Flutter Prevention Handbook: A Preliminary Collection

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Part B: Aerodynamic and Mass Balance Effects on Control Surface Flutter

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Foreword

This report was prepared by ZONA Technology, Inc. under the support of the Flight Dynamics Directorate, Wright Laboratory, USAF/AFMC/ASC, Wright-Patterson AFB, Ohio, 45433-7542, for the contractual period of January 1, 1995, through June 1, 1996, entitled “Flutter Prevention Handbook: A Preliminary Collection.” Mr. Ed Pendleton and Mr. Larry Huttself of Wright Laboratory (WL/FIB) were the technical monitors under work units 2401TI00 and 2401LE00.

At ZONA Technology, the Principle Investigator was Dr. Danny D. Liu; Mr. Darius Sarhaddi and Mr. Marc de Piolenc were the editors.

We at ZONA Technology are grateful to the author for his willingness to contribute his lifelong knowledge in flutter technology, wherein the lessons learned throughout the history will be best appreciated by the dynamics engineers for many generations to come. It is hoped that the present report will be a first contribution to a future volumetric Flutter Prevention Handbook collection, complete in its entirety of world aircraft.

Equally, we are indebted to all the reviewers who spent their time and energy to this project in spite of other pressing demands. During the course of the contractual performance, the technical advice and assistance received from Larry Huttself, Ed Pendleton, and Terry Harris of Wright Laboratory; Bob Moore of ASC/EN; Kenneth Griffin of Southwest Research; Thomas Noll of NASA Langley; Bill Reed of Dynamic Engineering Incorporated; and Victor Spain and Anthony Pototzky of Lockheed Engineering and Sciences Company are gratefully appreciated.

Finally, ZONA would like to acknowledge the USAF’s Aeronautical System Center’s History Office (ASC/HO) and the Air Force Museum research department (USAFM/MUA) for supplying many of the photographs used in this Handbook.

Abstract

Six cases of flutter of full scale aircraft or wind tunnel models, shown in the table below, are discussed as to flutter type, cause and correction. Also included are descriptions of several control surface/tab systems and how they function. Mass and aerodynamic balance types and design rules are also discussed.

<table>
<thead>
<tr>
<th>Case</th>
<th>Flutter</th>
<th>Cause</th>
<th>Cure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>aileron/wing torsion</td>
<td>stores distribution</td>
<td>relocate stores or placard</td>
</tr>
<tr>
<td>2</td>
<td>vertical fin/rudder</td>
<td>excess rudder aerodynamic balance</td>
<td>placard</td>
</tr>
<tr>
<td>3</td>
<td>vertical fin/rudder</td>
<td>concentrated mass balance</td>
<td>mass balance redistribution</td>
</tr>
<tr>
<td>4</td>
<td>stabilator rotation/bending</td>
<td>rotation/bending mode coupling</td>
<td>mass balance redistribution</td>
</tr>
<tr>
<td>5</td>
<td>wing/aileron</td>
<td>excess control surface rotational inertia</td>
<td>reduced inertia+static mass overbalance</td>
</tr>
<tr>
<td>6</td>
<td>elevon/wing torsion</td>
<td>wing torsion/aileron rotation coupling</td>
<td>not applied</td>
</tr>
</tbody>
</table>

It is imperative that flutter not occur within the useable flight envelope of an aircraft and that a safe-speed margin beyond envelope boundaries be maintained. Furthermore, flutter margins must be attained efficiently, to forestall the accumulation of excessive structure or ballast weight that could compromise payload.

A companion consideration to flutter in flight vehicle design is the provision of sufficient structure stiffness to prevent static aeroelastic divergence, control reversal and excessively large stability derivatives. Though not the primary subject of this handbook, static aeroelasticity methodology can be useful in the analysis of certain types of flutter and this is briefly discussed.

The common features of classical flutter phenomena and means of detecting them theoretically and experimentally are explored. Standard rules for designing aerodynamic geometry, internal structural arrangements and mass balance distributions to minimize the possibility of flutter without large weight penalties are discussed.

The cases cited are of flutter encountered, during the design/development phase of actual aircraft, in flight or in dynamically scaled wind tunnel model tests. In some cases flutter occurred despite application of the rules of good design for flutter prevention.

Introduction

The term “flutter” is applied to many differing dynamically unstable mechanisms produced by fluid flowing past structures and their mass distributions. Flutter implies unexcited (or self-excited) structure vibration amplitudes that increase exponentially in time without limit, (or to a limit fixed by some nonlinearity of the system). Among these are types not currently amenable of theoretical analysis such as: smokestack and bridge flutter induced by shed bluff-body vortex streets and the closely related highly-swept-wing flutter caused by leading-edge vortex shedding at high angle-of-attack at subsonic speed. At transonic speed, single degree-of-freedom aileron buzz induced shock boundary-layer interaction is another form of flutter. These nonanalytic forms and panel flutter (of aircraft skin panels) are not discussed here.

This contribution discusses types of aircraft flutter predictable through the use of linear attached-flow unsteady aerodynamic theories. These instabilities result from the interaction of two or more fundamental vibration modes. Such modes may include the overall vehicle “rigid” body and other mechanical modes as produced, for example, by hinged control surfaces and rotating propellers. In some cases, largely non-aerodynamic, natural modes of vibration such as: wing fore and aft motions coupled with fuselage yaw (wing scissors motion); vertical fin pitch coupled with fuselage vertical bending; and horizontal yaw coupled with fuselage lateral modes (horizontal stabilizer scissors) must be included.

Some Types of Flutter

Despite this limited view, the list of mechanisms that lead to “catastrophic” flutter continues to grow. A few are as follows:

Wing/aileron flutter.—An interaction of wing bending, wing torsion and aileron rotation. Found in both swept and unswept wings. Can be symmetric or antisymmetric. Is similar to fin-rudder and horizontal tail-elevator flutter. Full distributed static mass balance prevents bending/control surface flutter but may not prevent torsion/control surface flutter. This is discussed in Case 5.

Fixed surface/control surface/tab flutter.—Tab rotation induces a control surface rotation that in turn creates a fixed surface aerodynamic force. Freeplay or lack of adequate tab actuator stiffness can lead to flutter when the tab is not mass balanced.

Wing/body flutter.—Low-frequency interaction of wing bending and “rigid-body” plunge and pitch modes. Low body pitch inertia, as found in flying wings, for example, can lead to this form of flutter. Short period mode can couple with wing bending and in some cases with wing torsion, especially when large tip tanks are in use.

