Lecture 5

Flight Flutter Testing

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Flight flutter testing

- Despite all the efforts in developing design flutter tools, the only definitive method for clearing aircraft for flutter is **flight testing**

- All airworthiness and aircraft certification procedures require that aerospace constructors demonstrate that the flight envelope of a new aircraft is clear of flutter

- In fact, for added security, **there must be no flutter at 20% outside the flight envelope** (15% for military aircraft)
First flight flutter tests were very basic:

Aircraft flown to all the extremes of their flight envelope

They survived
→ Aircraft = safe

They were destroyed
→ To be redesigned

Clearly, this was not a satisfactory way of carrying out such tests.

Von Schlippe performed the first formal flutter tests in 1935 in Germany
Von Schlippe’s test

- Von Schlippe flew the aircraft at an initially low airspeed.
- He vibrated the aircraft structures at its natural frequencies at each airspeed and plotted the resulting vibration amplitude.
- He predicted flutter when the amplitude reaches a high value (theoretically infinite).
- He estimated the natural frequencies of the structure during ground vibration tests.
Further history

- Von Schlippe’s technique continued to be used until a Junkers Ju90 aircraft fluttered in flight and crashed.

- The problems with the procedure were:
  - Inadequate structural excitation in flight
  - Inaccurate measurement of response amplitude
  - Inaccurate stability determination techniques
1940s in the USA

Same technique in the 1940s
Example: Cessna AT-8 aircraft

At speeds near 230 mph, the wing oscillations were so large that the pilot became very much concerned. Fortunately, the flutter engineer had to kneel on the cabin floor in order to control the exciter and the recording equipment, and thus was unable to see the large wing oscillations or the tests would undoubtedly have been stopped before 230 mph had been reached.

A psychological incident was noted during these tests which was noted many more times in succeeding flight flutter tests in later years. This was that although the pilot was concerned over the large oscillations being induced in the aircraft, he was not frightened by the tests. In discussing this factor with other pilots of aircraft involved in flight flutter tests, most all of the pilots were of the opinion that if a flutter engineer was along on a test, that test couldn't be too dangerous. This is an instance of the old adage that 'ignorance is bliss'.
Progress

• Von Schlippe’s flight flutter testing method was good but the instrumentation not very advanced.

• Between the 50s and 70s several advances in actuation and instrumentation

• The response amplitude was replaced by the damping ratio as the flutter parameter
F111 Flight test apparatus (70’s)

Onboard recorder and TM transmitter

Aero tab excitation

Ground control and data processing

TM receiving and tape recording

Band pass filters

Brush recorders
16 channels
accel and aero tab
8 channels
flight parameters
and control system
(unfiltered)

X-Y frequency sweep plotters
Band pass filtered
to accel choice
Record two at one time

Test director

Postflight

Airplane tape

Brush record of all transducers

Manual data reduction
(g versus Mach)
Typical modern apparatus
Excitation systems

An ideal excitation system =

- Provide adequate excitation levels at all the frequency ranges of interest

- Be light so as not to affect the modal characteristics of the structure

- Have electrical or hydraulic power requirements that the aircraft can meet
Control surface pulses

• **Impulsively** moving one of the control surfaces and then bringing it **back to zero**
• **Theoretically** = perfect impulse (excite all the structure’s modes)
• **In practice** only modes of up to 10Hz are excited
• The transient response of the aircraft is easy to analyse for stability
• However, high damping rates and lots of measurement noise can make this analysis difficult
• The **repeatability** of pulses is low
Oscillating control surfaces

• Instead of just **pulsing** the control surfaces → **oscillate** them sinusoidally

• Three modes:
  – **Dwell**: Oscillation at constant frequency and amplitude
  – **Frequency sweep**: oscillation at constant amplitude but linearly increasing frequency
  – **Amplitude sweep**: oscillation at constant frequency but linearly increasing amplitude

• The demand signal is provided by the automatic control system. The excitation is accurate and can range from 0.1Hz to 100Hz.
Control surface excitation

C-5 Galaxy – Flight flutter test using control surface excitation
Control surface excitation

Airbus A350 – Flight flutter test using control surface excitation

- We are at 3.5 Hz.
Thrusters

= Small one-shot rockets that burn for 20ms and provide thrust up to 2,000Kg.

