Methods for Flutter Analysis

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Flutter: Dynamic Aeroelastic Instability

Cause: Interaction between **Inertia**, **Elasticity**, and Unsteady **Aerodynamic** Forces

Consequence: Unstable oscillations that may lead to structural failure

[NASA]

Certification requires aircraft to be flutter-free for all nominal conditions

Flutter Solutions in Nastran (MSC or Nastran95*)

Solution Sequence: Flutter Analysis (SOL 145)

- Frequency-based
- Predict flutter speed, the point from which oscillations become undamped
- Outputs: Eigenmodes and eigenfrequencies of the flutter modes

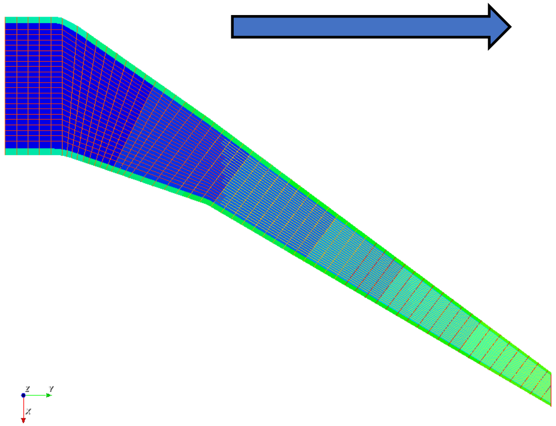
2 Types of Methods:

- British method: PK
- American methods: K and KE

*[https://github.com/nasa/NASTRAN-95]

Physical Models for Flutter

Interaction between **Inertia**, **Elasticity**, and **Aerodynamics** requires 2 physical models:



Finite Element Model: Inertia and Elasticity

$$[M]\{\ddot{u}_s\} + [K]\{u_s\} = \{F_A\}(\dot{u}_s, u_s)$$

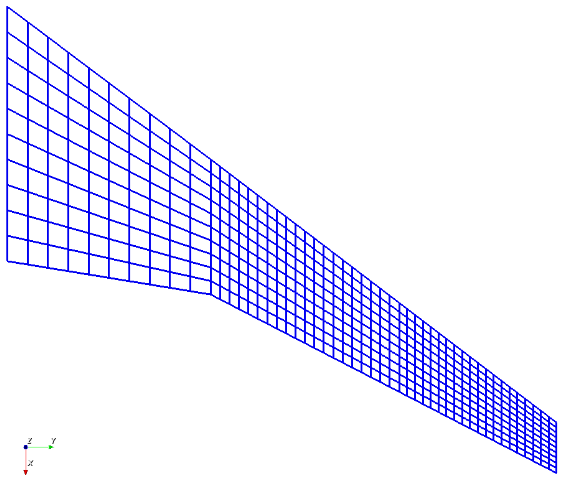
Aerodynamic Models:

- Doublet Lattice Method (Subsonic)
- ZONA51 (Supersonic, MSC only)

$$\{w_j\}(\dot{u}_s, u_s) = [A_{jj}]\{f_j/q\}$$

$$q = \frac{1}{2}\rho V^2$$

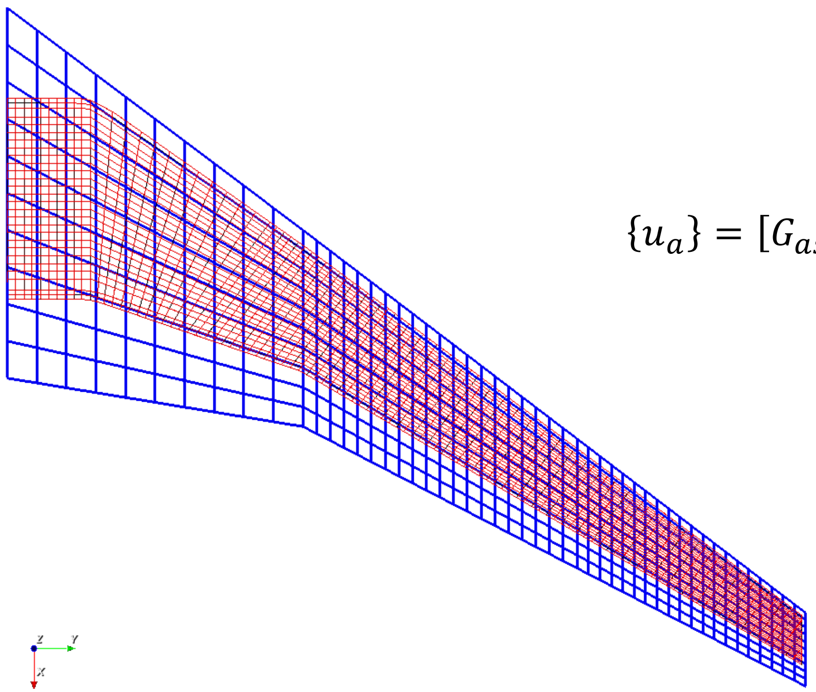
f: panel pressure



[Nastran Aeroelastic Analysis User's Guide]

Connection Between Models: Interpolation

Surface splines are used to relate the structural grid point deflections $\{u\}$ to the ones of the aerodynamic grid $\{u_a\}$.



$$\{u_a\} = [G_{as}]\{u_s\}$$

[Nastran Aeroelastic Analysis User's Guide]

Linear Aeroelastic Equation

$$[M]\{\ddot{u}_s\} + [K]\{u_s\} = [A_c]\{\dot{u}_s\} + [A_k]\{u_s\}$$

Assuming a harmonic solution:

$$(-\omega^2[M] + [K] - i\omega[A_c] - [A_k]\{u_s\})\{\eta\} = 0$$

$$Q = \frac{i\omega[A_c] + [A_k]}{\frac{1}{2}\rho V^2}$$

Reduced frequency:

$$\kappa = \frac{\omega c}{2V}$$

By using the natural modal basis $[\Phi]$:

$$\{u_s\} = [\Phi]\{\eta\}$$

$$[\bar{K}] = [\Phi]^T[K][\Phi] \qquad [\bar{M}] = [\Phi]^T[M][\Phi] \qquad [\bar{Q}] = [\Phi]^T[Q][\Phi]$$

$$\left(-\omega^2[\bar{M}] + [\bar{K}] - \frac{1}{2}\rho V^2[\bar{Q}](m,\kappa)\right)\{\eta\} = 0$$

Mach number: m

[J. R. Wright and J. E. Cooper, Introduction to Aircraft Aeroelasticity and Loads, 2014]
[Nastran Aeroelastic Analysis User's Guide]

Solution of the Flutter Equation (K-Method)

Strategy: An artificial structural damping g is introduced:

$$\left((1+ig)[\bar{K}] - \omega^2[\bar{M}] - \frac{1}{2}\rho V^2[\bar{Q}](m,\kappa)\right)\{\eta\} = 0$$

Reason: Formulate a complex eigenvalue problem

Consequence: The solution is physically meaningful **only** when $\boldsymbol{g} = \mathbf{0}$ (Flutter point)

$$\left(-\frac{(1+ig)}{\omega^2}[\bar{K}] + [\bar{M}] + \frac{\frac{1}{2}\rho V^2}{\omega^2}[\bar{Q}](m,\kappa)\right)\{\eta\} = 0 \qquad [F] = [\bar{M}] + \frac{\frac{1}{2}\rho V^2}{\omega^2}[\bar{Q}](m,\kappa) \qquad \lambda = \frac{(1+ig)}{\omega^2}$$

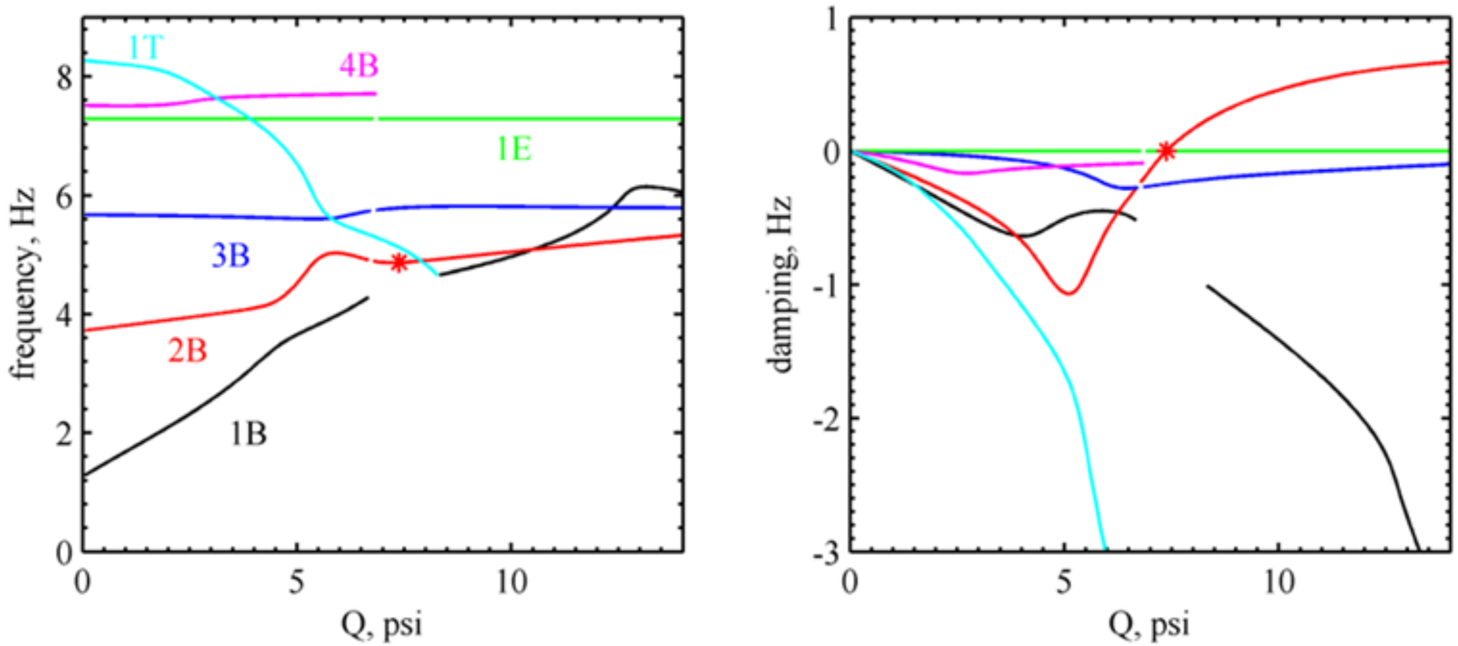
Complex eigenvalue problem:

$$([F] - \lambda[\bar{K}])\{\eta\} = 0$$

[J. R. Wright and J. E. Cooper, Introduction to Aircraft Aeroelasticity and Loads, 2014]
[Nastran Aeroelastic Analysis User's Guide]

In practice: Interpretation of the Results

V-g and V-f plots are used to obtain the flutter speed and frequency (*)



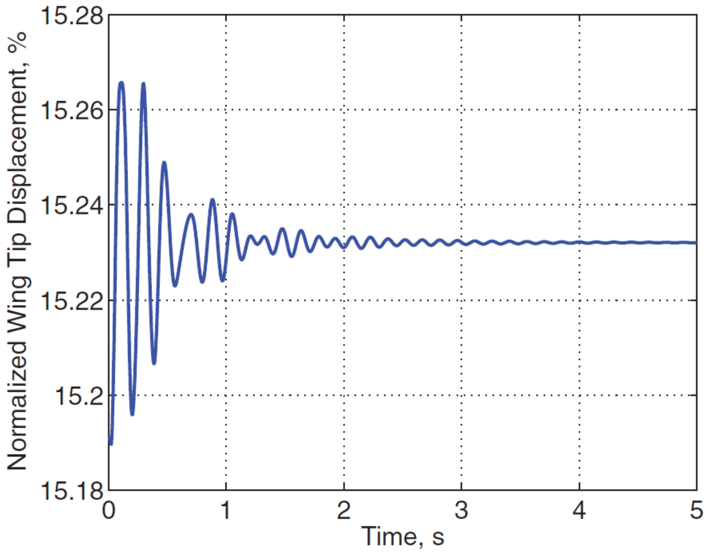
Note: g is **not** a physical damping, it is artificial. That means $g > 0$ implies unstable oscillations. This indicates a positive damping would be required for the oscillations to be neutrally stable.

[NASA]

Other Methods for Flutter (outside Nastran)

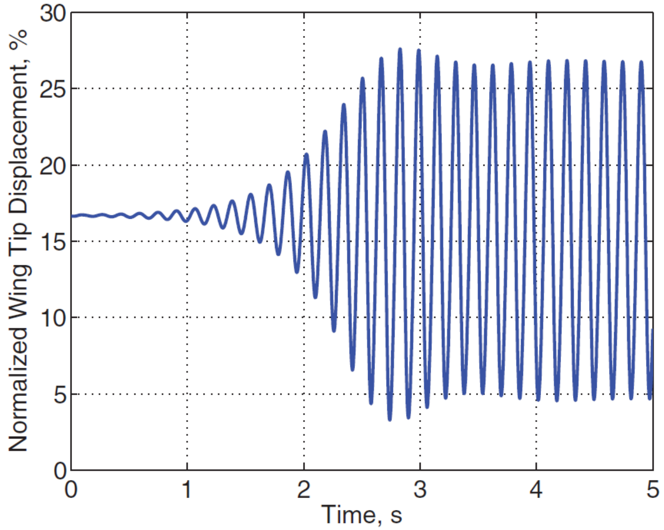
Time-Domain Methods : The time variable is discretized and the aeroelastic equations of motion are integrated to obtain the transient response

Before Flutter:



a) Speed: 147 m/s

After Flutter:



b) Speed: 162 m/s

✓ Can be applied to many physical models

x Expensive to sweep across velocities to find the flutter point

[W. Su and C. Cesnik, Journal of Aircraft, 2010]

[E. Jonsson et al., Progress in Aerospace Sciences, 2019]

Conclusion

- DLM Frequency-Domain Methods (Nastran SOL 145):
  - Inexpensive
  - Well known and widely used
  - Accuracy limited by the physical models available
  - Solution of the linearized equations
- Time-Domain methods:
  - Flexibility: They can be applied to many physical models of several fidelities (e.g., CFD)
  - Possibility to consider nonlinearities
  - Expensive to sweep through velocities to find the flutter point

Thanks for your attention !

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