Aerodynamic Flutter

Flutter is a dangerous phenomenon encountered in flexible structures subjected to aerodynamic forces. This includes aircraft, buildings, telegraph wires, stop signs, and bridges. Flutter occurs as a result of interactions between aerodynamics, stiffness, and inertial forces on a structure. In an aircraft, as the speed of the wind increases, there may be a point at which the structural damping is insufficient to damp out the motions which are increasing due to aerodynamic energy being added to the structure. This vibration can cause structural failure and therefore considering flutter characteristics is an essential part of designing an aircraft.

Flutter Motion

The basic type of flutter of aircraft wing is described here. Flutter may be initiated by a rotation of the airfoil (see t=0 in Figure 1). As the increased force causes the airfoil to rise, the torsional stiffness of the structure returns the airfoil to zero rotation (t=T/4 in Figure 1). The bending stiffness of the structure tries to return the airfoil to the neutral position, but now the airfoil rotates in a nose-down position (t=T/2 in Figure 1). Again the increased force causes the airfoil to plunge and the torsional stiffness returns the airfoil to zero rotation (t=3T/4). The cycle is completed when the airfoil returns to the neutral position with a nose-up rotation. Notice that the maximum rotation leads the maximum rise or plunge by 90 degrees (T/4). As time increases, the plunge motion tends to damp out, but the rotation motion diverges. If the motion is allowed to continue, the forces due to the rotation will cause the structure to fail. [Click here to see a wind tunnel test model exhibiting flutter.]

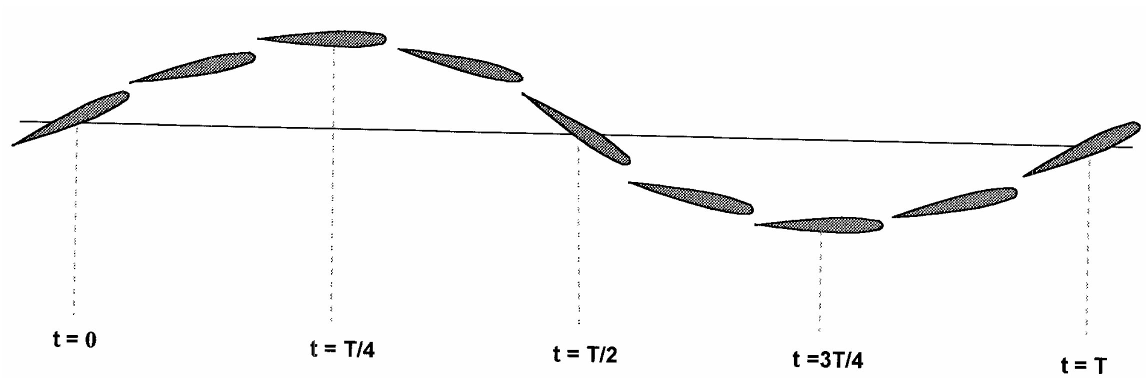

Figure 1 Rotation and Plunge Motion for an Airfoil Exhibiting Flutter

This flutter is caused by the coalescence of two structural modes – pitch and plunge (or wing-bending) motion. This example wing has two basic degrees of freedom or natural modes of vibration: pitch and plunge (bending). The pitch mode is rotational and the bending mode is a vertical up and down motion at the wing tip. As the airfoil flies at increasing speed, the frequencies of these modes coalesce or come together to create one mode at the flutter frequency and flutter condition. This is the flutter resonance.

Types of Flutter

Airfoils are used in many places on an airplane. The most obvious is the wing, but airfoil shapes are also used in the tail, propellers and control surfaces such as ailerons, rudders and stabilizers as shown in Figure 2. All of these conditions must be analyzed and tested to insure that flutter does not occur.

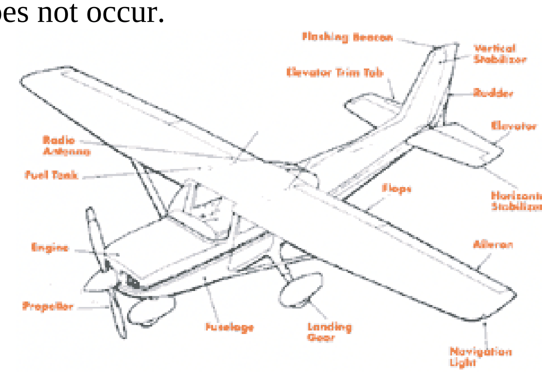

Figure 2 Airfoil Sections on a Typical Aircraft
(http://www.wingsoverkansas.com/learn/article.asp?id=256)

There is other flutter behavior that must be considered when designing aircraft: panel flutter, galloping flutter, stall flutter, limit cycle oscillations (LCO) or buzz, and propeller or engine whirl flutter. There can also be flutter due to stores mounted on the wing.

Panel flutter can occur when a surface is not adequately supported (think of the skin of an airplane acting like a drumhead). Figure 3 illustrates panel flutter motion.