• aka bonkers, ballistic exciters, impulse generators
• They are attached at points that allow the measurement of particular modes of interest
• They are not used very much now. They have several disadvantages:
  – Single shot
  – Difficult to fire two or more simultaneously
  – Need thrusters of different burn times to excite different frequencies
Inertial exciters

- Rotating eccentric weight or oscillating weight inertial exciters.
- Low excitation capability is at low frequencies and too high at high frequencies.
- Not very popular nowadays.
Aerodynamic vanes (1)

- Small winglets mounted on tip of a wing or a stabilizer
- The vanes are mounted on a shaft and oscillate around a mean angle (= rotating vane)
- The force depends on the size of the vane, the dynamic pressure and the oscillation angle
- They excite low frequencies adequately
- High frequency excitation depends on the frequency response of the mechanism
- Sweep frequency from 1Hz to 10Hz within 7 min.
- (-) Force depends on the square of the airspeed (i.e. at low speeds it is low)
- (-) Addition of mass, disturbing the flow at wind tip
Aerodynamic vanes (2)

- Fixed vane + rotating slotted cylinder
- The cylinder oscillates, deflecting the airstream either upwards or downwards and creating an oscillating lift force
- Main advantage: low power

Flutter exciter (patented)
Flutter exciter
US 4809553 A

ABSTRACT
A flutter exciter induces vibration either for actual aircraft flight testing or for wind tunnel model testing. The basic flutter exciter unit is a pair of rotatable concentric cylinders mounted on either a fixed vane or an aircraft wing or a tail surface. Each cylinder has a slot which allows the air flow to pass therethrough. By rotating the cylinders together, oscillating air pressures are induced on the fixed vane or the aircraft surface to which the cylinders are attached. The cylinders may be mounted at a trailing edge of either the fixed vane or the aircraft wing, to any tail surface, or on any other lifting surfaces of the aircraft itself. Thus, because the flutter exciter can be made as a completely self-contained unit, it may be simply mounted to any suitable hard point on either the test model or the aircraft. The power required to rotate the slotted cylinders is minimal, thus allowing the use of a low wattage motor.

IMAGES (3)
Aerodynamic vanes (4)

Figure 6. F-16XL with vane and rotating slotted cylinder excitation system (ref. 26).
Random atmospheric turbulence

Stable atmosphere vs Unstable atmosphere

- Free!
- No impact on the tested aircraft: does not change the modal or control characteristics.
- Low levels of excitation
- Not predictable
- Low signal-to-noise ratio of the response data.

Stratus clouds

Cumulonimbus clouds
Von Karman Spectrum

= Model of the frequency content of atmospheric turbulence

\[ \Phi_{11}(\omega) = \sigma_g^2 \frac{L}{\pi} \frac{1}{\left(1 + \left(1.339 \omega \frac{L}{V}\right)^2\right)^{5/6}} \]

\[ \Phi_{22}(\omega) = \sigma_g^2 \frac{L}{\pi} \frac{1 + \frac{8}{3} \left(1.339 \omega \frac{L}{V}\right)^2}{\left(1 + \left(1.339 \omega \frac{L}{V}\right)^2\right)^{11/6}} \]

Longitudinal turbulence

Lateral turbulence

where \( \omega = \) angular frequency

\( L = 762\text{m} = \) length scale of turbulence

\( V = \) is the aircraft’s speed

\( \sigma_g = 2.1-6.4 = \) turbulence intensity

Excites all surfaces simultaneously

\( \rightarrow \) Sym & anti-sym modes
Von Karman example

Airspeed = 200m/s and \( \sigma_g = 2.1 \).

Most of the power is concentrated at very low frequencies (< 1Hz).