Hump-mode flutter.—One of several flutter mechanisms produced by the interaction of podded engines and wing vibration modes. Found in transport aircraft. Similar effects can be seen when control surfaces couple with fixed surface modes.

External stores flutter.—Induced by added mass, can be affected beneficially by a lack of symmetry of the spanwise mass distribution. In fighter aircraft, use of wing pylon MER (Multiple Ejection Racks) and TER (Triple
Ejection Racks) external store configurations might still become critical for unsymmetric intermediate combinations of stores. An example involving a twin turbofan aircraft is presented in Case 1.

**Propeller whirl-flutter.**—A precessive oscillation of the propeller and engine relative to the airframe. Affected by low structural stiffness of the engine-propeller system mounting. Involves cross coupled yaw and pitch degrees of freedom driven by propeller aerodynamic and gyroscopic moments.

**Objectives**

This contribution addresses the following aspects of the classical forms of flutter found in aircraft:

- Aircraft design to minimize the possibility of catastrophic flutter.
- The definition, mathematical description and theoretical analysis of aeromechanical systems employed in flutter analysis.
- Ground vibration testing to verify the mathematical model of the aircraft inertia-elastic system.
- Wind tunnel flutter testing.
- Flight testing procedures that lead to minimum risk during flutter exploration.

The diversity of the flutter situations encountered in actual aircraft is illustrated by six examples. Each flutter mechanism and how it was found are discussed. The corrective actions taken and success or lack of success of steps on the way to a safe configuration are noted.

**Aircraft Design for Flutter Safety, Structural and Ballasting Efficiency**

**Flutter Mechanisms—General Discussion**

All mechanizations of flutter depend on the interaction of aerodynamic, inertia, and elastic forces. Structural elastic (or spring) forces react with inertia (or accelerated mass) forces to create the oscillatory character of flutter seen in the orthogonal (or independent) natural vibration modes of the system. Aerodynamic forces modify the elastic forces to change the frequencies of the fundamental natural modes. They also act to couple certain of the modes together. This creates timewise phase lags between them and results in positive or negative damping of the new combined modes of the total system. Aerodynamics may thus lead to strong damping, of the otherwise conservative (or nondissipative) system, or to the divergent oscillation, known as flutter.

**Configuration Effects on Flutter**

An aircraft typically consists of a slender body of small lift effectiveness but large forward-located mass and pitch and yaw moments of inertia. To this body are attached surfaces of great lift effectiveness and relatively little weight, such as the wings and tail surfaces. Engine, fuel and external pylon mounted store weights, however, may be distributed spanwise across the wing.

**Wing mass distribution effects.**—The chordwise location of the wing spanwise mass distribution plays a major role in the flutter stability of the wing-body system. Two dimensional unsteady aerodynamic theory shows that motions with node lines aft of the leading edge to about fifty percent of chord are stable. Location of the mass centroid distribution aft of the elastic axis tends to be destabilizing. (The elastic axis is the spanwise locus of chordwise points along which concentrated normal forces may be applied without inducing wing elastic twist, usually near forty percent of chord).

**Control surface effects.**—Trailing-edge control surfaces, unless irreversibly actuated, complicate the behavior of wing-body systems. This is due to the large aerodynamic forces delivered to the wing modes by such surfaces. At subsonic speeds, for example, a one degree rotation of a control surface of 30 percent chord produces lift equivalent to a 2/3 degree rotation of the whole wing section, across the span of the control surface. The centroid of the section lift added to the wing will be located 15 percent of the chord length aft of that produced on the wing by an equivalent angle-of-attack (AOA) change.
Any oscillation of a manually controlled (or essentially free floating) control surface therefore causes very large lift and twisting moments on the supporting surface with attendant vertical and rotational accelerations.

A control surface displacement producing a force or moment in phase with (or in the direction of) an elastic rate of change of deflection of the main surface promotes flutter. A flutter occurrence, however, requires a coupling between the control and the main surface degrees of freedom.

An example of such coupling is provided when the first moment of the mass of a control surface is located aft of its hinge line. If a wing tip, oscillating in plunge is at the top of its stroke and accelerating downward, an aileron with its mass center aft of the hinge line will rotate trailing-edge upward. This produces a downward aerodynamic force, in the direction of the wing tip velocity. Any lag in the control surface displacement or its aerodynamic force buildup, relative to the wing tip displacement can result in flutter.

**Mass balancing.**—The above problem is usually solved by shifting the mass centroid of the control surface to the hinge line by the addition of counterweights forward of the hinge line. This is called mass balancing. It is very effective in suppressing bending mode coupling but overbalance is required for torsion mode decoupling. This is discussed in Case 5.

Federal airworthiness requirements impose arbitrarily large design loads on mass balance support structure to make sure weights do not fall off. The supporting structure and attachment of concentrated mass balance weights used on control surfaces on small aircraft must withstand inertia limit loads normal to the control surface imposed by accelerations up to 24g.

**Effects of control surface tabs.**—A further complication to the flutter dynamics of an airplane with a free-floating (or manually operated) control surface occurs with the addition of a tab (a small hinged surface) to the control surface trailing-edge. This results in three surfaces in tandem with two intermediate hinges connecting them. The purpose of a tab is to reduce the control surface hinge moment to make manual control easier. It does this by rotating in the opposite direction to that desired of the control surface. Its position at the trailing-edge of the control surface allows its small force, in the wrong direction, to produce a large control surface hinge moment in the direction desired. Thus the system of three surfaces can provide the desired net lift force with a zero net hinge moment.

A trim tab is usually rotated to a fixed displacement relative to its elevator, for example, to produce a required steady tail lift force with zero hinge moment and stick force. It does not affect the rate of change of hinge moment application per unit deflection of the elevator. In some aircraft, tab rotation is, in addition, geared to elevator deflection for the purpose of reducing “stick force per g”. It is then referred to as a geared tab. Another variation consists of allowing the control surface to float free about its hinge axis while the stick force is applied directly to the tab. The tab then supplies the required hinge moment to the control surface with little force feedback to the stick. Tabs are usually not mass balanced unless free, as are spring tabs. All tabs must be irreversible, frequency criteria and free play requirements must be met, unless the tab is properly balanced and has no unsafe flutter characteristics.

