Characterization of Deficiencies in the Frequency Domain Forced Response Analysis Technique for Turbine Bladed-Disks

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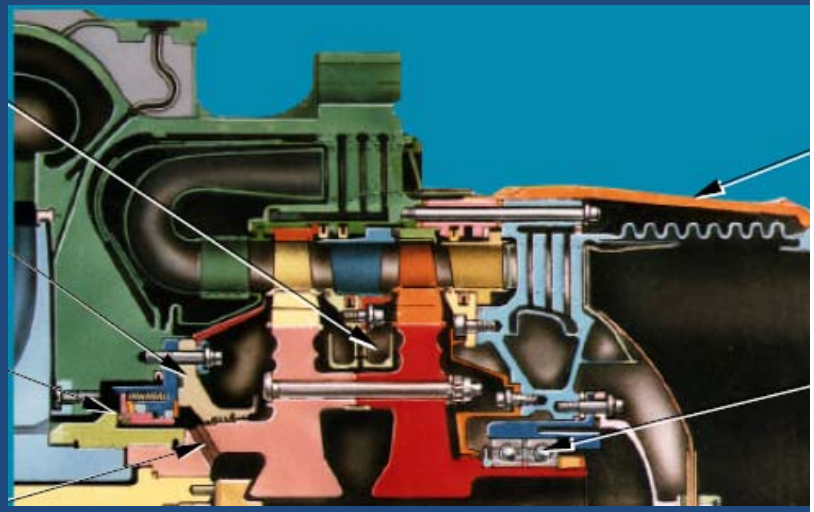
Agenda

- Introduction, Motivation, Previous Work
- Blade Beam Model Analysis
  - Tyler-Sofrin Blade-Vane Interaction Charts
  - Analysis at 5ND mode, Contribution of Sidebands
- Realistic Airfoil Solid Model Analysis
  - 74N Excitation of 5ND Mode
  - 57N Excitation of 12 ND Mode
- Conclusions and Future Work

Introduction and Motivation

- Turbine Blades experience large harmonic excitations.
  - Upstream, Downstream nozzles, vanes, and harmonics.
- Analysis in frequency domain therefore thought to be appropriate.
- Recent testing, analysis at MSFC has shown substantial asymmetric and non-periodic content.
  - Inlet asymmetry
  - Influence of Non-adjacent stages
  - Turbulence and other flow distortions.
- This content can only be captured by CFD over 360^{o} of revolution.
  - New technique applying 360^{o} on cyclic symmetric structural model described in another paper.



Problem Statement and Literature Survey

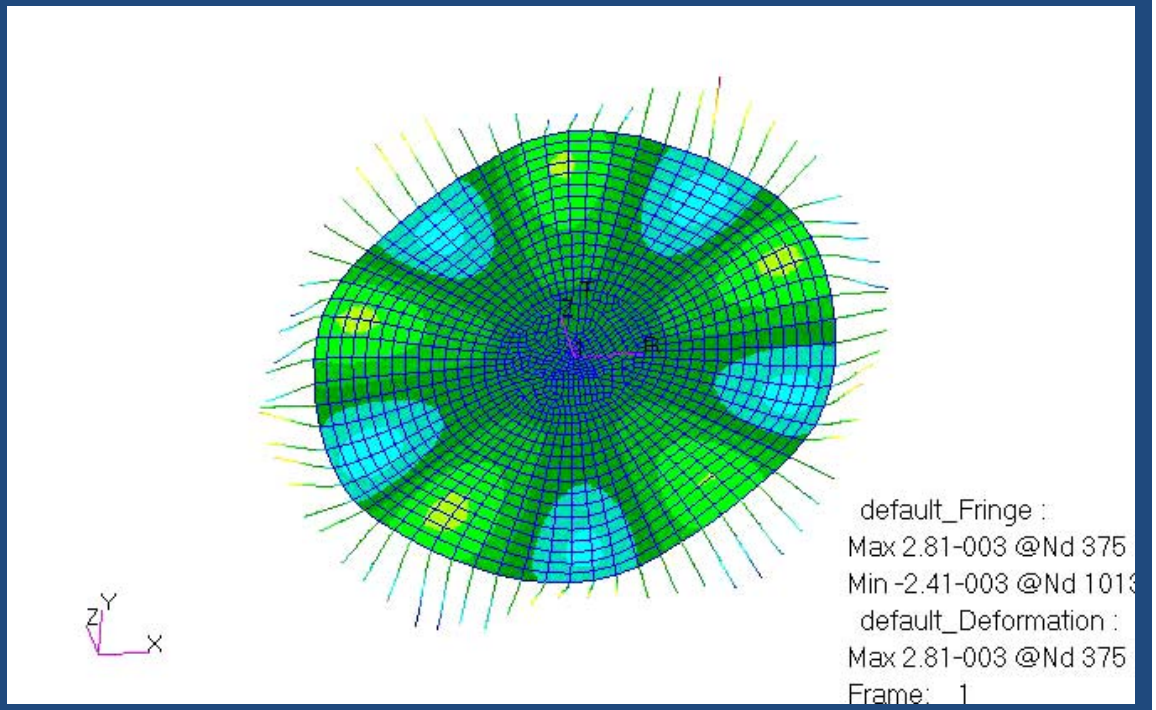
- Non-periodic content raises question: is Frequency Response Analysis itself accurate?
  - Might “enforced periodicity” increase response?
- Two Studies comparing Frequency Response Analysis with “Transient” (time history) analysis performed.
  - Bladed-disk with disk modeled as plates, blades as beams, to focus on disk-mode excitation and to enable rapid turnaround time.
  - Bladed-disk with disk and blades modeled as solids, accurate model of J2-X airfoil to focus on blade-mode excitation.
- Literature survey shows question has not been addressed.
  - Misek, et.al, recent paper detailing forced response analysis of bladed disk, states frequency response technique is adequate because forcing function harmonic.