The power at frequencies of 10Hz or more is very low.
Comparison of 2 excitation systems

Exciter sweep VS Random turbulence

Response amplitude power spectra:

\[ \text{Amplitude, } g^2 \]

\[ \text{Frequency, Hz} \]

\[ \text{Amplitude, } g^2 \]

\[ \text{Frequency, Hz} \]

(a) Exciter sweep.

(b) Random turbulence.

→ Only one mode at 8Hz appears when using atm. turbulence
Comparison of 2 excitation systems

Exciter sweep VS Random turbulence

Response amplitude power spectra:

→ Identified dampings are always smaller when using atm. turb.
## Summary of exciters

<table>
<thead>
<tr>
<th>Airplane</th>
<th>Surface</th>
<th>Location</th>
<th>Frequency range</th>
<th>Time to sweep, sec</th>
<th>Sweep law</th>
</tr>
</thead>
<tbody>
<tr>
<td>747</td>
<td>Wings</td>
<td>External vanes at wingtips</td>
<td>1.5–7.0 Hz</td>
<td>90</td>
<td>Exponential</td>
</tr>
<tr>
<td>DC-10</td>
<td>Wings horizontal Vertical tail</td>
<td>External vanes at tips of main surfaces</td>
<td>1–20 Hz and 1–10 Hz</td>
<td>90</td>
<td>Exponential</td>
</tr>
<tr>
<td>L-1011</td>
<td>Wing stabilizer</td>
<td>External vanes</td>
<td>1–18 Hz 3–25 Hz</td>
<td>90 30</td>
<td>Linear period</td>
</tr>
<tr>
<td>S-3A</td>
<td>Side of fuselage under stabilizer</td>
<td>External vanes</td>
<td>1.5–18 Hz 3–25 Hz</td>
<td>90</td>
<td>Linear period</td>
</tr>
<tr>
<td>C-5A</td>
<td>Wing stabilizer</td>
<td>External vanes on top of surfaces near tips</td>
<td>5–25 Hz</td>
<td>60 normal 30 dive only</td>
<td>Exponential</td>
</tr>
<tr>
<td>F-14</td>
<td>Wing fin</td>
<td>Aero-tab External vane</td>
<td>5–50 Hz</td>
<td>15</td>
<td>Exponential</td>
</tr>
<tr>
<td>F-15</td>
<td>Normal control Ailerons Stabilator</td>
<td></td>
<td>2–16 Hz 5–10 Hz</td>
<td>100–200 45</td>
<td>Linear frequency</td>
</tr>
<tr>
<td>F-111</td>
<td>Wing</td>
<td>Aero-tab</td>
<td>35–2 Hz</td>
<td>45</td>
<td>Exponential</td>
</tr>
</tbody>
</table>
Excitation Signals

• **Four main types** of excitation signals used:
  – Impulsive
  – Dwell (constant frequency and amplitude)
  – Sweep (constant amplitude but increasing frequency)
  – Noise

• Dwell only excites **one frequency at a time**. Therefore, it is **expensive** since the test must last longer.

• Impulsive, sweep and noise excite **many frequencies at a time**.
Frequency sweep (chirp)

Frequency sweep from 1Hz to 30Hz
Noise

Uniform noise from 1Hz to 30Hz

Time domain

Frequency domain
Real test data example

Data obtained during a flight flutter test

Three dwells between 5Hz and 6Hz and one sweep from 5Hz to 7Hz.

Excitation is control surface deflection.
Data Analysis

Steps:
1. Set an airspeed and an altitude
2. Apply excitation force

\[\text{The aircraft structure’s response is measured at several locations (e.g. wingtip, tail tip, engine mounts etc) by accelerometers.}\]

3. The excitation and response data are saved and/or transferred to a ground station
4. The analysis uses \textit{simple but effective modal analysis tools}
Data Analysis

- FFT within 1 sec
- Noise added by telemetry
- freq & dampings

 timpelit Uimg
Data Analysis

Response signal to deal with are:

- **Random response** caused by atm. turbulence

- **Transient response** caused by impulse input or exciter frequency dwell-quick-stop