**Effects of control-surface aerodynamic balance.**—A more common way of reducing the stick force per g is through the use of aerodynamic balance. This is accomplished by tailoring the control surface planform geometry so that some lifting area lies ahead of the hinge line. This area provides hinge moment in a direction opposite to that provided by regions aft of the hinge line. Two methods are in common use: the aerodynamic horn—an area projection well forward of the hinge line near the surface tip and the set-back hinge—that distributes the forward projected area uniformly along the control surface span by placing the control surface hinge line well aft of the leading-edge.

Aerodynamic balance partially balances the hinge moment produced by normal pressure aft of the hinge-line. The designer must be careful not to overbalance the control surface or it will statically diverge to full throw (to the mechanical stop).

Aerodynamic balance reduces the hinge moment per unit control surface rotation at a given dynamic pressure. This reduces the aerodynamic spring constant and frequency of the control surface rotational degree of freedom. Flutter of a wing and aerodynamically unbalanced aileron, for example, may take place when the rigid rotational frequency of the aileron approaches that of a higher frequency bending or torsion mode of the wing. The effect of aerodynamic balance is to raise the airspeed at which the frequency coalesces and flutter will occur.
In addition, movement of the hinge-line to a position aft of the control surface leading-edge progressively reduces damping of the surface rotation mode. These two effects can convert a mild low-speed flutter into a severe flutter problem at high speed.

**Control surface dampers.**—Control rotation-mode dampers may be employed when surfaces are too thin to house mass balances. They are also useful in the suppression of transonic buzz. Dampers may also be employed beneficially in wing-store cases of marginal stability.

## Aircraft Flutter Analysis

Flutter analysis has evolved from the consideration of two or three degrees of freedom, at a time, by a hand calculation, prior to about 1950, to the analysis of the interaction of thirty or more vibration modes today through the use of large digital computers. The lack of computing capability in the early days forced the flutter engineer to carefully study the degrees of freedom available to him to ascertain which small group would likely lead to flutter, before undertaking the tedious task of finding the unstable roots. He postulated flutter mechanisms and investigated them analytically.

With the computer resources available today there is a tendency to include all possible modes in an analysis of flutter safety. This sometimes leads to difficulty in identifying the dominant physical mechanism causing flutter and in finding the most efficient way to modify the design to effect a solution.

## Inertial-Elastic System

The theoretical analysis of flutter usually begins with a consideration of the dynamic behavior of the aircraft structure and its mass distribution in a gravity-free airless environment. An eigenvalue analysis provides the system resonant frequencies and the corresponding modes of natural vibration. These may be verified by direct experimentation on the completed aircraft by a ground vibration test.

**Elastic properties.**—The elastic properties of the free-free aircraft may be expressed as a flexibility matrix. (Each column of which is the distribution of deflections produced by a unit load applied at one loading point and reacted by rigid body inertia forces at all points. All deflections are measured relative to a common point or set of points in the physical structure). A flexibility matrix is the inverse of a stiffness matrix and may be calculated by finite element structural analysis methods.

**Inertia properties.**—The aircraft weight distribution is discretized into local masses and moments of inertia at the points employed in the flexibility matrix. (This may require the use of interpolation schemes).

**Vibration mode analysis.**—The above flexibility and inertia information is substituted into the matrix equation describing the dynamic oscillation of the conservative system. It is a set of unforced coupled second-order ordinary differential equations. The eigenvalues of its characteristic equation are extracted computationally and become the natural frequencies of the system. The eigenvectors (or mode shapes) associated with the eigenvalues then follow directly.

**Coordinate systems for flutter analyses.**—The theoretical vibration modes above are often employed in flutter analyses as the representative degrees of freedom of the system since they are orthogonal to each other and to the rigid body modes (or they are inertially uncoupled, i.e., inertia forces in one mode produce zero generalized forces in the others). They may not, however, be orthogonal to a control surface rotation degree of freedom when it is added as a general coordinate to describe control surface relative motion.

It is not necessary to employ the natural vibration modes as the describing degrees of freedom of the airplane, and in fact were not available in the early days of flutter analysis since they were then impossibly tedious to calculate. It is only required that the deflection describing modes be general enough to reproduce the important motions of the inertia-elastic system and the static aeroelastic system.

Notes: 1.) It may not be feasible to employ a sufficient number of natural vibration modes to adequately describe the static aeroelastic behavior of some low frequency flutter modes. In such cases it may be necessary to employ a smaller number of nonorthogonal modes specially tailored to include such effects.
The static aeroelastic deflection shapes due to AOA, pitch rate and control surface deflection make good candidates for inclusion with a set of elastic modes in analyses of flutter in which rigid-body motions are important, for example. If coordinates are employed that are not orthogonal, cross-coupling flexibility and inertia terms are present. Modern computers have no problem calculating and including these.

2.) Static aeroelastic problems are usually analysed in terms of the unreduced stiffness, (or flexibility), matrices of all load and deflection points on the aircraft structure rather than in terms of the reduced set of orthogonal elastic modes employed in flutter analysis. Though a small number of lower frequency elastic modes may adequately represent the dynamic motions involved in flutter, they will often not represent the elastic twist of the wing adequately for static aeroelastic analyses.

Unsteady Aerodynamics

Aircraft unsteady aerodynamics, at one value of nondimensionalized or reduced frequency, may be expressed as a matrix of complex aerodynamic forces on the set of contiguous elemental areas making up the thin lifting surfaces of wings, tails, control surfaces, etc. The differential pressures generating the forces are produced by the surface element motions: angular displacement and linear velocity normal to freestream flow.

The time lag between surface motion and pressure development is accounted for by the real and imaginary elements of the complex matrix.

The aerodynamic pressure distribution due to the motion of each mode, at one reduced frequency, is applied to all modes and integrated over the aircraft surface to yield the aerodynamic coefficients of a reduced set of flutter equations. This is the general procedure utilized with any general coordinates.

Detailed lifting surface computer programs are employed in generating the basic unsteady aerodynamic matrices, above. The primary methods in use today, for both steady and unsteady matrix prediction, are Strip Theory and Doublet Lattice for the subsonic flight regime and ZONA51 for the supersonic. In the transonic regime specialized codes are applied.

The analytical investigations of aircraft reported in this note, however, made use of MSC NASTRAN for the dynamic models, (structure-inertia systems), and unsteady Strip Theory and Doublet Lattice with steady-state weighting for the unsteady aerodynamics.

In discussing flutter prevention, however, a simpler implementation of unsteady aerodynamics has been employed in this note: incompressible two-dimensional unsteady aerodynamics operating on the plunge, pitch and control rotation degrees of freedom. This methodology provided the key to flutter analysis during the first fifty years of powered flight through its utilization in Strip Theory. Despite the lack of spanwise interference between sections in this theory it has been surprisingly effective. This may be due to the high aspect ratio of lifting surfaces common during this period.

