Tulinius in 1990 and granted in 1992. The intent of this effort was to provide a control system that was effective beyond the normal aileron reversal speed, not necessarily to focus on decreased drag itself.

"Smart" materials: Discernible in the future are "smart" materials that expand or contract slightly in response to electrical signals. "They're like muscles," says Tom Noll, head of the aeroelasticity branch at NASA's Langley center. "They're normally in a neutral state, but they can be 'flexed' when extra stiffness or resistance to deformation is needed." Another possible weapon against flutter comes from the new field of MEMS—micro electro-mechanical systems. Thin surface overlays could raise thousands of tiny spoilers on an electrical command, disrupting airflow and preventing the aerodynamic augmentation that is fundamental to flutter.

Finally, the infancy of an effort to develop “smart wings” or “morphing aircraft” has led us to dream about air vehicles for very different uses and with very different shapes and shape control. Aeroelasticity will play an essential role in this effort.

Airworthiness Directive Schedule DHC-3-040 Elevator Trim Tab Assembly:

COMMONWEALTH OF AUSTRALIA *(Civil Aviation Safety Regulations 1998)*, PART 39 - 105
CIVIL AVIATION SAFETY AUTHORITY
SCHEDULE OF AIRWORTHINESS DIRECTIVES



AIRWORTHINESS DIRECTIVE

For the reasons set out in the background section, the CASA delegate whose signature appears below issues the following Airworthiness Directive (AD) under subregulation 39.001(1) of CASR 1998. The AD requires that the action set out in the requirement section (being action that the delegate considers necessary to correct the unsafe condition) be taken in relation to the aircraft or aeronautical product mentioned in the applicability section: (a) in the circumstances mentioned in the requirement section; and (b) in accordance with the instructions set out in the requirement section; and (c) at the time mentioned in the compliance section.

DHC-3 (Otter) Series Aeroplanes

AD/DHC-3/40 Elevator Trim Tab Assembly 4/2006

Applicability: Model DHC-3 “Otter” turbine-powered aircraft which incorporate Supplemental Type Certificate (STC) SA01-111, SA89-32, or SA02-15.

Requirement: Install one of the following elevator flutter prevention kits:

a. Viking Air Ltd. Retro Kit No. V3MK1148 Issue 3, or later Transport Canada approved revision; in accordance with Viking Air Ltd. STC SA99-219 Issue 3, or later Transport Canada approved revision;

b. American Automotives Inc STC SA01059SE with new elevator servo-tab and redundant control linkage; or

c. Other modifications, approved by Transport Canada, designed to prevent the elevator servo-tab flutter.

Compliance: Within 300 flight hours after 13 April 2006 or before 31 May 2006, whichever occurs first. This Airworthiness Directive becomes effective on 13 April 2006.

Background: Transport Canada received several reports of incidents on turbine-powered DHC-3 aircraft whereby the control rod of the elevator servo-tab system detached from the servo-tab. This failure can cause severe flutter of the elevator servo-tab and could lead to loss of control of the aircraft.

Turbine engines are more powerful, allow for a higher cruise speed, and therefore may reduce the elevator servo-tab flutter margins. This Directive requires installation of a kit to reduce the probability of elevator servo-tab failure due to flutter.

Human Power Airplane: Both the I-beam spars and the styrene paper mentioned in Mark Drela’s review were reinforced with carbon fiber. The result was an aircraft that could fly (at a height of 2 meters) needing only 160 watts of power input to the pedals, a world minimum for an HPA. Yoshikawa wrote, “It has a composite structure, CFRP on spar and GFRPed styrene paper on skin.” He wrote also that the team is “working to realize a new circling method,” described thusly: “The new circling method is by twisting the flexible wings during banking by applied aeroelasticity. “The twist of the right wing is applied in the opposite direction of that of the left wing. This has been found to reduce power loss during the HPA’s turn.” Circling flight is difficult because of the greatly increased power losses and the control difficulty in the turns. (The “inside” wing goes much slower than the outer wing and tends to lose lift.) Stressed-skin construction allows the use of wing warping (in opposite directions) during the turn. It also greatly reduces wing deflection and permits the use of a very high aspect ratio, 43.7, further reducing the aerodynamic losses.

