A Modal Identification Method for Highly-Symmetric Turbine Rotors

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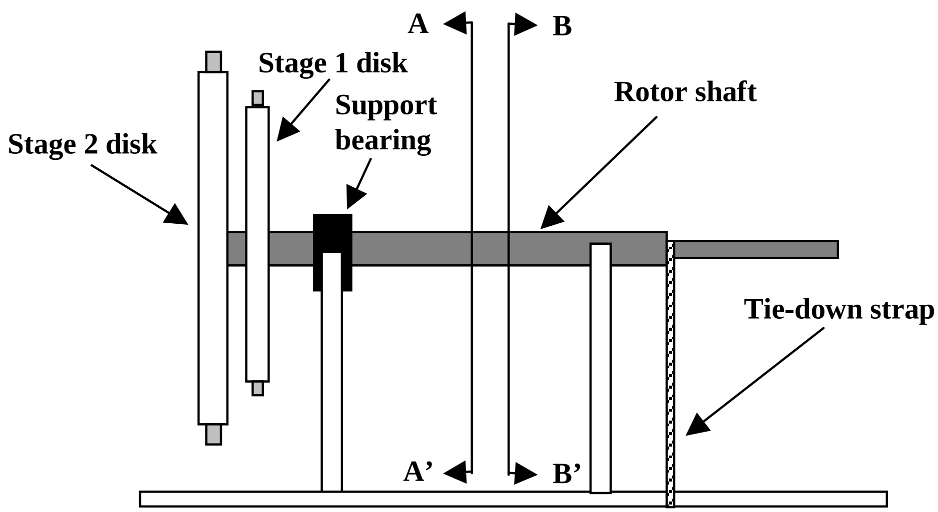
Overview

- Background
- System description
- Highly-symmetric bladed disks
  - Well-understood behavior due to previous research by many investigators
- Single blade test article
- Frequency response functions
- Modal identification
- Summary

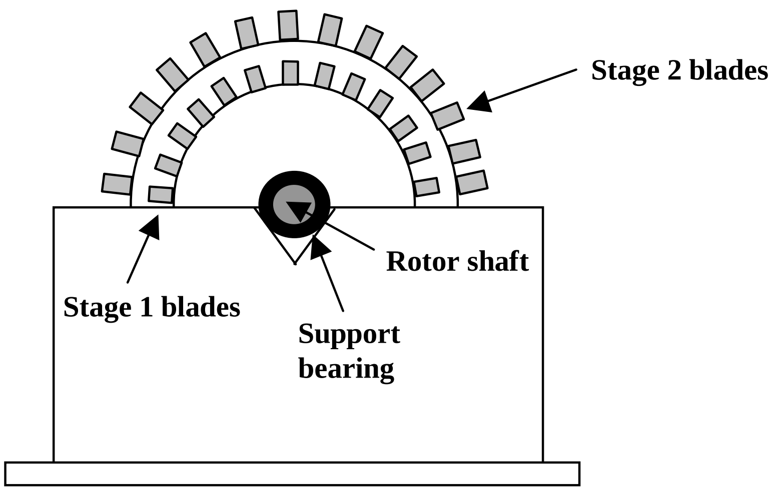
Background

- Turbine blade cracks observed during development stage of rocket engine test program
  - Identify potential blade resonant response frequencies
- Show Campbell interference margin for production units (0-20 kHz)
  - Modal testing required for initial hardware builds
    - Analytical adjustment for actual operating conditions
    - Establish unit-to-unit variability
- Timely modal test and identification necessary
  - Use well-understood behavior of highly-symmetric bladed disks
  - Acquire least amount of data required to produce reliable results
  - Use simple mode extraction procedures

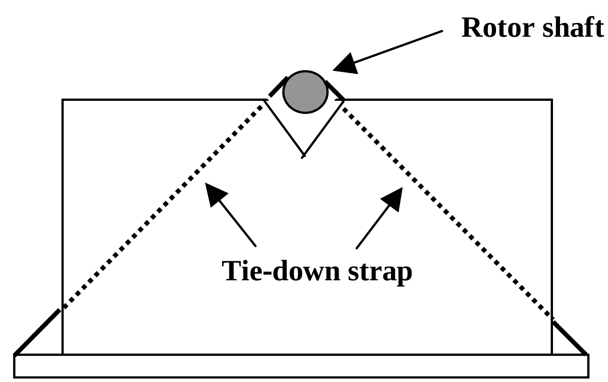
System Description



- Two stage rocket engine turbine
  - Stage 1 of interest (123 blades)
- Coupling of blade response between stages negligible
- Highly-symmetric, lightly damped
- Symmetry not affected by measurement system



Section A-A'



Section B-B'