Flutter Experience

The following cases of flutter have been chosen to illustrate the diversity and complexity of flutter mechanisms occurring in actual flight, encountered in wind-tunnel testing of new aircraft designs or found by analysis and corrected prior to flight.

Case 1: Effect of Wing-Store Distributions on Aileron/Wing Torsion Flutter

Aircraft description.—The twin-turbofan aircraft, see figure 1, has its engines mounted on the aft fuselage. Its swept low-wing has upper surface fences at 47 percent semi-span. Wing thickness varies from 10.5 percent at the root to 8 percent at the tip and sweep of the quarter-chord is 30 degrees. Conventional ailerons are actuated hydraulically with artificial feel and are almost irreversible.
The swept vertical fin has a swept tailplane mounted at its semi-span.

- Maximum Mach Number = 0.80
- Maximum Cruise Speed = 461 knots TAS at 40,000 ft altitude

Though originally designed as a light commercial transport, it is currently employed in the military services of several countries. Two of its uses are as an aerial refueling trainer and maritime reconnaissance.
The configurations investigated, employed symmetrically-arranged inboard and outboard external store attachment points under the wing as is shown in figure 1 and table 1. Twenty-seven store configurations were considered.

The ailerons were not mass balanced and thus depended on a high irreversibility frequency and rotation mode damping to maintain aileron/wing coupled flutter margins. Ground vibration tests showed the following values:

**TABLE 1.—SYMMETRIC VIBRATION MODES OF THE TEST AIRCRAFT**

<table>
<thead>
<tr>
<th>Hydraulic Power</th>
<th>Left Aileron Frequency (Hz)</th>
<th>Damping (g)</th>
<th>Right Aileron Frequency (Hz)</th>
<th>Damping (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On</td>
<td>49.3</td>
<td>0.06</td>
<td>50.3</td>
<td>0.05</td>
</tr>
<tr>
<td>Off</td>
<td>47.6</td>
<td>0.07</td>
<td>48.2</td>
<td>0.07</td>
</tr>
</tbody>
</table>

(Note: Vibration peak width at the half power point divided by the center frequency furnished the measured damping value, g).

FUEL TANKS EMPTY (SYMMETRIC MODES)

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Vibration Mode Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.51</td>
<td>Wing 1st bending, A/P pitching</td>
</tr>
<tr>
<td>6.12</td>
<td>Wing 1st bending, A/P pitching</td>
</tr>
<tr>
<td>7.57</td>
<td>Stabilizer bending coupled with wing bending</td>
</tr>
<tr>
<td>10.57</td>
<td>Fuselage vertical bending-stabilizer bending</td>
</tr>
<tr>
<td>12.99</td>
<td>Fuselage vertical bending-engine pylon bending</td>
</tr>
<tr>
<td>15.77</td>
<td>Stabilizer bending</td>
</tr>
<tr>
<td>18.34</td>
<td>Wing 2nd bending-engine pitch</td>
</tr>
<tr>
<td>18.34</td>
<td>Engine pitching</td>
</tr>
<tr>
<td>31.23</td>
<td>Wing torsion</td>
</tr>
<tr>
<td>32.19</td>
<td>Wing torsion-aileron rotation</td>
</tr>
<tr>
<td>36.53</td>
<td>Wing 3rd bending</td>
</tr>
<tr>
<td>37.75</td>
<td>Elevator rotation (1 hydraulic system)</td>
</tr>
<tr>
<td>40.30</td>
<td>Elevator rotation (2 hydraulic system)</td>
</tr>
<tr>
<td>--</td>
<td>Higher-order wing torsion</td>
</tr>
<tr>
<td>55.01</td>
<td>Higher-order wing bending-torsion</td>
</tr>
<tr>
<td>--</td>
<td>Stabilizer 2nd bending</td>
</tr>
<tr>
<td>--</td>
<td>Stabilizer torsion</td>
</tr>
</tbody>
</table>

A twin hydraulic booster system rotated each aileron at its spanwise center. Each system also included a viscous damping circuit to prevent flutter.

Ground vibration tests also provided symmetric and antisymmetric overall vibration modes and natural frequencies for the aircraft with no fuel or stores, as described in tables 1 and 2. Note the outer wing torsion mode frequency identified during the antisymmetric tests as approximately 51 Hz. The above ground-measured aileron rotational modes for the various booster conditions range from 47.6 Hz through 50.3 Hz and exhibited g-damping levels of 0.05 to 0.07.

In the one configuration that was predicted to be flutter critical, near a frequency of 51 Hz, two unsymmetrical stores only were carried: of 300 and 140 lb weight respectively. These stores were carried on the outboard pylon stations.

**Flutter experience.**—Four flutter clearance programs were conducted on 27 store configurations. Most were symmetrical mixes of inboard and outboard stores on the four pylons. Analyses, ground and flight tests indicated no flutter within flight operational boundaries with all but one configuration, the only unsymmetrical one.
TABLE 2.—ANTISYMMETRIC VIBRATION MODES OF THE TEST AIRCRAFT FUEL TANKS EMPTY (ANTISYMMETRIC MODES)

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Vibration Mode Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.58</td>
<td>Fuselage torsion</td>
</tr>
<tr>
<td>6.33</td>
<td>Fuselage torsion-stabilizer rocking</td>
</tr>
<tr>
<td>7.43</td>
<td>Stabilizer rocking</td>
</tr>
<tr>
<td>9.62</td>
<td>Fuselage side bending-stabilizer rocking</td>
</tr>
<tr>
<td>12.23</td>
<td>Wing bending</td>
</tr>
<tr>
<td>13.85</td>
<td>Wing bending-fuselage side bending</td>
</tr>
<tr>
<td>17.05</td>
<td>Fin bending</td>
</tr>
<tr>
<td>20.66</td>
<td>Engine pitching</td>
</tr>
<tr>
<td>23.49</td>
<td>Rudder rotation (1 hydraulic system)</td>
</tr>
<tr>
<td>26.11</td>
<td>Rudder rotation (2 hydraulic system)</td>
</tr>
<tr>
<td>28.66</td>
<td>Wing 2nd bending</td>
</tr>
<tr>
<td>31.76</td>
<td>Wing torsion</td>
</tr>
<tr>
<td>40.47</td>
<td>Stabilizer bending</td>
</tr>
<tr>
<td>42.20</td>
<td>Elevator rotation (1 hydraulic system)</td>
</tr>
<tr>
<td>42.20</td>
<td>Elevator rotation (2 hydraulic system)</td>
</tr>
<tr>
<td>50.70</td>
<td>Higher order wing torsion</td>
</tr>
<tr>
<td>68.97</td>
<td>Stabilizer torsion</td>
</tr>
</tbody>
</table>

It consisted of one store per side located on the outboard pylon stations but of different weights (300 and 140 lb) and moments of inertia.