3.6 Prevention–regulations

Flutter is not a recent phenomenon; aeronautical engineers detected it and developed its prevention in the 1920s. They found that adding weight to the control surface (ahead of the hinges, so the CG of the combination moved forward to the hinge line) would prevent flutter. It is called "control-surface mass balancing."

An manufaturer engineer of home built airplane isn't a aeroelastician or perhapes he don't know about aileron reversal and divergance. So he need a simple means/tehnique to evaluate and check his airplane. A small airplane manufacture company can't be support many aeroelastic research up to approve that its airplane is free from flutter. So both need a approved regulations with simple method (but overestimate) to check there vehicles. Here, we introduce briefly subpart D of Federal Aviation regulations for this purpose.

Subpart D - Design and Construction - Sec. 23.629 – Flutter (briefly)

> [(a) It must be shown by the methods of paragraph (b) and either paragraph (c) or (d) of this section, that the airplane is free from flutter, control reversal, and divergence for any condition of operation within the limit V-n envelope and at all speeds up to the speed specified for the selected method. In addition--]
>
> (1) Adequate tolerances must be established for quantities which affect flutter, including speed, damping, mass balance, and control system stiffness; and
>
> (2) The natural frequencies of main structural components must be determined by vibration tests or other approved methods.
>
> [(b) Flight flutter tests must be made to show that the airplane is free from flutter, control reversal and divergence and to show that--]
>
> (1) Proper and adequate attempts to induce flutter have been made within the speed range up to VD;
>
> (2) The vibratory response of the structure during the test indicates freedom from flutter;
>
> (3) A proper margin of damping exists at VD; and
>
> (4) There is no large and rapid reduction in damping as VD is approached.
>
> [(c) Any rational analysis used to predict freedom from flutter, control reversal and divergence must cover all speeds up to 1.2 VD.]
>
> d) Compliance with the rigidity and mass balance criteria (pages 4-12), in Airframe and Equipment Engineering Report No. 45 (as corrected) "Simplified Flutter Prevention Criteria" (published by the Federal Aviation Administration) may be accomplished to show that the airplane is free from flutter, control reversal, or divergence if
>
> (1) VD/MD for the airplane is less than 260 knots (EAS) and less than Mach 0.5,
>
> (2) The wing and aileron flutter prevention criteria, as represented by the wing torsional stiffness and aileron balance criteria, are limited in use to airplanes without large mass concentrations (such as engines, floats, or fuel tanks in outer wing panels) along the wing span, and
>
> (3) The airplane:
>
> [(i) Does not have a T-tail or other unconventional tail configurations;]
>
> (ii) Does not have unusual mass distributions or other unconventional design features that affect the applicability of the criteria, and
>
> (iii) Has fixed-fin and fixed-stabilizer surfaces.
>
> (e) For turbopropeller-powered airplanes, the dynamic evaluation must include—
>
> (1) 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, and
>
> (2) Propeller, engine, engine mount, and airplane structure stiffness and damping variations appropriate to the particular configuration.

(f) Freedom from flutter, control reversal and divergence up to VD/MD must be shown as follows:

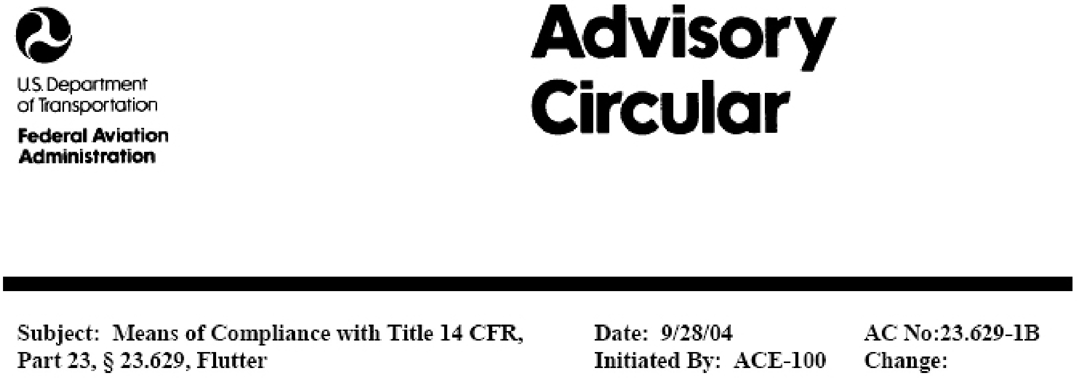
(1) For airplanes that meet the criteria of paragraphs (d)(1) through (3) of this section, after the failure, malfunction, or disconnection of any single element in any tab control system.