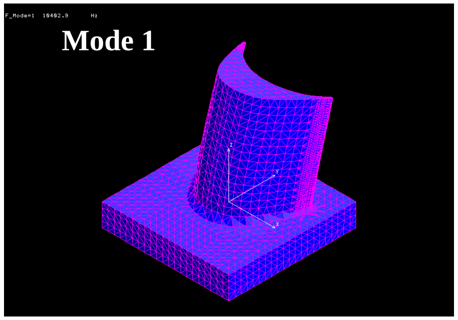
Highly-Symmetric Bladed Disks

- For resonant frequency in which blades deform relative to disk, all blades exhibit response shape similar to a cantilevered blade mode
- Amplitude and phase vary in periodic manner around circumference of disk with given number of nodal diameters, or diametrals
- Example: 3rd diametral, 2nd blade mode
  - Blades deform relative to disk with shape characteristic of 2nd cantilevered mode
  - Amplitude of response varies sinusoidally around circumference with 3 full waves
- Total number of diametrals possible for *N* odd is

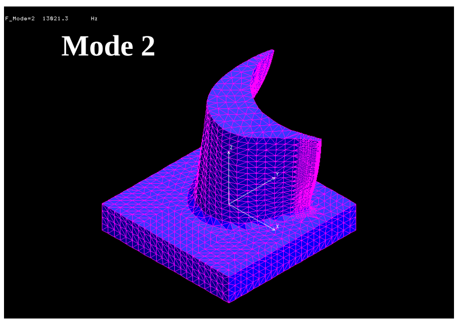
$$m = (N - 1)/2 = 61$$
$$N = \text{number of blades} = 123$$

- As number of nodal diameters for given modal family increases, natural frequencies asymptotically approach value less than respective cantilevered frequencies

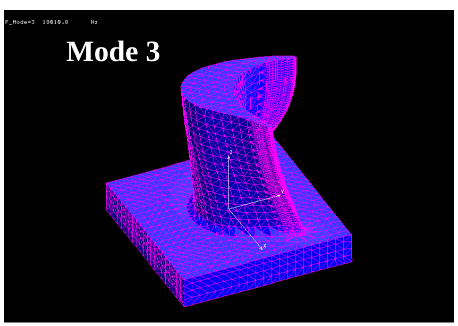
Highly-Symmetric Bladed Disks



Mode 1 (Bending around X axis)