**Analyses.**—This configuration was analyzed as a complete aircraft, i.e., with each side described independently, using NASTRAN with Doublet Lattice unsteady aerodynamics. The analyses were conducted with aileron damping set at $g = 0.03$ and with the measured aileron rotation springs. Analyses were run with the full predicted unsteady aerodynamic aileron hinge moments and with hinge moments reduced to 50 percent of full value. Solutions were found for $M = 0.76$ over a range of altitudes from sea level to 40,000 ft.

The clean aircraft was entirely free of flutter with acceptable margins. With the unsymmetric stores on the outboard pylons only, the outer wing torsion mode coupled with the aileron rotation mode and resulted in flutter at approximately 51 Hz primarily involving motions on the light side, within the flight envelope, even though $g = 0.03$ had been included in the analysis.

**Flight tests.**—The unsymmetrical stores configuration was the first of the 27 configurations flight tested in each of the four test periods.

The instrumentation, see figure 2, emphasized wing structural strains and pylon store accelerations and recorded all control surface displacements.

Horizontal and vertical tail elastic strains were also recorded to permit the monitoring of any loss of empennage stability.

The strain monitoring gauges were added to give some indication of excessive load over a wide range of frequency and to make up, to a certain extent, for the lack of the large number of instruments usually found on prototype aircraft. Strains are proportional to structural deflection while accelerations are proportional to the product of deflection and frequency squared. Hence if an accelerometer is chosen to measure high frequency vibration, it will not pick up even large amplitude low frequency oscillations that could indicate large loads.

Since strain is directly indicative of structural damage, strain gauges can provide a limited but quantitative indication of excessive dynamic loads.

At the extreme edge of the flight envelope at 25,000 ft altitude the aileron rotation mode damping reduced from $g = 0.06$ to $g = 0.02$ over the last 50 Kts EAS, as determined by RDMDEC (random decrement) analysis of the test data. The test was repeated and gave the same result, thus in the interest of flight safety the aircraft was placarded (restricted) against flight with damping below the ground measured value.
With the stores, described above, on the outboard racks aileron/wing torsion flutter was predicted to occur. On the inboard racks the flutter disappeared.
Postulated flutter mechanism.—The presence of the light store on the outboard pylon led to the observed instability. Its light weight but significant moment of inertia produced a change to the outer wing torsion mode without significantly changing its frequency. This substantially increased the unbalanced mass/inertia coupling between the aileron rotation mode and outer wing torsion mode without increasing the frequency separation. The opposite side of the aircraft with the heavier store remained stable due to its increased frequency separation. A symmetric configuration of light stores on each side, had it existed, would have had a much lower flutter speed.

Corrective action taken.—The simple remedy to this problem was to restrict the airspeed for this configuration. The second choice was to move the stores to the inboard pylons where the problem did not exist. Choice of arrangement made it possible for all 27 configurations in four subsequent programs to meet the full flight envelope of this aircraft without wing stores. The predicted most critical flutter cases were all flight flutter tested to the full design envelope, supported by FM telemetry and lattice filter analysis of the test results. These configurations, approximately ten aircraft, were FAA STC’d and are now operating under CAA regulations in the UK.

Case 2: Effect of Aerodynamic Balance on Vertical Fin/Rudder Flutter

Aircraft description.—A WWII light bomber with twin radial piston engines and an unswept shoulder-mounted wing of high aspect ratio (AR = 9.5) is the subject aircraft of Case 2 (see fig. 3). The aircraft was of metal monocoque construction except for the rudder and tabs which were fabric covered. The unswept fin and rudder and horizontal stabilizer and elevator were of conventional geometry.

Originally developed as an attack bomber during World War II, served in both Korean War and the Southeast Asian Conflict.

Figure 3.—Aircraft flight tested for effect of aerodynamic balance on vertical fin/rudder flutter.
The rudder, of approximately 35 percent chord, was marked by a very large distributed aerodynamic balance of approximately 8 percent of the fin and rudder chord.

The particular aircraft flutter tested was retrofitted for counterinsurgency service. Eight wing pylons were added for rocket and gun pods, bomblet dispensers and other external stores. The tip tanks were not installed during the reported test.

Maximum speed at 10,000 ft was 323 knots, true air speed (KTAS). The design dive speed was 370 knots, equivalent air speed (KEAS).w

**Flutter experience.**—The fin and rudder exhibited a limited amplitude flutter at 375 KEAS that did not induce structural failure and the aircraft landed normally. The flutter, at 5 KEAS faster than the design dive speed, oscillated at 12 Hz, and was of the fin bending/rudder rotation type.

The flight test had been conducted to examine the clean aircraft prior to the addition of external wing stores outboard of the propellers. The test was considered perfunctory, a test of the instrumentation, since no changes were known to have been made to the fuselage/empennage system. The test, however, did include tail instrumentation and was conducted so as to provide a slow build-up in airspeed.

**Postulated flutter mechanism.**—With little inertial coupling between the fin bending and rudder rotation modes, the mechanism of Case 3 is not likely to be the major cause of this unexpected flutter. With inertia coupling out of the picture aerodynamics became suspect.

The large distributed aerodynamic balance is somewhat unusual, but may be investigated by two-dimensional unsteady aerodynamics theory. Aerodynamic stiffness and damping of the rotation mode as the hinge-line progressively moves aft of the leading-edge of a control surface is provided by the equation in figure 4. The real part becomes the aerodynamic stiffness and the imaginary part is proportional to the damping.

At $k = 0.16$, and $e = 0.4$ the aerodynamic stiffness (real part) reduces to zero at $c = 0.58$ and the aerodynamic damping (imaginary part) reduces to approximately $1/3$ the value it had with the hinge line at the rudder leading-edge. The distance from the leading-edge to the hinge line is $c - e = 0.18$ in terms of the half chord, $b$; that is, the hinge-line is 9 percent of the fin and rudder chord behind the control surface leading-edge.

The hinge-line on the bomber rudder is approximately at that chord station; thus it appears that the rotation mode frequency increase with airspeed will be relatively small. Furthermore, its modal damping is also quite small relative to that of a leading-edge hinged control surface.