(2) For airplanes other than those described in paragraph (f)(1) of this section, after the failure, malfunction, or disconnection of any single element in the primary flight control system, any tab control system, or any flutter damper.

[(g) For airplanes showing compliance with the fail-safe criteria of Secs. 23.571 and 23.572, the airplane must be shown by analysis to be free from flutter up to VD/MD after fatigue failure, or obvious partial failure, of a principal structural element.

(h) For airplanes showing compliance with the damage tolerance criteria of Sec. 23.573, the airplane must be shown by analysis to be free from flutter up to VD/MD with the extent of damage for which residual strength is demonstrated.

(i) For modifications to the type design that could affect the flutter characteristics, compliance with paragraph (a) of this section must be shown, except that analysis based on previously approved data may be used alone to show freedom from flutter, control reversal and divergence, for all speeds up to the speed specified for the selected method.]



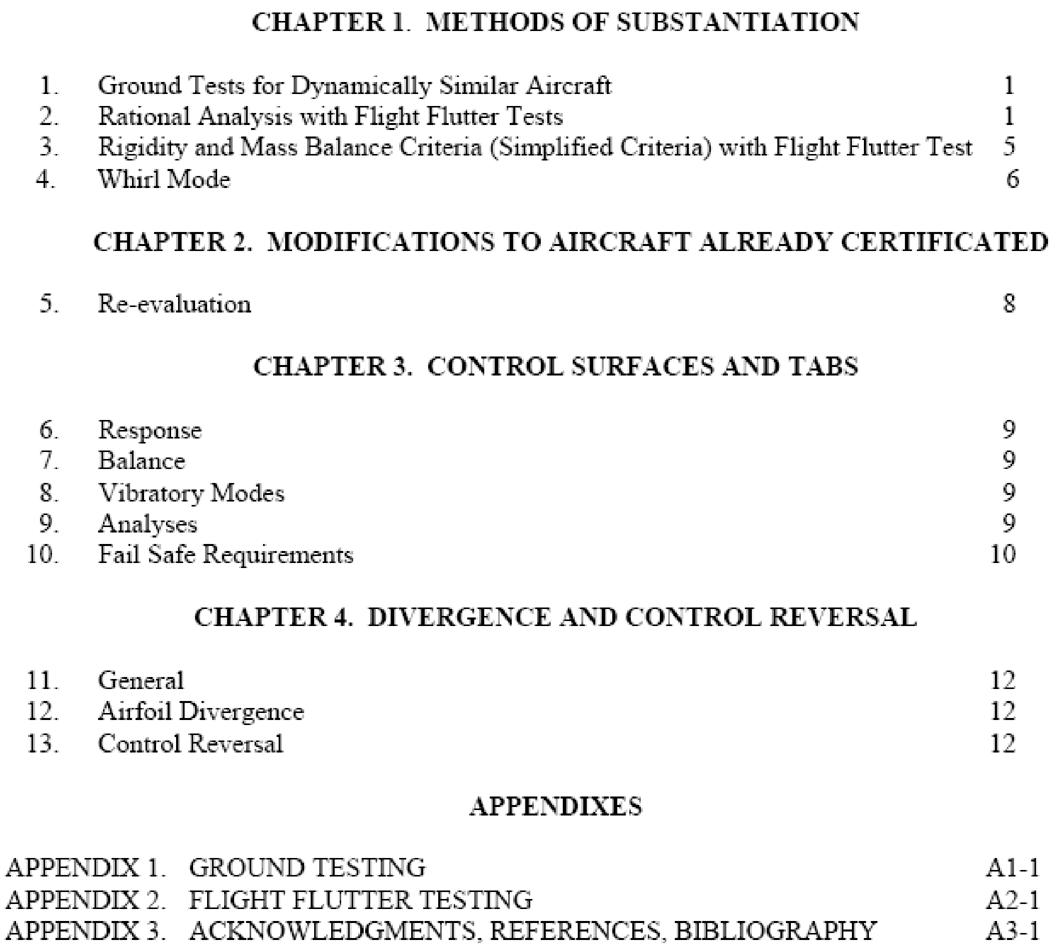
U.S. Department
of Transportation
Federal Aviation
Administration