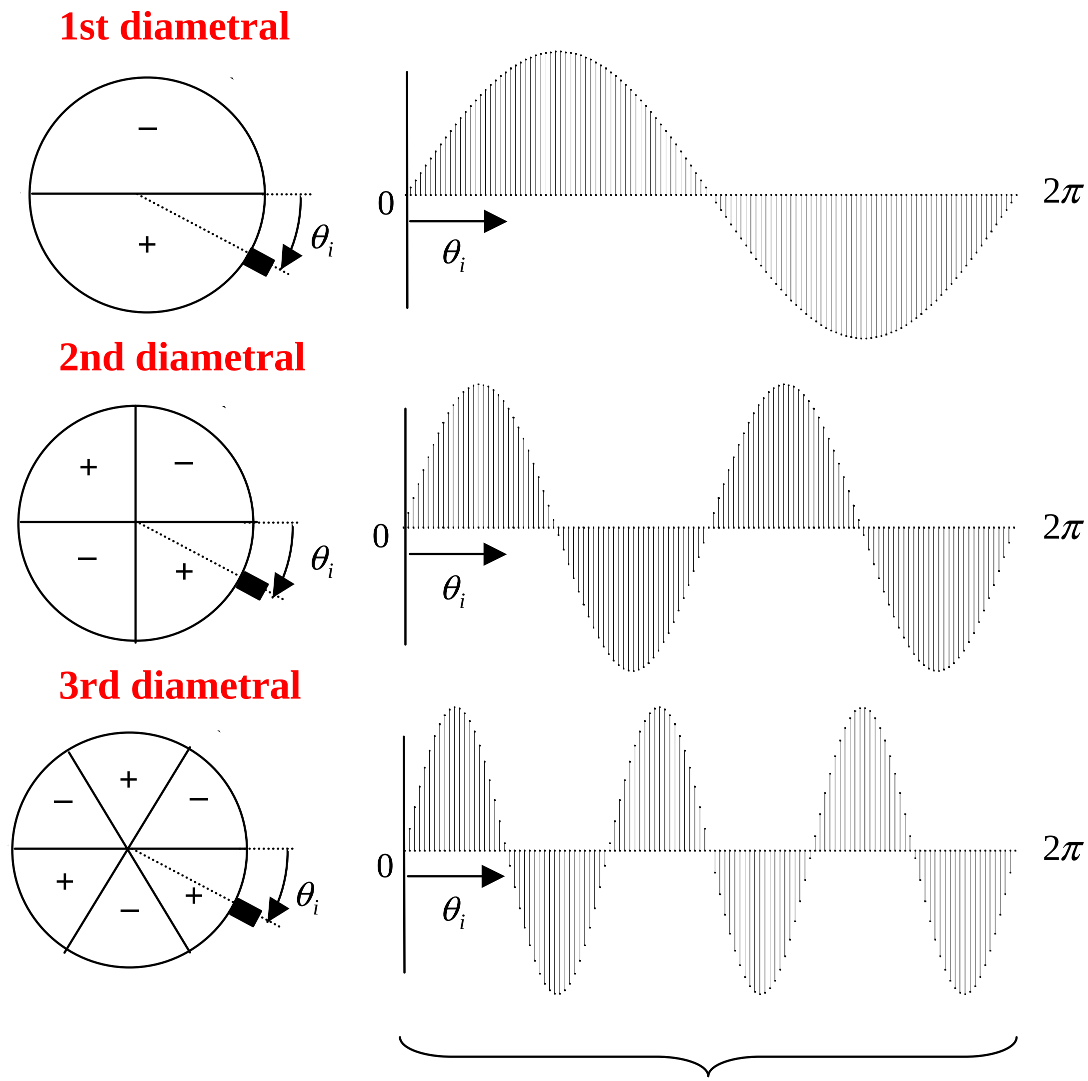


Mode 2 (Bending around Y axis)



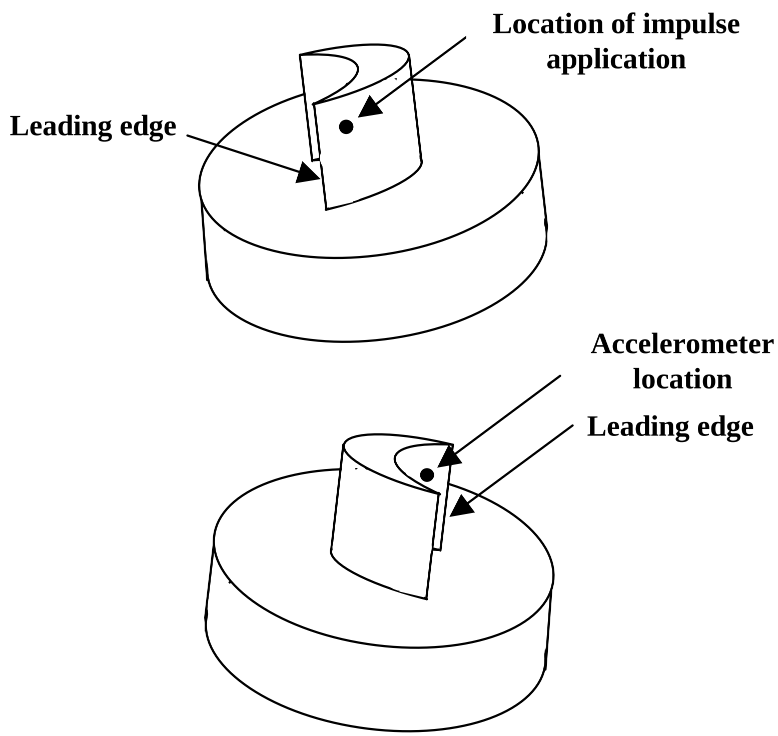
Mode 3 (Torsion)