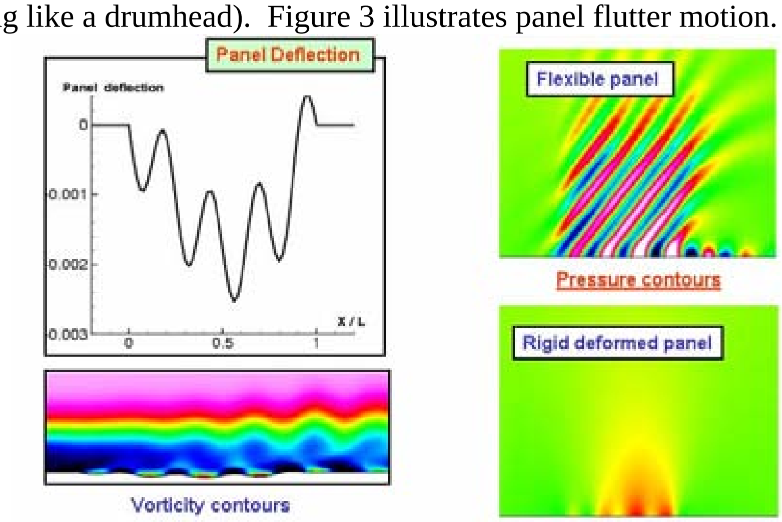

Figure 3 Panel Flutter
(http://www.va.afrl.af.mil/coe/comp/research/MDC/mdc_images/panel.jpg)

Galloping flutter, or wake vortex flutter, was the cause of failure of the Tacoma Narrows Bridge. [Click here to view video.] This phenomenon can be observed frequently along the roadside when telephone and power lines "gallop" due to strong winds. You may also observe car radio antenna aerials whipping under certain driving speeds. The cause of the galloping motion is formation of wake vortices downstream of the object. As shown in Figure 4, the vortices are shed alternately from one side of the object and then the other. These cause oscillatory forces and produce the back-and-forth motion. This type of flutter is an important design consideration for launch vehicles exposed to ground winds. [If you want to experiment with wake vortex shedding, click here.]

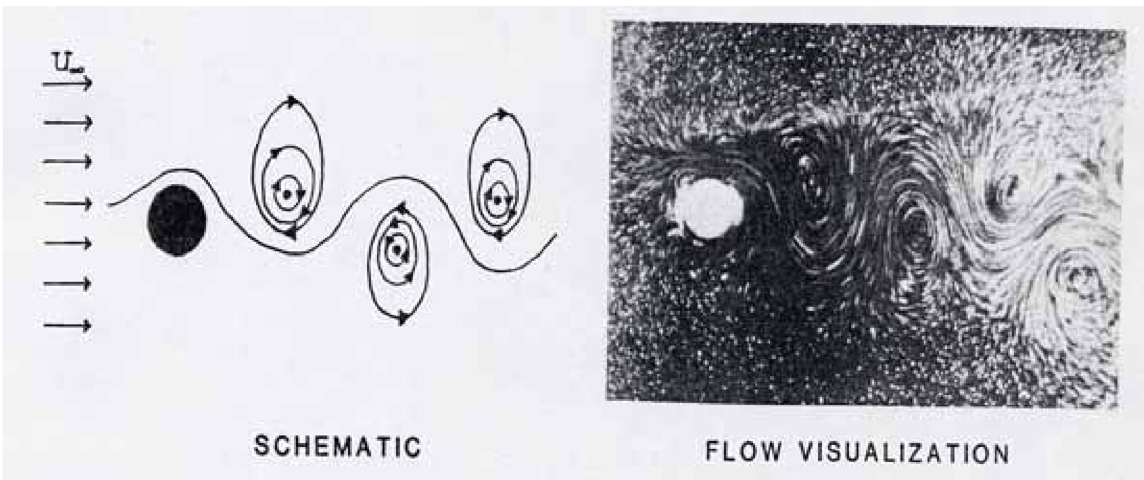

Figure 4 Wake Vortex Shedding from a Cylinder

Stall flutter is a torsional mode of flutter that occurs on wings at high loading conditions near the stall speed. Because the airflow separates during stall, this single degree-of-freedom flutter cannot be explained by classical flutter theory.

Limit cycle oscillation (LCO) behavior is characterized by constant amplitude, periodic structural response at frequencies that are those of the aeroelastically-loaded structure. LCO is typically limited to a narrow region in Mach number or angle-of-attack signaling the onset of flow separation.

Engine whirl flutter is a precession-type instability that can occur on a flexibly mounted engine-propeller combination. The phenomenon involves a complex interaction of engine mount stiffness, gyroscopic torques of the engine and propeller combination, and the natural flutter frequency of the wing structure. [Click here to see a model exhibiting whirl flutter.]