- **Steady state response** caused by exciter frequency sweeps.
Modal Analysis (1)

As only one excitation is applied at any one time, the system is Single Input Multiple Output (SIMO).

\[ y_i(t) = i^{th} \text{ measured response} \]
\[ f(t) = \text{excitation force} \]

The \( i^{th} \) Frequency Response Function of the system is defined as:

\[ H_i(\omega) = \frac{Y_i(\omega)}{F(\omega)} \]

where \( Y_i(\omega) \) is the Fourier Transform of the \( y_i(t) \) signal and \( F(\omega) \) is the Fourier Transform of the \( f(t) \) signal.
Modal Analysis (2)

• Better FRF estimators could be applied but are not used in practice (speed and simplicity).

• FRFs are plotted and inspected by the test operator, along with the time domain responses and the response predictions from an aeroelastic mathematical model.

• The FRFs are also analysed in order to extract the natural frequencies and damping ratios.
Simulated Example

Excitation force and three responses from a simulated flight flutter test

Excitation signal = chirp from 1Hz to 45Hz.

Natural frequencies of the aircraft (from GVT) are 8Hz, 16Hz and 39Hz.
Simulated Example

All three FRFs show three modes in the interval from 1Hz to 45Hz.

Only two modes are clearly visible in response 1.

Response 3 is best for observing all three modes.

→ Important to analyze many responses from the aircraft

\[ H_i(\omega) = \frac{Y_i(\omega)}{F(\omega)} \quad i=1,2,3 \]
Simulated Example

Effect of airspeed: The three modes are affected

Peaks height changes

High peak $\rightarrow$ low damping

2nd mode:
- $15 < V < 30$ $\rightarrow$ height falls
- $V > 35$ $\rightarrow$ height increases
- At $V=40$ m/s $\rightarrow$ high peak

$\rightarrow$ The damping of this mode will go to zero at flutter.
Parameter Estimation

- The **damping** ratio and **natural frequency** of each mode are the parameters of the mode.
- They must be estimated in order to determine how close the system is to flutter.
- There are **many parameter estimation methods**, ranging from the simple to the most accurate.
- The quality and resolution of data available from flight flutter tests suggests that **simpler methods should be used**.
- The simplest method is the **Half Power Point**
Nevertheless, it is always used, even when more sophisticated parameter estimation techniques are applied.

The best algorithms and computers are no replacement for an engineer with a ruler and plotting paper, apparently.

Half Power Point method = **graphical approach**,

→ Not very accurate.
Rational Fraction Polynomials (1)

The FRF of any dynamic system can be written as:

\[
H(\omega) = \frac{Y_i(\omega)}{F(\omega)} = \frac{b_{nb}(i\omega)^{nb} + b_{nb-1}(i\omega)^{nb-1} + \cdots + b_0}{(i\omega)^{na} + a_{na-1}(i\omega)^{na-1} + \cdots + a_0}
\]

where the coefficients \( a_i, b_i \) are to be estimated from \( L \) measured values of the FRF at \( L \) frequency values.

\[
\begin{bmatrix}
H(\omega_1)(i\omega_1)^{na} \\
\vdots \\
H(\omega_L)(i\omega_L)^{na}
\end{bmatrix} = -\begin{bmatrix}
H(\omega_1)(i\omega_1)^{na-1} & \cdots & H(\omega_1)(i\omega_1)^{nb} & \cdots & 1 \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
H(\omega_L)(i\omega_L)^{na-1} & \cdots & H(\omega_L)(i\omega_L)^{nb} & \cdots & 1
\end{bmatrix} \begin{bmatrix}
a_{na-1} \\
\vdots \\
a_0 \\
b_{nb} \\
b_0
\end{bmatrix}
\]
Rational Fraction Polynomials (2)

• The denominator is the system’s characteristic polynomial.

• Once the $a_i, b_i$ coefficients are estimated, the system eigenvalues can be calculated from the roots of the denominator.