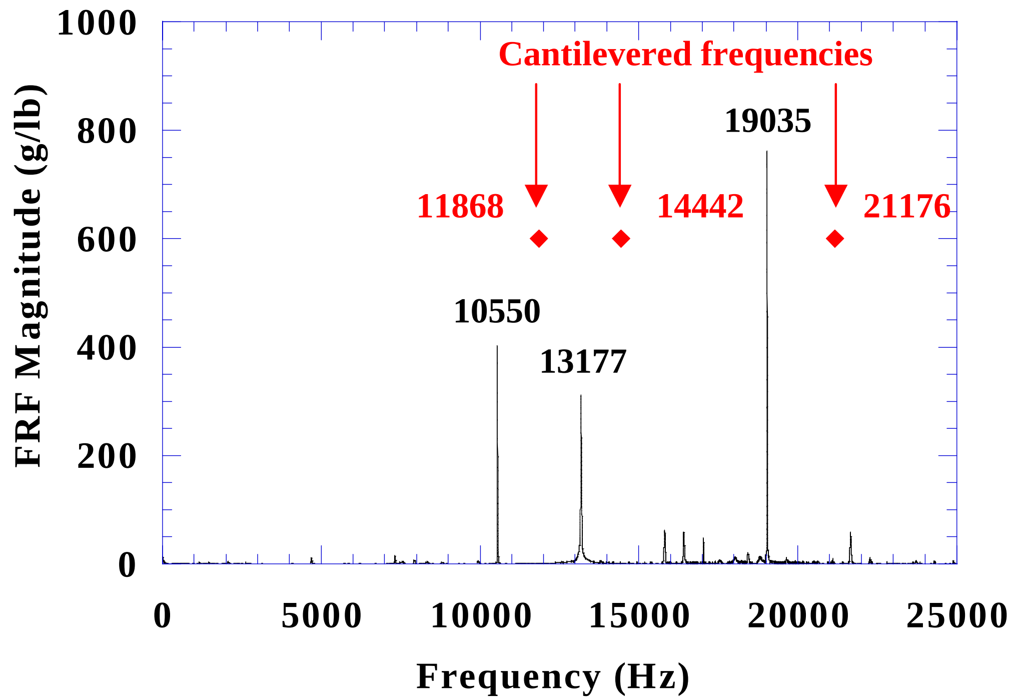
Cantilevered Mode Shapes



Deflection form at circumference

Single Blade Test Article

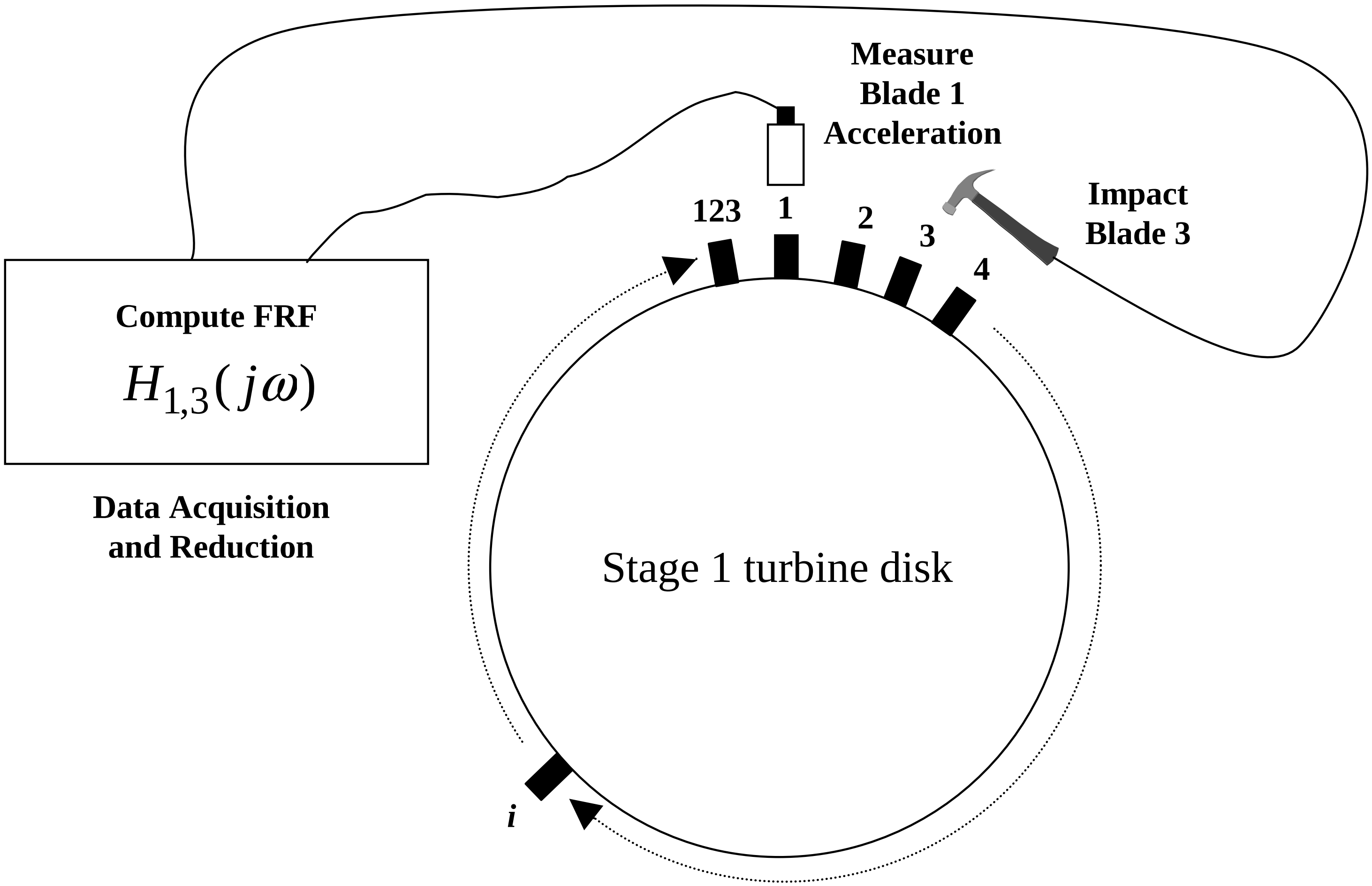




Summary of Single Blade Frequencies

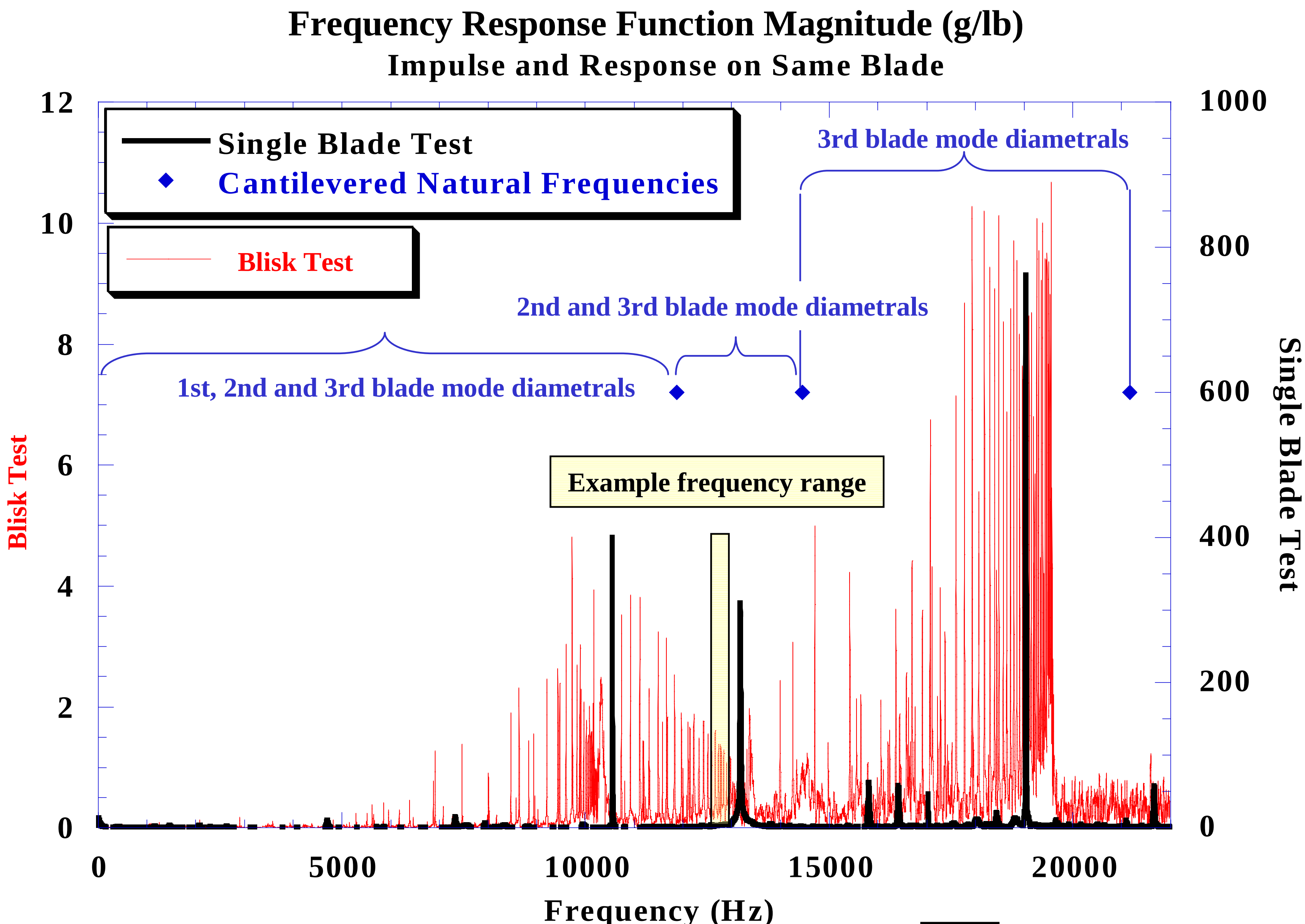
Mode	Experimental Results	Numerical Model Flexible Base	Numerical Model Cantilevered
1	10550	10551	11868
2	13177	13181	14442
3	19035	19000	21176

Stage 1 Turbine Disk Test



- FRFs determined for blades 1-24 only
- Impulse and response measurement locations same as for single blade test article

Effect of Disk Flexibility



Modal Identification

- Measured FRF estimates for each blade used to determine mode shapes
- At a particular frequency, response on each blade *i (i=1,…,24)* is assumed to be

$$y_i = |H_i(\omega)| \sin(\omega t + \phi_i)$$

- Select reference measurement location (arbitrary) where modal response equals measured FRF magnitude estimate, or