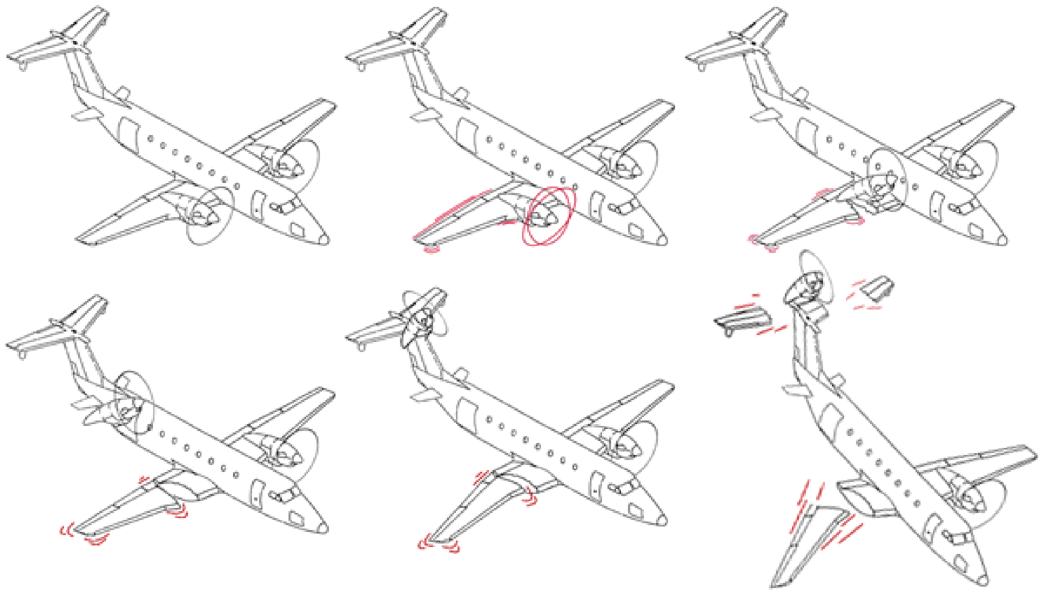

Figure 5 Engine Whirl Flutter
(http://www.acoustics.org/press/133rd/2psa1.html)

Classical Flutter Definition

As early aircraft were able to fly at greater speed, flutter may have caused many crashes. The flutter phenomenon was first identified in 1918 on a Handley Page bomber in Lanchester, England. The flutter mechanism consisted of a coupling of the fuselage torsion mode with an anti-symmetric elevator rotation mode. The elevators on this airplane were independently actuated. The solution to the problem was to interconnect the elevators with a torque tube.

Scientists and engineers studied flutter and developed theories for the cause and mathematical tools to analyze the behavior. In the 1920s and 1930s, unsteady aerodynamic theory was developed. Closed-form solutions to simple, academic problems were studied in the 1940s and 1950s. In the next thirty years, strip theory aerodynamics, beam structural models, unsteady lifting surface methods (e.g. double-lattice) and finite element models expanded analysis capabilities. The advent of digital computers has further supported the development of other powerful methods. Disciplines involved in analyzing flutter include aerodynamics, structural finite element modeling, control theory (specifically aeroservoelasticity), and structural dynamics.

The following example of a simple two degree-of-freedom model is fundamental to understanding flutter behavior. Aerodynamic forces excite the structural spring/mass system (see Figure 9). The plunge spring represents the bending stiffness of the structure and the rotation spring represents the torsional stiffness. The shape of the airfoil determines the aerodynamic center. The center of gravity is determined by the mass distribution of the cross-section (that is, how the airfoil is constructed). The model represents two “modes” – plunge and rotation as shown in Figure 6. Figure 7 shows a similar model for an airfoil with a control surface. The aerodynamic forces are illustrated in Figures 8 and 9.