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:**

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.

For example, the contents of this AC are:



CHAPTER 1. METHODS OF SUBSTANTIATION

CHAPTER 2. MODIFICATIONS TO AIRCRAFT ALREADY CERTIFICATED

CHAPTER 3. CONTROL SURFACES AND TABS

CHAPTER 4. DIVERGENCE AND CONTROL REVERSAL

APPENDIXES

For example, the text of that section:

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).

……….

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

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 VD

(2) A wing torsional flexibility factor, F, is defined and a limit established as a function of VD. 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 …

……….

d. Tabs. In accordance with reference 1, all reversible …

……….

4. WHIRL MODE. (23.629(e))

……….

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

About the Control Surfaces And Tabs Balance:

……….

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.

……….

About The Divergence and Control Reversal

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

About GROUND TESTING

……….

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.

……….

About the control surface without mass balance in airplanes with category FAR-25:

Report no. ANM100-2000-00106

Federal Aviation Administration

Free-play limits and inspection procedures for flutter prevention, § 25.629 and Advisory Circular (AC) 25.629-1A

The FAA has historically considered the very conservative free-play limits of Military Specification MIL-A-8870 to provide assurance of freedom from vibration and has accepted these limits for certification without further question. However, in many cases, these limits are considered too conservative and too small to be practically controlled in a realistic service environment. In such cases the manufacturers have provided analyses and/or flight tests to confirm the adequacy of the larger amounts of free-play.

Service experience is showing that some of the free-play check procedures that have been established during certification may not be reliable for checking for all the relevant free-play in the system. Free-play in the control surface hinges as well as in the actuator attachments all contribute to the total surface free-play and the check procedure must be able to reliably measure the total free-play. One factor affecting the ability to check for free-play is the large size of the main control surfaces. For small tabs, the inspector could simply move the surface with a hand while using a dial indicator to measure trailing edge motion. With the unbalanced main control surfaces it takes a much greater force to move them and for the surfaces envisioned for larger airplanes it may be impossible to check for free-play without some automatic powered means.

Advisory Circular (AC) 25.629-1A guidance of the FAA is inadequate and not standardized when applying these airworthiness requirements to certain unbalanced control surfaces. The following memorandum provides interim guidance and standardized methods of compliance to support the design, certification, and continued airworthiness of unbalanced control surfaces until the FAA revises AC 25.629-1A(above maintained). Of Course the current guidance is inadequate for validating maintenance requirements during certification.

The FAA has also accepted higher freeplay limits than the military limits when based on service experience or flight test. However, in some cases the presence of freeplay in control surfaces was not addressed until excessive vibration resulted.

Interim Guidelines.

a. Freeplay In Control Surface Design

Section 25.629 requires that control surfaces and tabs, actuating systems and supporting structure be designed such that the airplane is free from aeroelastic instability and will not result in an aeroelastic LCO (freeplay-induced vibration) in any airplane configuration during normal operation in any phase of flight.4

Meeting one or more of the following conditions will satisfy this requirement:

(1) The control surface or tab is demonstrated by analysis or test to be free from flutter to V_D/M_D with all restraint stiffness and damping lost.

(2) The control surface in-service freeplay limits will not exceed the values established using the criteria in section b, below, “Freeplay Limits For Unbalanced Control Surfaces,” throughout the service life of the airplane.