<table>
<thead>
<tr>
<th>$k$</th>
<th>$T_{b}$</th>
<th>$T_{z}$</th>
<th>$P_{z}$</th>
<th>$P_{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16</td>
<td>$-1.94111 - 0.29845i$</td>
<td>$0.00851 - 0.31053i$</td>
<td>$-0.01542 - 1.55072i$</td>
<td>$-9.7045 - 1.0184i$</td>
</tr>
</tbody>
</table>

Figure 4.—Rudder unsteady aerodynamic hinge moment, $T'$, due to rudder deflection at $k = 0.16$. 
Hinge moment, $T'$, due to control surface deflection, $\beta$, is given by:

$$\lambda = \frac{Kb}{SI} < T' = \pi \rho b^4 \omega^2 \left\{ \left[ \frac{T_\beta}{\omega} - (c - e) \left( P_\beta + T_z \right) + \left( c - e^2 \right) P_z \beta \right] \right\}$$

The reduced frequency $k = \frac{b\omega}{V} = 0.16$ at 12 Hz at the design dive speed gives the real and imaginary parts plotted below. Values for $T_\beta$, $T_z$, $P_\beta$, and $P_z$ in the table below are adapted from Scanlan and Rosenbaum, reference 1.

It is postulated that a very slow growth of rotation frequency with forward speed led to a coalescence with the fin bending mode frequency just above the design dive speed. This coalescence, in conjunction with reduced rotation mode damping, led to the observed flutter.

Flutter corrective action.—The flutter took place at a speed almost outside of the operational overspeed envelope. A simple airspeed restriction would therefore be sufficient to meet airworthiness requirements. The nature of this flutter, however, is such that an increase in mechanical rotation-mode torsion spring stiffness would cause the flutter to occur at a lower airspeed, that could be well within the flight envelope.

This dangerous condition is a consequence of large aerodynamic balance and should be avoided.

Case 3: Vertical Fin/Rudder Flutter Despite Meeting Flutter Prevention Design Criteria

Among the rules that guide designers toward flutter-free configurations are those provided by the US CAA (Civil Aeronautics Administration) in the early 1950s. Some are presented in Airframe and Equipment Engineering Report 45, “Simplified Flutter Prevention Criteria for Personal Type Aircraft,” by Rosenbaum and Vollmecke (ref. 2).

Its empennage design criteria for rudders recognize that flutter will most likely result from a coupling of rudder rotation with either the aft fuselage lateral bending or torsional natural modes.

It specifies a parallel axis criterion to prevent rudder coupling with aft fuselage lateral bending and a perpendicular axis criterion to prevent rudder coupling with aft fuselage torsion (see figs. 5 and 6).

The parallel axis criterion requires that the ratio, $\gamma = \frac{bS_\beta}{I}$, not exceed a value given in figure 5. Its parameters are as follows:

- $S_\beta$, rudder static unbalance.
- $b$, fin and rudder semi-chord.
- $I$, rudder moment of inertia about the hinge axis.

The maximum allowable ratio is a function of the flutter speed factor (the inverse of a reduced frequency based on the aft fuselage natural bending frequency, $f_h$, the semi-chord and the design dive speed, $V_D$).

The perpendicular axis criterion is similar but requires the ratio, $\lambda = \frac{Kb}{IS}$, to be less than a value given in figure 6. Its parameters are as follows:

- $K$, product of inertia of the rudder mass about the torsion and hinge axes.
- $b$, fin and rudder semi-chord.
- $I$, rudder moment of inertia about the hinge axis.
- $S$, the distance from the torsion axis to the tip of the fin.
The maximum allowable ratio is dictated by the flutter speed factor (or inverse of the reduced frequency at \( V_D \) based on the fuselage torsional frequency, \( f_\alpha \), and the fin and rudder semi-chord).

The present case indicates that even though the flutter design criteria, above, are met, flutter may still be possible.

**Aircraft description.**—A two-seat, twin-engined light aircraft, see figure 7, is the test aircraft in Case 3. The all metal unswept low-wing is of semi-monocoque construction. Its external skin surfaces are formed by chem-milling and stretching. The aircraft has a conventional tail with swept vertical surfaces and an conventional horizontal fixed stabilizer and elevator.

The swept fin and rudder are shown schematically in figure 8. Rudder mass balance was concentrated at the rudder tip to minimize the product of inertia of the rudder about the fuselage torsion and hinge axes with the smallest possible balance weight that would meet the perpendicular axis criterion.

\[
K = m_r x_r y_r + m_{nb} x_{nb} y_{nb} \quad (\text{lb ft}^2)
\]

\( K \) must be such that \( \lambda = \frac{Kb}{SI} < \) the value from figure 6 for \( V_f = \frac{V_D}{bf_\alpha} \), where:

\[
I = \text{mass moment of inertia about the hinge line (lb ft}^2\text{)}
\]
\[
b = c_{midspan}/2 \quad (\text{ft})
\]
\[
f_\alpha = \text{fuselage torsion mode natural frequency (cps)}
\]
\[
V_D = \text{design dive speed (mph)}
\]
\[
S = \text{effective fin span (ft)}
\]
Flutter experience.—Vertical fin/rudder flutter was experienced in flight despite adherence to the flutter design criteria of CAA Rept 45.

Ground vibration testing disclosed a fin and rudder bending node line at approximately 60 percent fin span at a natural frequency near the inflight measured flutter frequency.

Postulated flutter mechanism.—In a rudder rotation/aft fuselage torsion flutter, locating a single rudder mass balance at the maximum distance from the fuselage torsion axis, i.e. at the rudder tip, yields the maximum compensating product of inertia per unit distance forward of the hinge line for that weight. (See fig. 8). The rudder was balanced in accordance with this logic.

In the flutter observed, however, the mode participating with the rudder rotation was not aft fuselage torsion but vertical fin and rudder lateral bending. The mode possessed a node line at 60 percent of the fin span as shown in figure 9. The tip located mass balance inertia force, in this case, is in a direction opposite to that of the inertia force
on the rudder aft of the hinge line. Thus, instead of canceling the inertial hinge moment as it would in the case of fuselage torsion, it adds to it, and thereby strongly couples the bending mode to the rudder rotation mode. In other words, fin bending motion induces rudder rotation that in turn induces lateral airloads on the fin that amplify the fin bending motion. Thus, the precondition for flutter is in place.