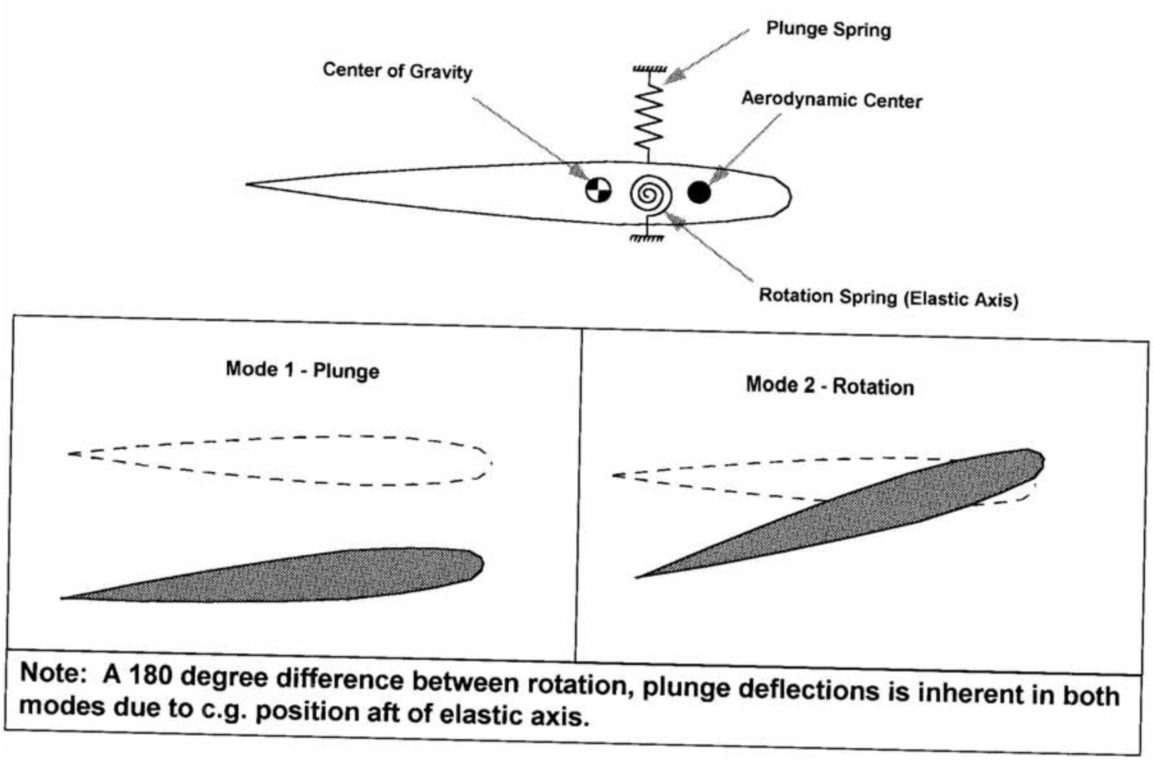

Figure 6 Airfoil Flutter Model and Modes

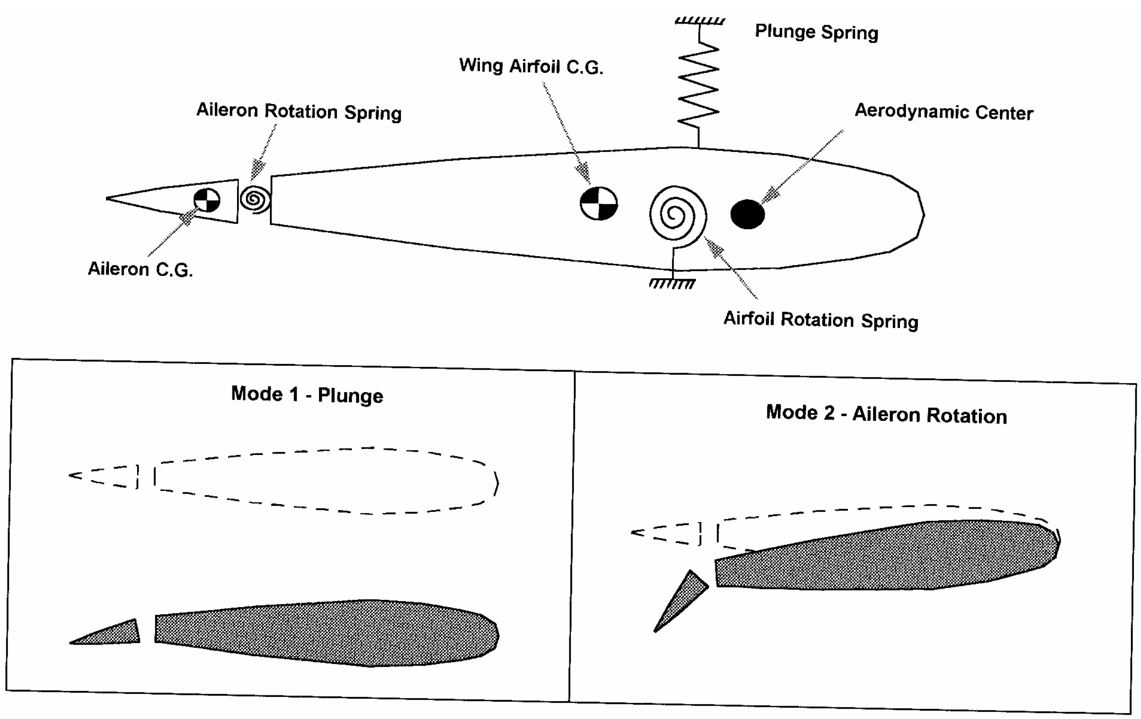

Figure 7 Wing/Aileron Flutter Model and Modes

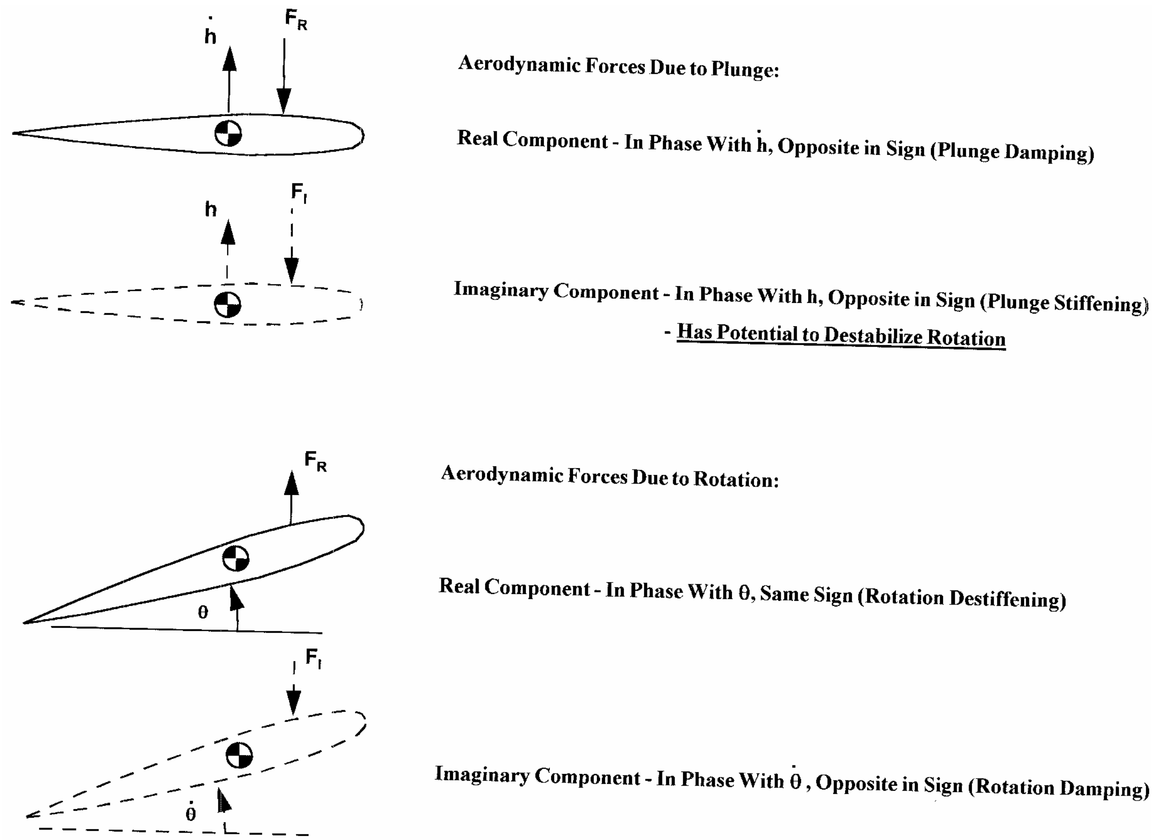

Figure 8 Phasing of Aerodynamic Forces

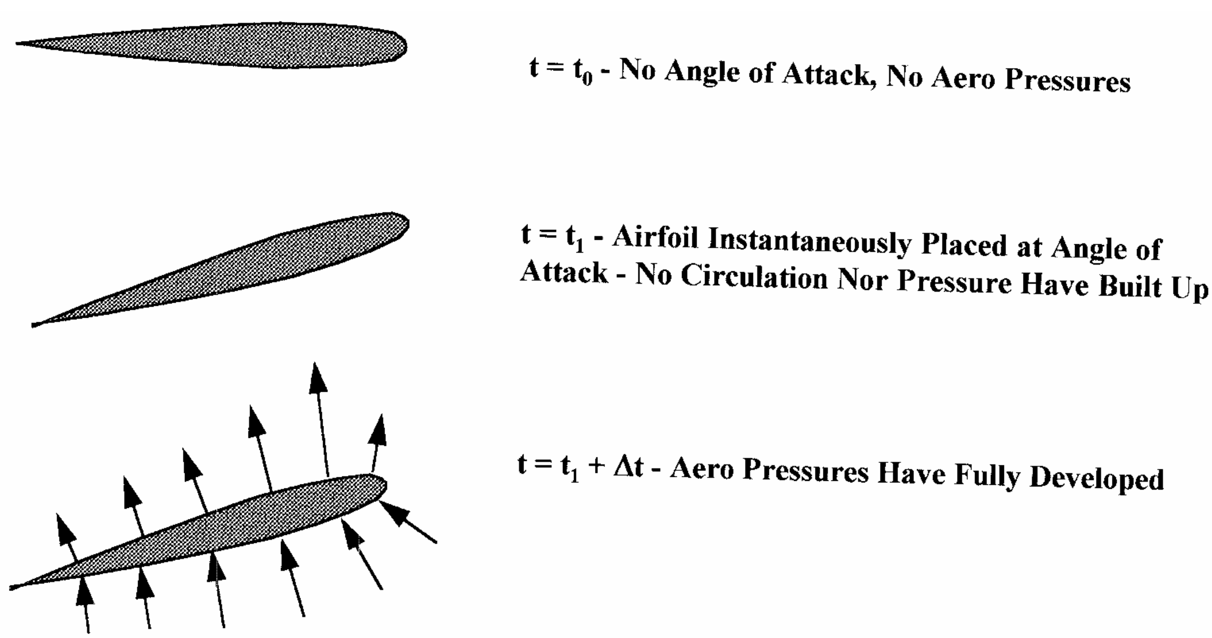

Figure 9 Aerodynamic Lag

Flutter Equation of Motion (for the more advanced student)

If modes of structural vibration are used in a dynamic analysis, the below equation can be used to determine a model's flutter characteristics. This equation is the result of assuming simple harmonic motion $\{u(t)\} = \{u_h\}e^{i\omega t}$ and placing this into the corresponding second order ordinary differential equations that describe the linear dynamic behavior of a structure that is subjected to forces and moments due to fluid flow. Figure 10 shows a flow diagram with the operations to solve the below equation.

$$\left[M_{hh} p^2 + \left(B_{hh} - \rho c V Q^I_{hh} / 4k \right) p + \left(K_{hh} - \rho V^2 Q^R_{hh} / 2 \right) \right] \{u_h\} = 0$$