• The polynomial orders $na$ and $nb$ are usually given by $na=2m$ and $nb=2m-1$ where $m$ is the number of modes that we desire to model.

• In order to allow for experimental and signal processing errors, the polynomial order can be chosen to be higher than $2m$. 
Latest modal analysis

• Until recently, only very basic modal analysis was used in flight flutter testing

• The quality of data, the number of transducers and the cost of the flight testing programme prohibited the use of more sophisticated methods.

• These days, more and more high end modal analysis is introduced in flight flutter testing, e.g.
  – Polyreference methods
  – Stabilization diagrams
  – Operational modal analysis
  – Model updating
Damping trends

• The damping ratio trends are plotted and a linear extrapolation is usually performed to determine whether the next planned flight condition will be tested.

= most important part of the flight flutter test.
The objective of the test is not to reach the flutter point, nor to predict it accurately. It is to clear the flight envelope:
• If the flight envelope has been cleared (i.e. all flight points tested) the test is finished.
• If one flight point is deemed unsafe (i.e. too close to flutter), the test is finished.
Modal parameter variation

Complete variation of the modal parameters with airspeed

→ Obtained gradually by the test director
Initially, the damping increases.

→ Flight conditions are considered safe until $V=30\text{m/s}$.

At $V=40\text{m/s}$ the damping ratio of mode 2 drops suddenly and significantly

→ Flight condition is near critical and the flight flutter test is finished.
Damping Extrapolation

• An estimate of the stability of each flight condition can be obtained if the damping ratio is plotted against dynamic pressure. The resulting graphs are nearly linear.

• At each flight condition the last two measured damping ratio values can be linearly extrapolated to estimate the flutter flight condition.

• If \( \mathbf{d} \) is the vector containing the damping ratio measurements for mode 2 and \( \mathbf{q} \) the vector containing the flight dynamic pressures:

\[
q_{\text{crit}} = -\frac{c}{a} \quad \text{where} \quad \mathbf{d} = \begin{bmatrix} \mathbf{q} & 1 \end{bmatrix} \begin{bmatrix} a \\ c \end{bmatrix}
\]
At $V=35\text{m/s}$ the predicted flutter speed is over $70\text{m/s}$.

At $V=40\text{m/s}$ the predicted flutter speed is $48\text{m/s}$.

The true flutter speed is $44\text{m/s}$.
Hard flutter

= very sudden drop in damping ratio
Other stability criteria

• Damping ratio can be misinterpreted as a stability criterion.
• Alternative stability criteria have been proposed and some of them are used in practice.
• The most popular of these are:
  – The Flutter Margin
  – The Envelope Function
Flutter Margin (1)

- The Flutter Margin is defined for the case of a classical binary flutter mechanism.
- The aircraft may have many modes but the Flutter Margin procedure is only applied to the two modes that combine to cause flutter.
- The characteristic polynomial is of the form:
  \[ a_4 \lambda^4 + a_3 \lambda^3 + a_2 \lambda^2 + a_1 \lambda + a_0 \]
- The Routh stability criterion requires that:
  \[ a_3 a_2 a_1 - a_4 a_1^2 - a_0 a_3^2 = 0 \]
Flutter Margin (2)

Without loss of generality we can set $a_4=1$ and divide by $a_3^2$ to get:

$$F = -\left( \frac{a_1}{a_3} \right)^2 + a_2 \left( \frac{a_1}{a_3} \right) - a_0 = 0$$

where $F$ is called the Flutter Margin. Writing the four eigenvalues as

$$\lambda_1 = \beta_1 + i \omega_1, \lambda_2 = \beta_1 - i \omega_1, \lambda_3 = \beta_2 + i \omega_2, \lambda_4 = \beta_2 - i \omega_2$$

yields

$$F = \left[ \left( \frac{\omega_2^2 - \omega_1^2}{2} \right) + \left( \frac{\beta_2^2 - \beta_1^2}{2} \right) \right]^2 + 4 \beta_1 \beta_2 \left[ \left( \frac{\omega_2^2 + \omega_1^2}{2} \right) + 2 \left( \frac{\beta_2^2 + \beta_1^2}{2} \right) \right]^2 -$$

$$\left[ \left( \frac{\beta_2 - \beta_1}{\beta_2 + \beta_1} \right) \left( \frac{\omega_2^2 - \omega_1^2}{2} \right) + \left( \frac{\beta_2^2 + \beta_1^2}{2} \right)^2 \right]$$
Flutter Margin (3)