**Flutter corrective action.**—With the flutter mode identified it became possible to neutralize it. Reducing the tip weight until it just balanced the fraction of rudder weight above the node line and adding a second weight near the bottom of the rudder to balance the rudder weight below the node line, as shown in figure 10, decoupled rudder rotation from fin and rudder bending.

Decoupling was due to the fact that bending mode induced accelerations produced balanced, (or zero), hinge moments separately both above and below the node line.

In the subject airplane, the balance weights were distributed 1/3 to the rudder tip and 2/3 to the rudder base. This redistribution of mass balance weights was slightly heavier than the original that covered only fuselage torsion coupling.

This exercise, in addition, illustrates the “flutter design rule” that control surface spanwise inertial hinge moment should be balanced locally at each span station by distributed balance weights when possible.

**Case 4: Flutter of a Stabilator**

**Aircraft description.**—The aircraft in Case 4 is a high-performance, single engine, two-seat (side-by-side), low-wing homebuilt monoplane of all-metal semi-monocoque construction and a conventional fin and rudder (see fig. 11). The design employed a stabilator (all moving tailplane hinged to the aft-fuselage with no elevator). The stabilator contained a servotab (trailing-edge tab geared to stabilator rotation).

To prevent flight-normal acceleration from producing inertia hinge moments, the first moment of the stabilator mass about its hinge-line was brought to zero by the use of a single centerline counterweight. (See fig. 12).

The maximum sea-level speed was 200 miles per hour. Flight tests were conducted to 230 miles per hour.

**Flutter experience.**—Following an in-flight failure, without witnesses, a speed placard of 180 mph was applied to all aircraft of this type. A second accident at very high speed produced similar damage and this time the flutter and departure of the stabilator were witnessed.

A flutter investigation, initiated by the designer, began with flight tests to calibrate flutter instrumentation. These were terminated at 190 mph despite the fact that the configuration had previously been flown to 230 mph. Dynamic results recorded at 160, 170, 180 and 190 mph showed a mode, consisting of symmetric pitch, stabilator rotation and first bending, to be losing damping with airspeed and to be approaching instability.
An apparent cause of this was the center-line installed balance weight arm that supported the only balance weight on the stabilator. It was an L-shaped structure attached to the stabilator with its short side pointed down and long side, with the lead balance weight attached, pointed forward. (See figs. 12 and 13).

In the approaching flutter mode, at 31 Hz, the central mass-balance arm took on a cantilever bending oscillation reacted by an almost rigid rotation of the stabilator. (See fig. 13).

The flutter specialist suggested, based on ground vibration tests, that the balance arm be stiffened by a gusset across the L. Stiffening the support arm changed the rotation mode ground vibration frequency from 16 to 20 Hz.

Following the modification, in planning the flight tests with the stiffened balance arm, it was thought possible that the change might have made the flutter situation more critical, since it had been based on limited data and no analysis. The test series was therefore conducted in an orderly manner with a gradual build-up in flight speed.
During the flight tests, with the stiffened balance arm, the symmetric rotation mode coupled with the symmetric stabilator first bending mode and became unstable at 175 mph, or at a 15 mph lower speed than with the unstiffened balance arm. Fortunately, though the damage was severe, the aircraft remained flyable and made a safe landing.

The flutter specialist then advised the designer that the single central mass-balance configuration should be replaced by a more conservative, distributed balance, arrangement.

Following the logic outlined in the next section, the final modification moved one-third of the centerline mass balance to the stabilator tips, i.e. one-sixth to each tip. This cured the flutter problem and no flutter was experienced in flight tests to 231 mph. The aircraft was cleared to a never-exceed-speed of 210 mph.

**Postulated flutter mechanism.**—The rotation mode, described above, changed frequency with aircraft forward speed due to the aerodynamic hinge moment acting as a spring-to-ground. That is, the hinge moment due to surface unit rotation increased as the square of the forward speed. The stabilator bending mode, on the other hand, did not twist significantly with deflection and therefore did not encounter a spring-to-ground. Its frequency did not change significantly with aircraft forward speed.

Aside: Because surface vibration velocities normal to the wind are small in the rotation mode, its modal damping would be small if unaffected by other modes. Bending-mode surface normal velocities, however, are much larger and produce modal damping that grows linearly with aircraft forward speed increase, if not influenced by other modes.

It is clear that in streaming air the lower rotation-mode frequency will approach that of the bending mode at some forward speed. In addition, the oscillating rotation mode should be able to produce an aerodynamic force distribution that excites the bending mode. This is illustrated in figure 14.

![Diagram of aircraft plane of symmetry and bending mode shape](image)

**Figure 14.**—Bending mode generalized force applied by rotation, (torsion), mode aerodynamics.
For one mode to influence another, its motion-produced force distribution must apply a nonzero *generalized force* to the other. The generalized force is defined in figure 14. It is clear from the figure that oscillations of the rotation mode will excite the bending mode at high forward speed.

If the rotation mode supplies an input generalized force to the bending mode at a frequency well below the bending-mode resonance, the responding bending-mode displacement will be essentially in phase with the input force and of amplitude dictated by bending-mode flexibility. (See fig. 15).

If the rotation mode supplies the input force at a frequency well above the bending-mode resonance, the bending-mode-displacement response will be 180 degrees out of phase with the input force or will be in the opposite direction. Its amplitude is then dictated by the *generalized mass* of the bending mode resisting the input force.

The generalized mass of a mode is defined as follows:

\[
G.M. = \int_{-y_{tip}}^{y_{tip}} m(y) \phi^2(y) \, dy \quad m = \text{distributed mass, slugs/ft}
\]

If, on the other hand, the rotation-mode-induced bending-mode generalized force has a frequency equal to the bending-mode resonant frequency, the bending-mode displacement will respond with a 90 degree lag to the input force, as shown in figure 15. Its amplitude will be dictated by the *viscous damping* reactive force in the bending mode. (The bending-mode viscous force is proportional to and opposes mode velocity.)

Figure 15.—Bending mode response to rotation, (torsion), mode generated forcing function, GF\(_B\).
In other words, the rotation-induced generalized force in bending will be in phase with, not bending displacement, but bending velocity. By this means energy is input to the bending mode. The bending-mode amplitude will increase until its viscous resisting (or damping) force equals the bending generalized force input by the torsion mode.

An input force to a mode near its natural frequency from a driving mode is not sufficient to cause flutter (a dynamic instability). Instability requires the responding degree-of-freedom, in turn, to feed back a generalized force to the driving mode. In this way the increasing amplitude of the responding mode causes a continual increase in the driving-mode motion. The mutual reinforcement results in increases, without limit, of displacements in both modes, or a dynamic divergence or flutter.