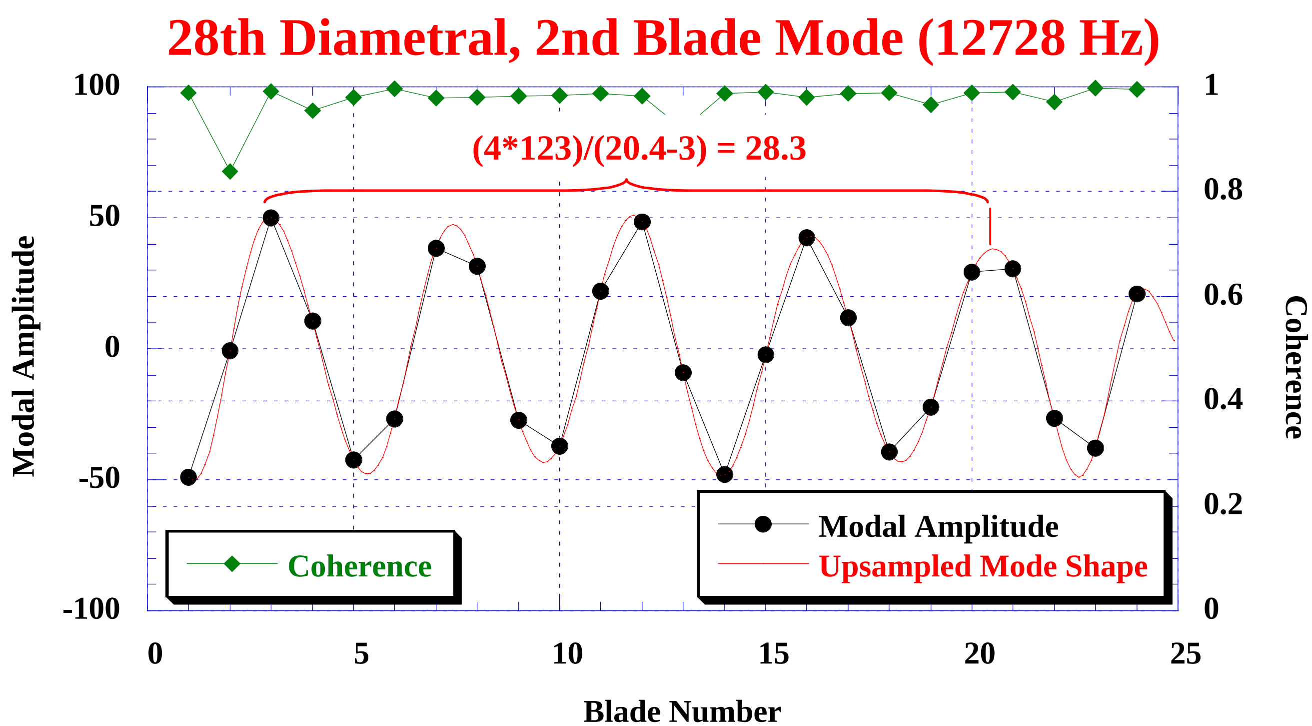
$$y_{ref} = |H_{ref}(\omega)| \qquad \sin(\omega t + \phi_{ref}) = 1 \qquad t_{ref} = \frac{1}{\omega}\left(\frac{\pi}{2} - \phi_{ref}\right)$$

- Synchronize all responses to time

$$y_i = |H_i(\omega)| \sin(\omega t_{ref} + \phi_i)$$

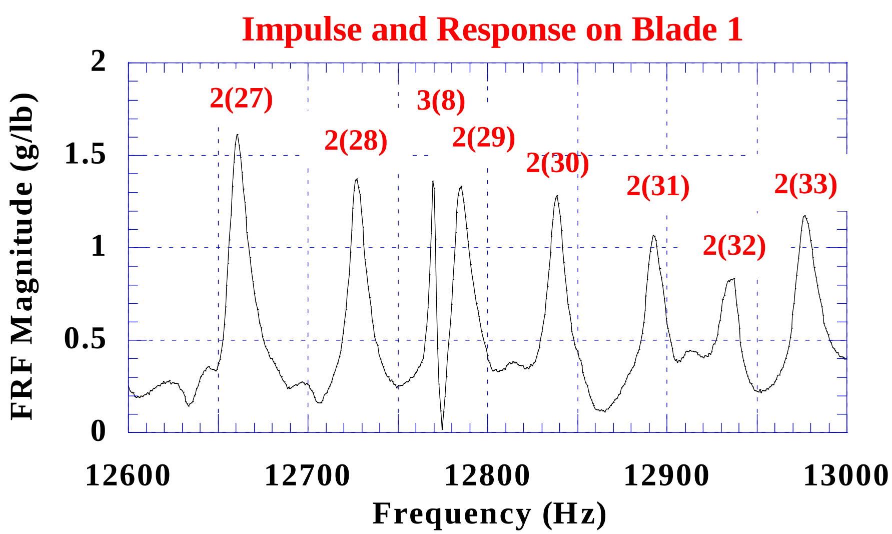
- Response at all blades observed at same instant of time on circumference of disk
- At an FRF magnitude peak, spatial representation of mode shape results (max./min. amplitude arbitrarily set to 50)
- Assumes no modal interference or coupling (lightly-damped systems)