(3) The control surface in-service freeplay limits will not exceed the values established using the criteria in section b. Additionally, a design feature(s) is provided to compensate for the loss of restraint in the control system due to freeplay.

i. The design feature may be a structural element added in parallel with the control system to provide adequate restraint stiffness to preclude freeplay-induced vibration. It should be established that the design feature is effective over the permitted range of freeplay expected to occur in service.

ii. The compensating feature for some designs may be a continuous aerodynamic loading of the control surface. For such a design, it should be shown by tests or analyses that the aerodynamic loading is sufficient in any phase of flight with the control surface at the in-service freeplay limits.

b. Freeplay Limits For Unbalanced Control Surfaces

In-service freeplay limits should be established for all control surfaces that depend on the retention of stiffness to comply with the aeroelastic stability requirements of *§ 25.629*. The criteria of military specification MIL-A-8870C, reproduced below, provide acceptable limits of freeplay. These may be used without additional substantiation.

Trailing Edge Control Surface	Extends outboard of 75% main surface span – 0.13 degree	Extends outboard to between 50% to 75% main surface span – 0.57 degree	Extends outboard to less than 50% main surface span – 1.15 degree
Tab	Tab span equal to or greater than 35% control surface span – 0.57 degree	Tab span less than 35% control surface span – 1.15 degree	
All-movable Control Surface	0.034 degree		

CONTROL SURFACE AND TAB IN-SERVICE FREEPLAY LIMITS

Aircraft have demonstrated acceptable service experience using freeplay limits greater than those in MIL-A-8870C. If those control surfaces are used on a new derivative model with similar aeroelastic characteristics, the same freeplay limits may be applied without additional substantiation.

For new or modified control surfaces, MIL-A-8870C limits may be too small to be practically controlled in a realistic service environment. In such cases, the applicants may provide analyses and/or flight tests to confirm the adequacy of larger freeplay limits. For these larger freeplay limits, the applicants should verify the absence of freeplay-induced vibration by flight or wind tunnel test to VDF/MDF, and/or by aeroelastic analysis to VD/MD using a configuration containing the proposed in-service freeplay limits. They should use a validated method of analysis, as described in section c, for verification.

The applicant should establish reliable inspection procedures during certification and validate them by engineering test, which would include a determination of load versus deflection characteristics to isolate freeplay from elastic deformation of the airframe. The applicant should assess the human factors of the inspection procedure to avoid the possibility of not measuring freeplay accurately.

Control surfaces vary in size and weight so inspection procedures are generally tailored for each surface. For small tabs, an inspector can simply move the surface with his hand while using a dial indicator to measure trailing edge freeplay. On the other hand, it might be impossible to check for freeplay in large unbalanced control surfaces without the assistance of ground equipment to move the surface. Some manufacturers have employed automatic powered means, including on-board systems that check or continuously monitor freeplay

NOTE:

Three major areas of flutter testing: flutter model design, flight flutter testing and ground vibration testing. Another approach to flutter analysis is testing scale models in a wind tunnel. This is tricky, requiring duplication in the proper scale of not only the geometry of the airplane but the mass and elastic characteristics as well.

Figure-18: Static load test - Boeing 767

Weight- and cost-conscious full-scale designers add only sufficient weight to prevent flutter at slightly beyond the "never exceed" speeds of their designs. For model aircraft, full balancing to the hinge line is recommended. High-lift devices do not require mass-balancing

In the absence of detailed computer analysis or costly ground vibration testing, airplanes can be tested for flutter resistance in an ad hoc way. The late John Thorp, whose design career spanned the glory days from 1930 to 1960, called this "tickling the dragon's tail." Beginning at a low speed where the airplane was known to be flutter-free, the test pilot would accelerate by a mile or two per hour, then deliver a sharp slap or "pulse" to the control stick or the rudder pedal. He would pay careful attention to the immediate aftermath of the disturbance. Did the stick or pedal immediately return to center, and the airplane appears unperturbed? This was a "dead beat" response; it indicated that no tendency to flutter was present at that speed. The pilot would then increase speed by a small amount and repeat the test. They then discovered that putting a heavy load on the tail reduced its flutter margins.

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