M_{hh} – modal mass matrix
B_{hh} – modal damping matrix
K_{hh} – modal stiffness matrix
Q^I_{hh} – generalized aerodynamic damping matrix
Q^R_{hh} – generalized aerodynamic stiffness matrix
ρ – air density
c – mean aerodynamic chord length
V – airspeed
$k = \omega c/2V$ – reduced frequency
ω–circular frequency
p- iω – ($i = \sqrt{-1}$)
u_h – modal displacements

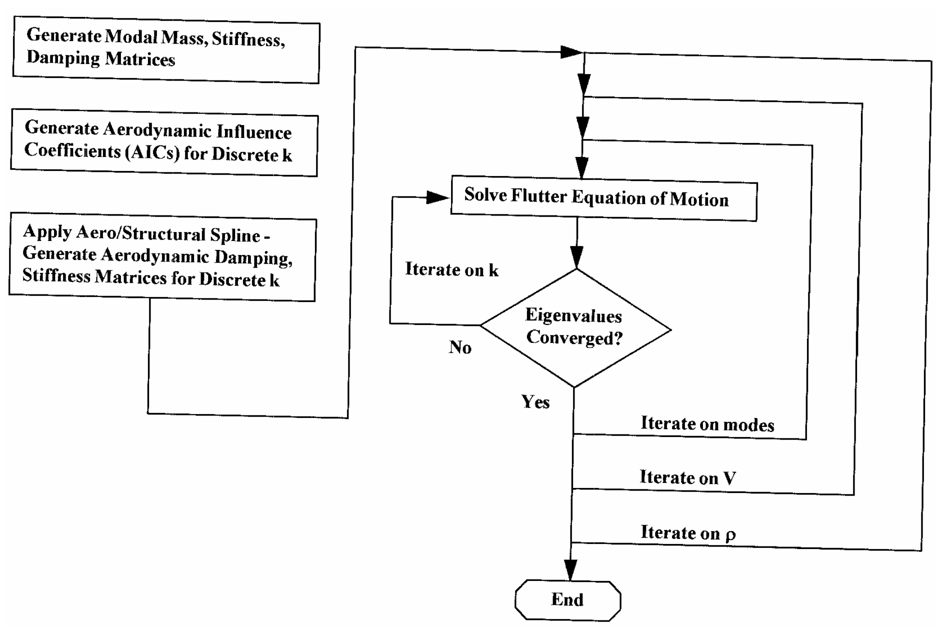

Figure 10 Flow Diagram for Solution of Flutter Equations of Motion (at a Single Mach Number)

One common form of flutter analysis is the V-g analysis. In V-g analysis, the structural damping of all the modes of vibration is assumed to have one unknown value, g. In Figure 11, the results for two modes (roots of the flutter determinant) of the simple wing model with 2 degrees of freedom are shown in the form of frequency versus velocity and damping versus velocity curves. In the bottom plot of Figure 11, the velocity at which the upper curve passes through g=0 corresponds to the flutter velocity of the model if the (conservative) assumption of zero structural damping is made. One is then able to determine the flutter frequency of the model using the upper plot of Figure 11 and picking off the frequency value of the unstable mode at the flutter velocity value. The slope of the damping versus velocity curve as it passes through the flutter velocity can be thought of as a qualitative measure of how violently the oscillations would occur during accelerated flight.