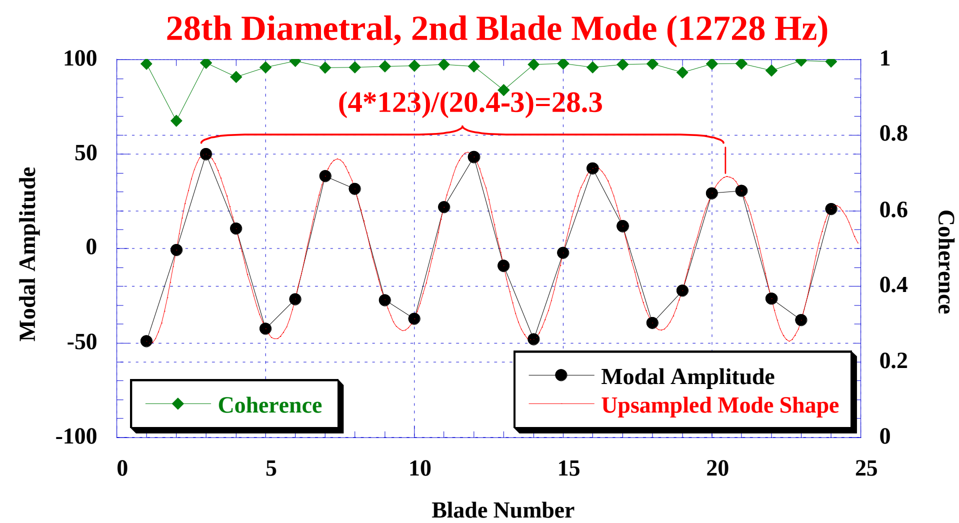
Particular Example Frequency (12728 Hz)

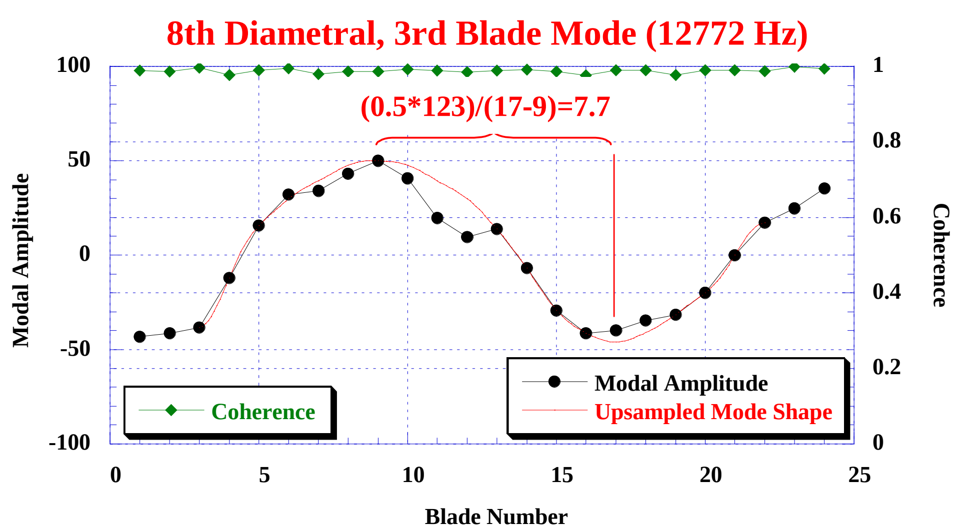


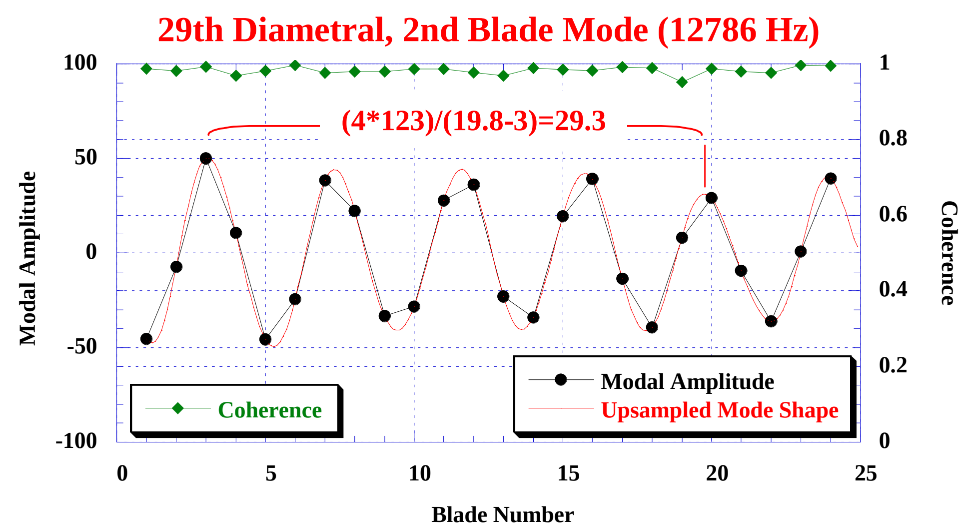
- Create best sinusoidal curve fit using discrete response measurements
- Determine best estimate for number of diametrals per blade
- Multiply by 123 to get number of diametrals for entire disk