In the present case of stabilator flutter the primary feedback was provided by the unbalanced first moment of section inertia about the hinge line produced in the outboard region of the tail surface by the bending mode. Due to the small normal acceleration of the centerline mass balance at its location in the bending mode, in this case, it could not react to this large inertial hinge-moment.

The feedback hinge-moment is in-phase with the rotation-mode angular velocity or in the direction to add energy. Thus the ingredients are in place to cause flutter. It is only necessary that the destabilizing energy being added to the system be larger than the bending-mode damping energy being removed.

**Flutter corrective action assessment.**—The movement of one-third of the mass balance to the stabilator tip effectively balanced the inertial hinge-moment generated in the bending mode. This essentially zeroed the feedback generalized force thereby neutralizing the flutter instability. This is another application of the distributed mass balance design rule.

**Case 5: Wing-Aileron Flutter Due to Excessive Control Rotational Inertia**

**Aircraft description.**—The subject aircraft of Case 5 is a low-wing, long-range naval patrol aircraft with four tractor propellers driven by turboprop engines mounted on an unswept wing of high aspect ratio. (See fig. 16). The all metal aircraft of semi-monocoque construction had a conventional unswept tail.

Control surfaces were hydraulically actuated with a reversion to manual control in the event of a failure. This meant that the control surfaces could be restrained by a rotation spring or treated as rotationally unrestrained in wind tunnel flutter tests.

The never exceed speed, $V_{ne}$, was 405 KEAS.

Note: This was a proposed new aircraft of increased capability based on an existing aircraft. Comparisons of characteristics with those of the original aircraft were therefore possible.

**Flutter experience.**—A 1/12 scale flutter model of the aircraft experienced violent wing tip torsion-mode flutter with aileron rotation participation. This took place at an equivalent full scale frequency of 17.1 Hz at a full scale flight speed of 417 KEAS.

A flutter analysis by the p-k Method, employing Doublet Lattice unsteady aerodynamics and making use of the FAMAS-MADOL computer system, confirmed the observed behavior. Free-free natural vibration modes of the aircraft that participated in the flutter are shown in figures 16 and 17.

The variations with flight speed of the aileron rotation and wing tip torsion-mode frequencies are shown in figure 18. The corresponding dampings of the coupled modes are shown in figure 19.

Flutter occurred despite the use of aileron mass balance to reduce the static unbalance to zero. The configuration included full wing fuel tanks and no external stores.

A number of distributions of mass balance weights along the aileron span were examined analytically, and it was concluded that the flutter problem could not be corrected solely by the use of mass balance. The moment of inertia of the basic aileron about the hinge line was so large that it became impractical even to overbalance the surface to uncouple the rotation mode. It became necessary to recommend a completely new lightweight aileron design to reduce rotational inertia.
Postulated flutter mechanism.—Inertial coupling of the plunge, pitch and control surface rotation degrees of freedom can be shown for rigid body motions as indicated in figure 20.

Control mass balancing (static balance) is accomplished by reducing the control surface mass offset arm to zero, \( \bar{x}_\beta = 0 \), so that \( S_\beta = 0 \). Examination of figure 20 then indicates that control rotation acceleration no longer produces vertical (or lift, \( L \)) inertia force and plunge acceleration, \( \dot{h} \), contributes no hinge moment (HM) to the control surface. Thus static balance uncouples the plunge and control rotation modes.

Control surface static balance, however, still permits control rotation acceleration to contribute pitching moment (M) to the section by virtue of the \( I_\beta \) term in the 2,3 matrix position and section pitch acceleration to produce hinge moment through the 3,2 term. Thus the pitch and control rotation degrees of freedom remain coupled even with statically balanced control surfaces. Control rotation/section pitch flutter thereby remains a possibility.
Overbalancing the control surface, i.e., by employing negative $\beta$, may allow

$$c_1 S_\beta + I_\beta = 0$$

and this uncouples the pitch and control surface rotation modes. Such a remedy may, however, introduce coupling of the control surface and plunge modes that leads to a different form of instability.

If this occurs it may be necessary to redesign the control surface to reduce its moment of inertia about the hinge line.

Flutter corrective action assessment.—A region of unacceptable flutter stability with the original aileron design is shown in figure 21. Analysis of an aileron of reduced moment of inertia and 110 percent overbalance static first moment is shown in figure 22. The second design was judged to be marginally satisfactory.

Overbalance, in this case, is defined as an additive nose-heavy balance equal to 110 percent of the original tail-heavy balance without counterweights.
Case 6: Elevon-Wing Torsion Flutter of a Delta Wing Model

This case, communicated to the authors by word of mouth, is included because of its similarity to Case 2. Both indicate the destabilizing effects of control surface aerodynamic balance.

Aircraft description.—A delta-wing wind tunnel model with its structure dynamically scaled to represent that of a full scale aircraft is the subject of Case 6. It had a single control surface per side that performed the functions of elevator and aileron. Such a surface is called an elevon.

The model was tested for flutter stability with the control surface, of constant size, hinged along the leading edge and along two chordwise positions aft of the leading edge.

Flutter Experience.—Three tests were performed of elevons of the same size, i.e., the same percent chord. The hinge axis was progressively moved aft from the leading edge in succeeding tests. This was expected to have the effect of increasing the aerodynamic balance, by the distributed balance method, and to progressively reduce hinge moment per unit control surface deflection.

In addition to the effect expected, however, a progressive decrease in flutter speed was noticed. This occurred even though a zero static mass balance condition was maintained in the three tests.

Postulated flutter mechanism.—It is suspected that the flutter mechanism is a coupling of an essentially wing-torsion mode with elevon rotation, and that an elevon rotation mechanical spring has been employed that raises the rotation-mode frequency to nearly that of the wing quasi-torsion mode.

The fact that the elevon is statically mass balanced does not uncouple the two modes, as is indicated in Case 5. The \( I_\beta \) coupling still exists.
With the progressive aft movement of the hinge axis, the aerodynamic spring-to-ground reduces, eventually to zero, and thus is ineffective in splitting the frequencies of the two modes. In addition the damping of the rotation mode also reduces with aft movement of the hinge axis to about 1/3 its value with the hinge at the control surface leading edge.

It is this reduction in damping that is suspected as the cause of the gradually reducing flutter speed with hinge-axis aft movement.

References