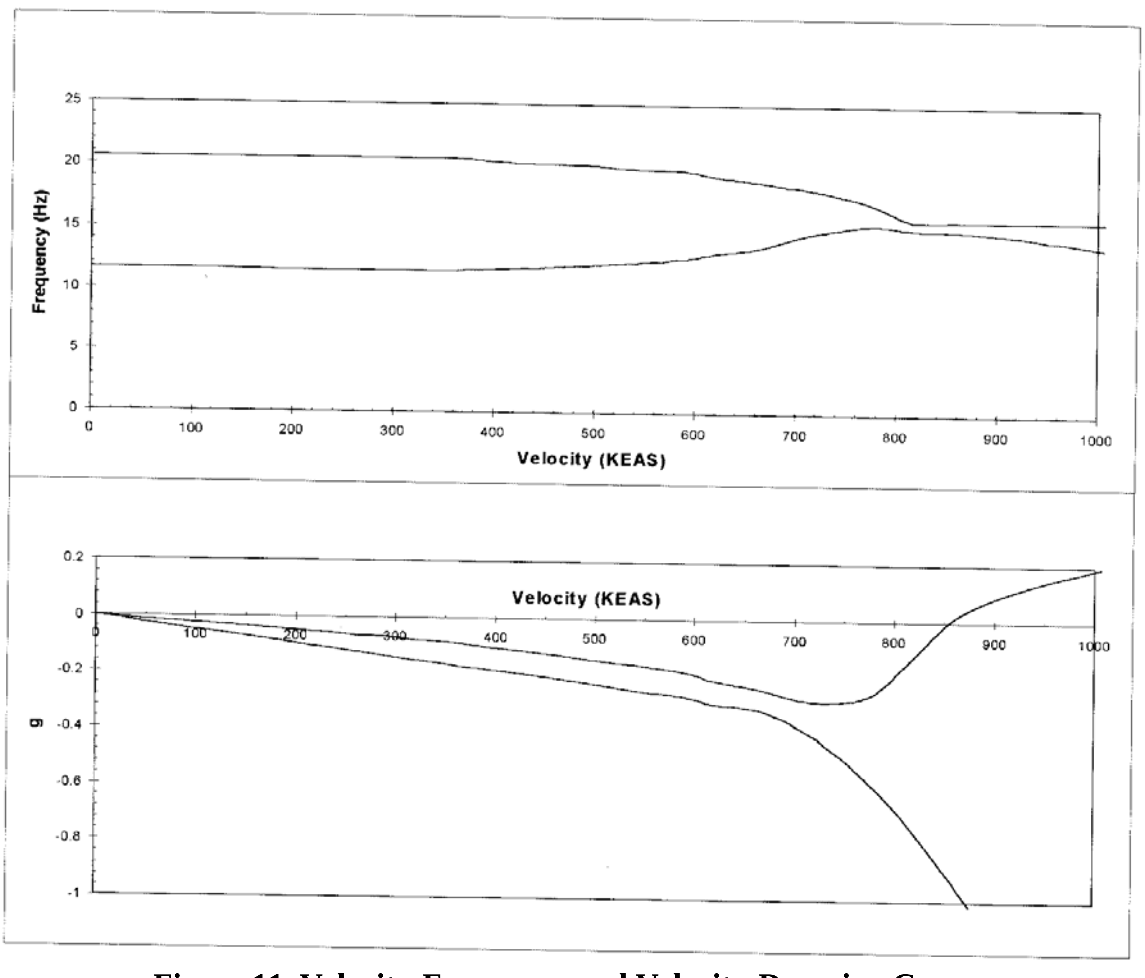

Figure 11 Velocity-Frequency and Velocity-Damping Curves

Flutter Fixes

Because flutter can be analyzed, designs can be modified to prevent flutter before an aircraft is built, tested and flown. One design parameter is the maximum air speed. In particular, the ratio of the energy input to the energy dissipated will depend on the air speed. A steady oscillation may occur when this ratio is unity. The air speed for this case is called the "critical air speed." An aircraft may have various possible flutter modes. Ideally, the lowest critical speed exceeds the highest possible flying speed by a reasonable safety margin.

There are several additional measures to prevent flutter. One method is to uncouple the torsion and bending motion by modifying the mass distribution to move the center of gravity closer to the center of twist (see Figure 12 for some examples). Another method is to increase the stiffness/mass ratios within the structure. This would increase the natural frequencies. Note that the energy input per cycle during flutter is nearly independent of frequency. The energy dissipated per cycle is proportional to frequency, however.

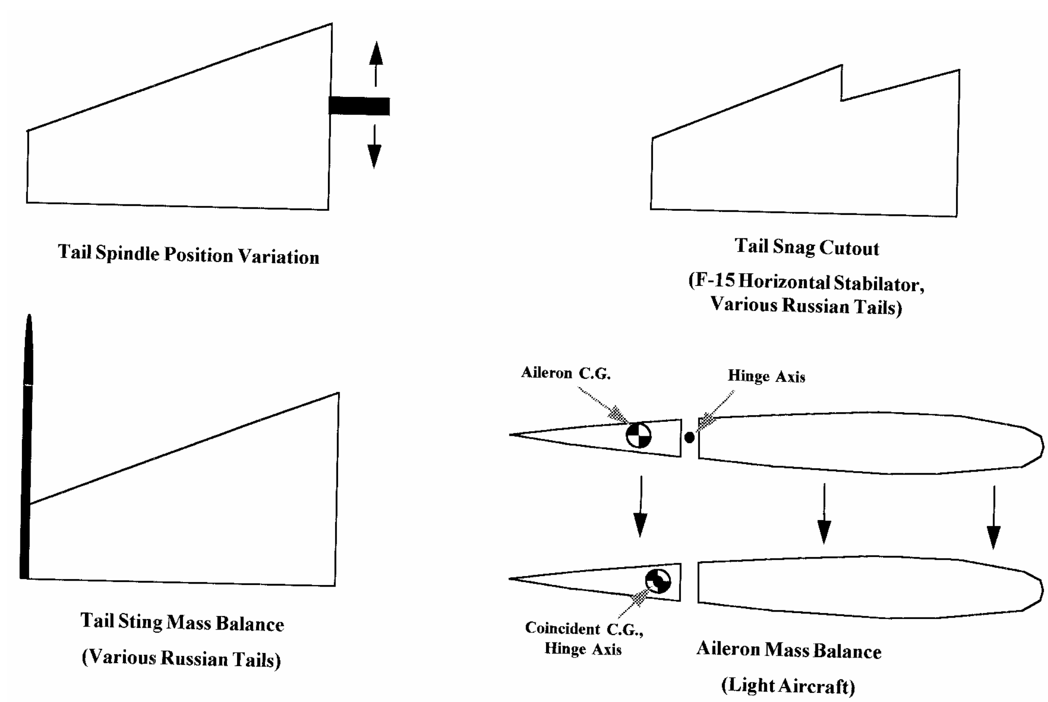

Figure 12 Potential Modifications to Mass Balance of Aileron

Flutter characteristics of a model are a function of many structural parameters including the shape of the airfoil section, the elastic axis position, the position of the center of gravity, the airfoil section mass and mass moment of inertia about the elastic axis, the torsion rigidity and the frequency separation between the plunge and rotation mode.