Example Frequency Range

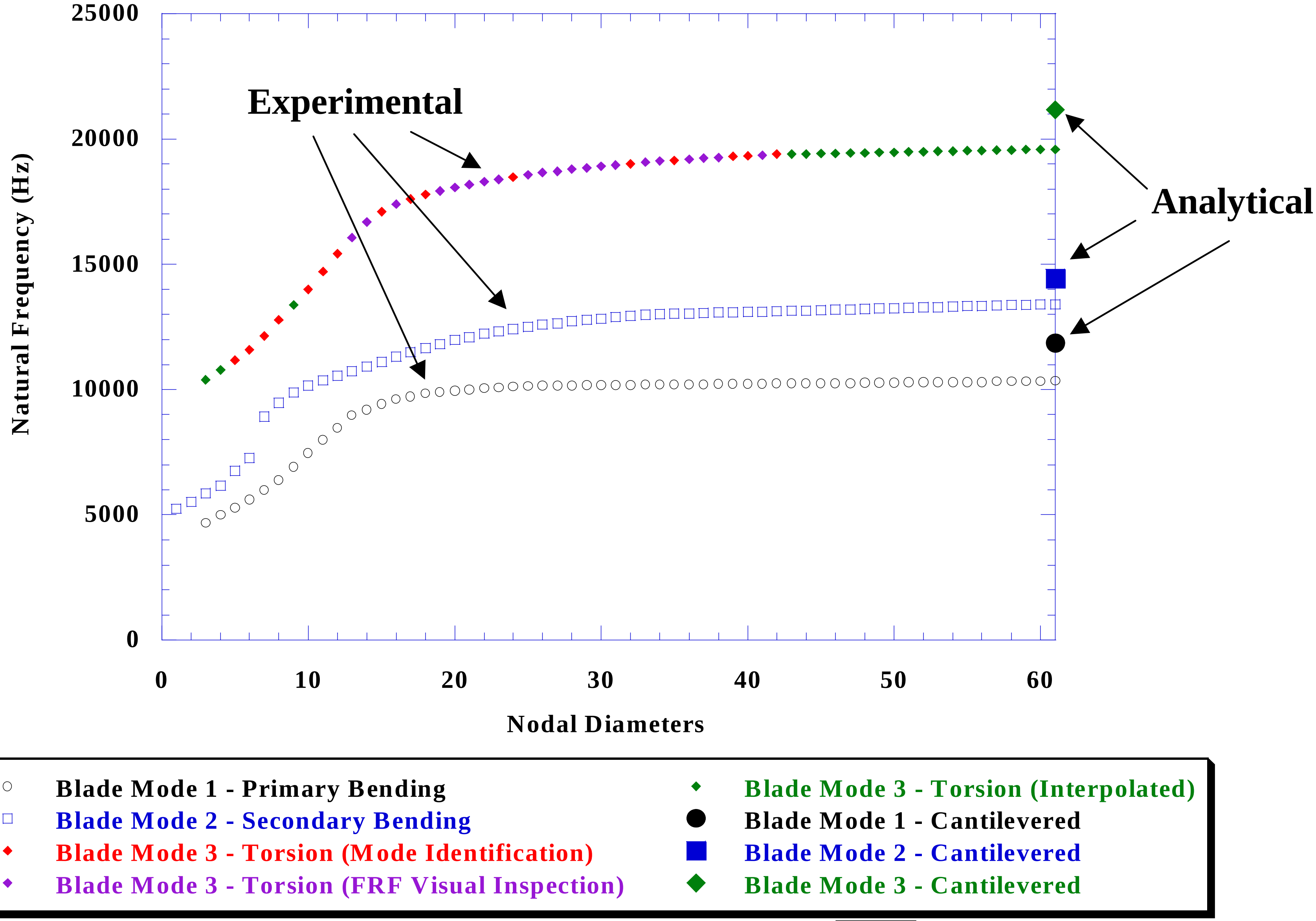








Stage 1 Blade Mode Natural Frequencies



Summary

- Method for extracting modal information from highly-symmetric, lightly-damped turbine disks
  - Simple and easy to interpret results
  - Good for rotors with short, lightly-damped, stiff blades
    - Modal identification required into high-frequency regime
    - Test considerations
  - Expedient from a test time and post-processing standpoint
- Useful for Campbell diagram and analytical model validation
- Limitations
  - True mode shapes not acquired
    - Orthogonality of modes not enforced
  - Lower order diametrals difficult to discern
    - Need to process more than 24 FRFs
    - Interference with “disk” modes