\( \beta_i \) and \( \omega_i \) are linked to the modal parameters of the \( i^{th} \) mode through:

\[
\beta_i = \omega_{n,i} \xi_i \quad \omega_i = \omega_{n,i} \sqrt{1 - \xi_i^2}
\]

If \( F > 0 \) then the aircraft is aeroelastically stable.

If \( F \) begins to approach 0, then the aircraft is near flutter.
Flutter Margin evolution

Using the pitch-plunge quasi-steady equations, it can be shown that the ratio $a_1/a_3$ is proportional to the dynamic pressure, i.e.

$$\frac{a_1}{a_3} \propto q, \quad q = \frac{1}{2} \rho U^2$$

→ Flutter Margin = quadratic function of $q$

$$F = -\left(\frac{a_1}{a_3}\right)^2 + a_2\left(\frac{a_1}{a_3}\right) - a_0 = 0 \quad \rightarrow \quad F = B_2 q^2 + B_1 q + B_0$$
Flutter Margin conclusions

• Flutter Margin is as good a stability criterion as the damping ratio.
• Its variation with airspeed and density is known.

\[ F = B_2 q^2 + B_1 q + B_0 \]

• In fact, true aeroelastic systems are **unsteady** not quasi-steady.

→ \( F \) is not really a known function of \( q \).
→ But it behaves more smoothly than the damping ratio in the case of hard flutter.
Comparison to damping ratio

FM drop is less abrupt than the drop of the damping ratio
Envelope Function

Envelope function = absolute value of an analytic signal = the envelope in which the function oscillates.

• The analytic signal of a function $y(t)$ is given by

$$Y(t) = y(t) + iy_h(t)$$

where $y_h(t)$ is the Hilbert Transform of $y(t)$

$$y_h(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{y(\tau)}{t - \tau} d\tau$$

= convolution of the function over all times.
Hilbert Transform

Hilbert Transform can be more easily calculated from the Fourier Transform of \( y(t), Y(\omega) \)

\[
Y_h(\omega) = -j \frac{\omega}{|\omega|} Y(\omega)
\]

where \( \omega \) is the frequency in rad/s

Transforming back into the time domain and noting that only positive frequencies are of interest gives

\[
y_h(t) = F^{-1} \left( \text{Im} \left( Y(\omega) \right) - j \text{Re} \left( Y(\omega) \right) \right)
\]

→ The envelope function is calculated from

\[
E(t) = |Y(t)| = \sqrt{y^2(t) - y_h^2(t)}
\]
Example of envelope

![Graph of envelope function and signal over time](image)
Envelope variation with flight condition
**Time centroid**

**Stability criterion** = the position of the **time centroid** of the envelope:

\[
\bar{t} = \frac{\int_{0}^{t_1} E(t) t \, dt}{\int_{0}^{t_1} E(t) \, dt}
\]

where \( t_1 \) is a reference time representing the duration of the response signals.
At flutter, the time centroid is close to the centre of the time window, i.e. $t_1/2$.

$\rightarrow$ Stability criterion is

$$S = \frac{1}{t} - \frac{2}{t_1}$$

Flutter occurs when $S \sim 0$
Variation of $S$ with flight condition

Example of wind tunnel flutter test with envelope function-based stability criterion
Conclusion

• Flight flutter testing is still as much an art as it is a science
• Best flutter predictions are obtained when the aircraft is flown near the flutter flight condition
• If this condition is inside the flight envelope the test can be very dangerous
• Good excitation, good instrumentation, good data analysis and a lot of experience are needed for a successful flight flutter test

References: