Basics of Blade and Disk Vibration

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14:00
Stresses in a Bladed-disk Assembly

• **Steady stresses**
  – CF loads
  – Gas bending
  – Thermal stresses

• **Alternating stresses (HCF)**
  – Blade vibration due to BPF excitation

• **Transient stresses**
  – Impacts (e.g. bird strike)
  – Blade-off
  – Gyroscopic effects
  – Transient thermal effects

• **Unexpected stresses (HCF)**
  – Flutter
  – Low-engine order excitation
  – Acoustic resonance, rotating stall, etc
Consequences of Vibration

- Noise
- Discomfort
- Malfunction
- Shutdown
- Structural failure
Modal Properties

- Natural frequency
- Mode shape
- Damping factor

Mass and stiffness properties determine the natural frequencies and mode shapes of the structure.

Excitation levels and damping determine the actual amplitude of the vibration response.
Vibration Properties vs Vibration Characteristics

• **Properties** are determined by the structural features alone.
  – Natural frequencies, mode shapes, damping

• **Characteristics** are determined by the vibration properties **AND** external forcing
  – Resonance, response levels, response time histories, etc.
Tools in Structural Dynamics

- Experimental route:
  - Modal Testing and Analysis

- Theoretical routes:
  - Closed-form analytical solutions
  - Lumped parameter models
  - Finite element method
  - Boundary element method
  - ......
Theoretical & Experimental Routes

THEORETICAL ROUTE

SPATIAL MODEL

MODAL PROPERTIES

RESPONSE CHARACTERISTICS

EXPERIMENTAL ROUTE

RESPONSE CHARACTERISTICS

MODAL PROPERTIES

MODAL MODEL

MODAL ANALYSIS

SYSTEM IDENTIFICATION

EIGEN-SOLUTION

MODAL SUPERPOSITION

Spatial & Disk Vibration

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Basics of Blade & Disk Vibration
Mathematical Models

The models are interchangeable for linear systems and SHM.
Blade Vibration

• Vibration terminology
  – Axial, tangential & radial directions
  – Flapwise, edgewise and torsional vibration: E, T & T

• Blade modes
  – Beam modes: no chordwise bending, (coupled) flap & edgewise
  – Plate-type modes: chordwise bending is present
  – Fixture modes
  – Assembly modes
Beam & Plate Modes

Beam & Plate Modes
FE Modelling

1T mode

2F mode
Factors Affecting Blade Vibration - I

• End fixings - Roots
  – Root flexibility may not be negligible
  – Non-linear behaviour when friction dampers are fitted

• End fixings - Shrouds
  – Very difficult to model the shroud interface
  – Non-linear behaviour may be significant
Factors Affecting Blade Vibration - II

- Operating Conditions
  - CF forces change the datum position of the blade: untwist
  - CF forces increase the stiffness
  - Gas bending changes the datum position of the blade: untwist
  - Temperature effects change the material properties, causing natural frequency variations.
Blade Vibration Testing

- For small blades, excitation mechanism may interfere with structural properties.
- Root clamping may be very difficult to achieve.
- Air jet excitation is relatively common.
- Damping estimates may contain large errors.
Disk Vibration - I

- Consider a rectangular plate which has two modes of vibration: one about height and the other about length. The two modes will have different frequencies.

- Consider now a square plate. The two modes will still exist but they will occur at the same frequency.
Disk Vibration - II

- Disks vibrate in **double** Nodal Diameter modes: same frequency but different orientation of the mode shape
Disk Vibration - III

- The vibration can take place in axial, radial or tangential directions.
Disk Vibration - IV

- As one goes up in frequency, the nodal diameter modes will start exhibiting nodal circles. Therefore, disks vibrate in terms of nodal diameters and nodal circles.
Disk Vibration - V

- In summary, disk vibration is characterised by families of nodal diameters. The modes are double, except the 0 nodal diameter mode, also known as the umbrella mode.
- Each family is associated with a nodal circle.
Disk Vibration - VI

- All circular components such as cylinders, rings, shafts, etc exhibit the same vibration characteristics.
- If there are non-uniformities (holes, manufacturing imperfections, etc), the double modes will split into close-frequency pairs.
- The disk rotation will also have an effect. More of this later.
**Bladed-disk Vibration - I**

- If the disk is rigid (e.g., fan assembly), the vibration modes will be dominated by blade modes.
- If the disk is flexible (e.g., turbine disk), disk and blade characteristics will co-exist.

*At low nodal diameters, the disk will dominate.*

*At high nodal diameters, the cantilevered blade modes will dominate.*
Bladed-disk Vibration - II

• Bladed-disk modes are also displayed in nodal-diameter family format.

• Bladed disk natural frequencies are affected by blade stagger and disk/blade coupling.

• For a discrete lumped-parameter system with N blades, the maximum nodal diameter value is $N/2$ (even N) or $(N-1)/2$ (odd N).

• For continuous systems, higher values are possible but these become indistinguishable from the corresponding lower nodal diameter values if N blades only are considered.
Bladed-disk Vibration - II

• The addition of a part-span or tip shroud makes the vibration characteristics even more complicated.

• General behaviour is similar to unshrouded disks, except for asymptotic behaviour towards cantilevered blade frequency.

• Continuous or non-interlocking shrouds may have significant effects on dynamic behaviour.
Bladed-disk Vibration - III

- Modes with 0 nodal diameters
  - Single mode
  - Affected by shaft and bearing (axial)
- Modes with 1 nodal diameters
  - May be coupled with shaft bending
- N/2 nodal diameters (even blades)
  - Two such single modes: the nodal diameters go through the blades or pass symmetrically between the blades.
  - Split double mode
Analysis Tools for Bladed-disk Vibration

Analytical solution for cantilever blade

Lumped parameter models

Receptance coupling for beams, disks and rings

Whole-annulus FE models

Single blade (or sector) FE models
Sources of Excitation

- Self-excitation or flutter
- General unsteadiness and random turbulence
  - Low engine-order excitation
- Non-uniformities in working fluid pressure
  - Blade passing engine-order excitation.

Angular non-uniformity in pressure causes dynamic excitation of rotating blades at frequencies that are multiples of the rotation speed AND with spatial distributions that match nodal diameter modes.
Blade-passing Excitation

Two conditions must be met:

• The excitation frequency, $n\omega$, must be equal to an assembly natural frequency.

• The excitation pattern must match the associated nodal diameter mode shape.
Campbell Diagram
Critical Vibration Modes in Aeroelasticity

• Fan Flutter
  – Usually the first family, occasionally the second family
  – Very stiff disk, hence assembly modes are dominated by the blade characteristics
  – Usually the 1-6 nodal diameter modes, arising from the blade’s 1F mode

• Forced response
  – Blade passing excitation. Typically, high nodal diameter modes.
  – General unsteadiness. Typically, low nodal diameter modes.
  – In both cases, the first 4-5 families may be affected.