The two plots in Figure 13 show how varying two of these parameters, rotational stiffness and elastic axis, affects the flutter and divergence characteristics of a two-dimensional flutter model. In the top plot of this figure, for a given rotational stiffness, the flutter speed of the model is plotted versus the position of the elastic axis (point where springs act through in Figure 6). In the bottom figure, the required rotational stiffness value so that a particular form of instability will not occur is plotted versus elastic axis position. Using this figure, one can determine for a given elastic axis position, what the rotational stiffness must be such that flutter and static divergence do not occur.

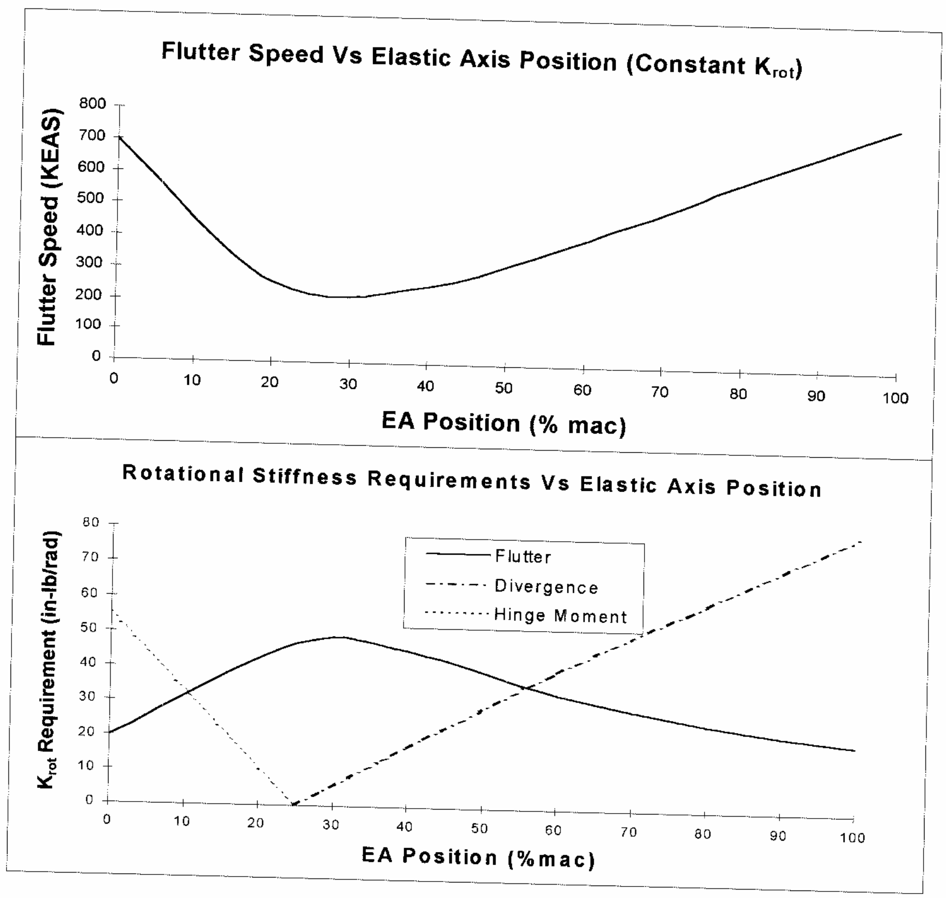

Figure 13 Stiffness Requirements

Testing

After the design is analyzed the aircraft undergoes wind tunnel testing (Figure 14) and flight-testing to verify the analysis. Low-speed wind tunnel testing of the full-span model with scaled stiffness and mass properties visually identifies instabilities. [Click here to see a video of a wind tunnel test.] High-speed wind tunnel tests investigate the transonic flight regime. The models are heavily instrumented to verify aerodynamic forces and reactions.

One facility used extensively for flutter clearance testing (which means to insure that flutter does not occur within the envelope of where the aircraft will fly) is the NASA Langley Research Center's Transonic Dynamics Tunnel (TDT). The NASA Langley TDT has provided a unique capability for aeroelastic testing for over forty years. [Click here to learn more about flutter testing.]

Flutter clearance or risk reduction tests are aimed at uncovering potential flutter problems and identifying potential solutions of a specific design through airplane configuration studies and tests of various components.

Wind-tunnel models are dynamically and aeroelastically scaled to a "theoretical" airplane configuration. The results from these tests are considered experimental research that contributes to the flutter clearance of the aircraft configuration.

Finally, flight-testing is performed at many conditions in the flight envelope. The control surfaces are excited and response characteristics are measured. As speed is incrementally increased, frequency and damping trends are calculated from the measured responses. A successful design exhibits no flutter behavior in the flight envelope.

Figure 14 Wind Tunnel Test Model in the NASA Langley TDT
(http://lisar.larc.nasa.gov/UTILS/info.cgi?id=EL-1996-00023)

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