Blade Beam Model Analyses

Tyler-Sofrin Blade-Vane Interaction Charts

Upstream Nozzle Multiples	37	74	111	148		Downstream Stator Multiples	57	114	171	228
Blade multiples						Blade multiples				
69	32	-5	N/A	N/A		69	12	N/A	N/A	N/A
138	N/A	N/A	27	-10		138	N/A	24	-33	N/A
207	N/A	N/A	N/A	N/A		207	N/A	N/A	N/A	-21

- 20” x 1” disk, 69 blades 4” x 1” x .1”
- 74N excites 5ND mode at 40,167 hz
- 4 revolution CFD analysis
  - Scaled such that primary temporal Fourier component $F_o e^{i\Omega t}$ has frequency of 40,167 hz.

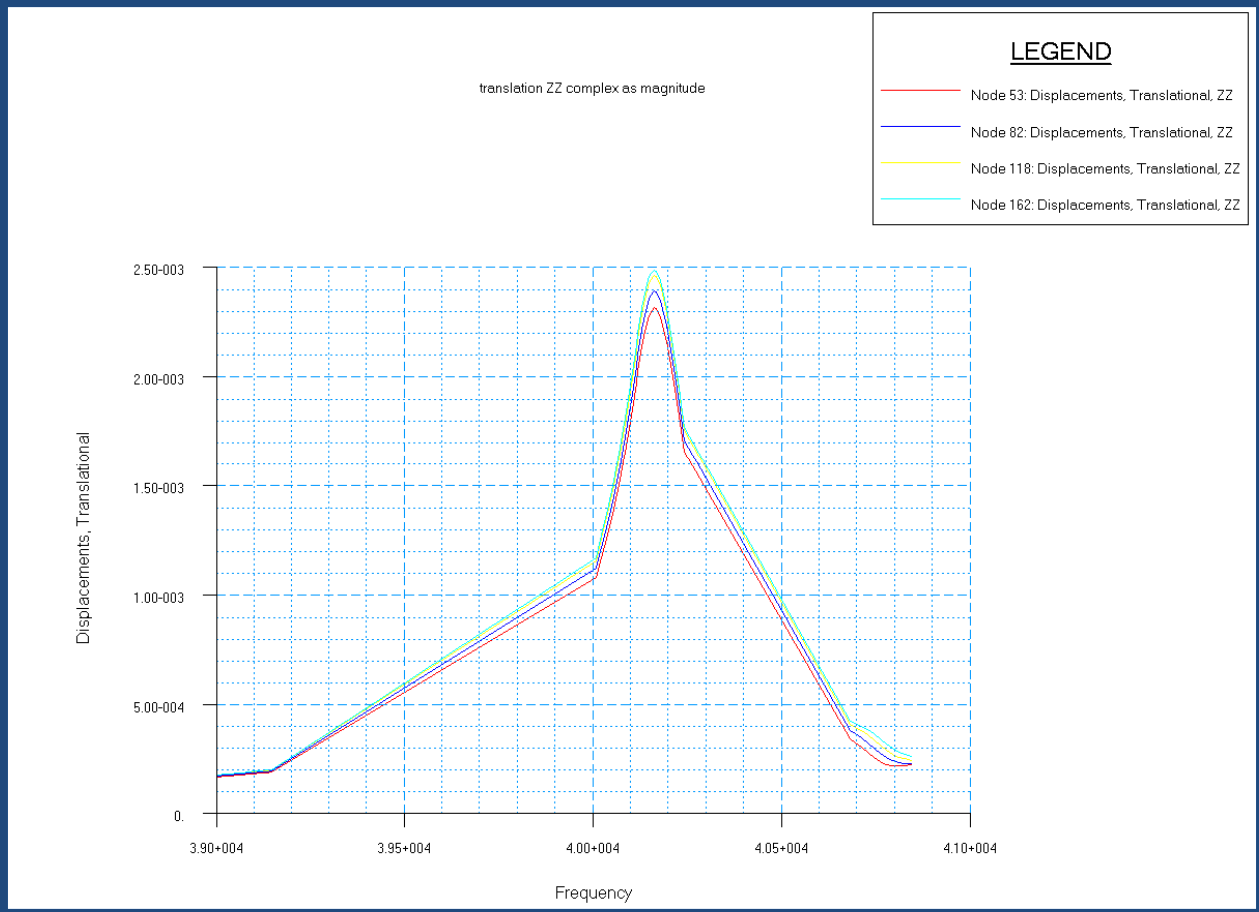


Frequency Response Analyses, 5ND Mode

- Frequency response analysis:

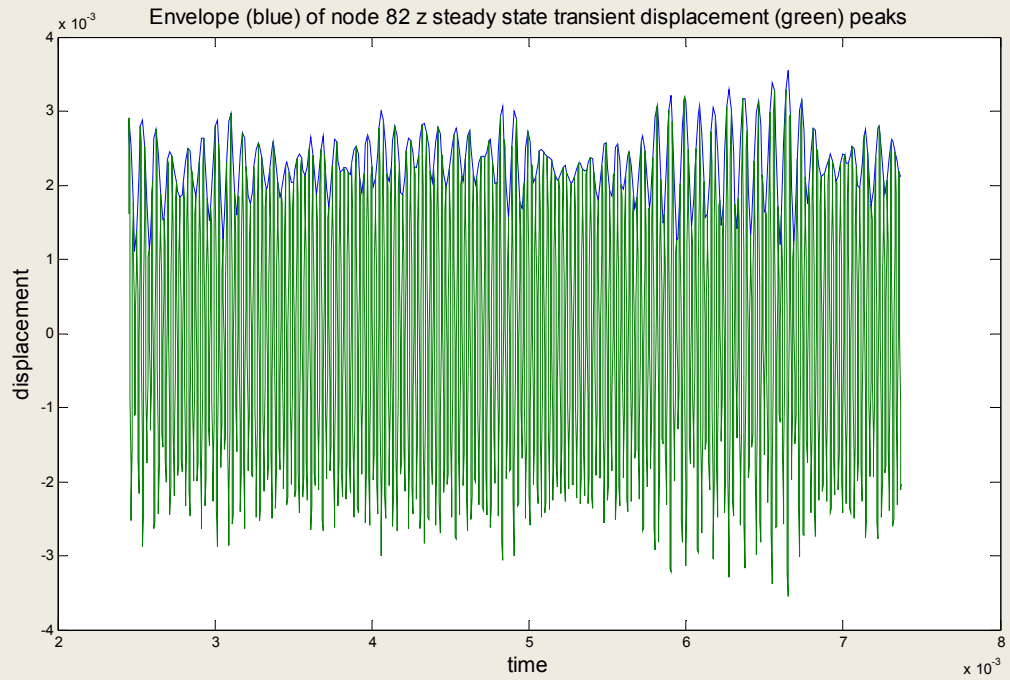
$$\{u\} = [\Phi]\{q\}$$

$$q(t) = \bar{H}(\Omega)\bar{U}_{static} = \left[\frac{1 - \Omega/\omega_i^{\,2}}{\left(1 - \Omega/\omega_i^{\,2}\right)^2} + i \frac{-2\zeta\,\Omega/\omega_i}{\left(1 - \Omega/\omega_i^{\,2}\right)^2} \right] \frac{F_o e^{i\Omega t}}{\lambda_i^2}$$



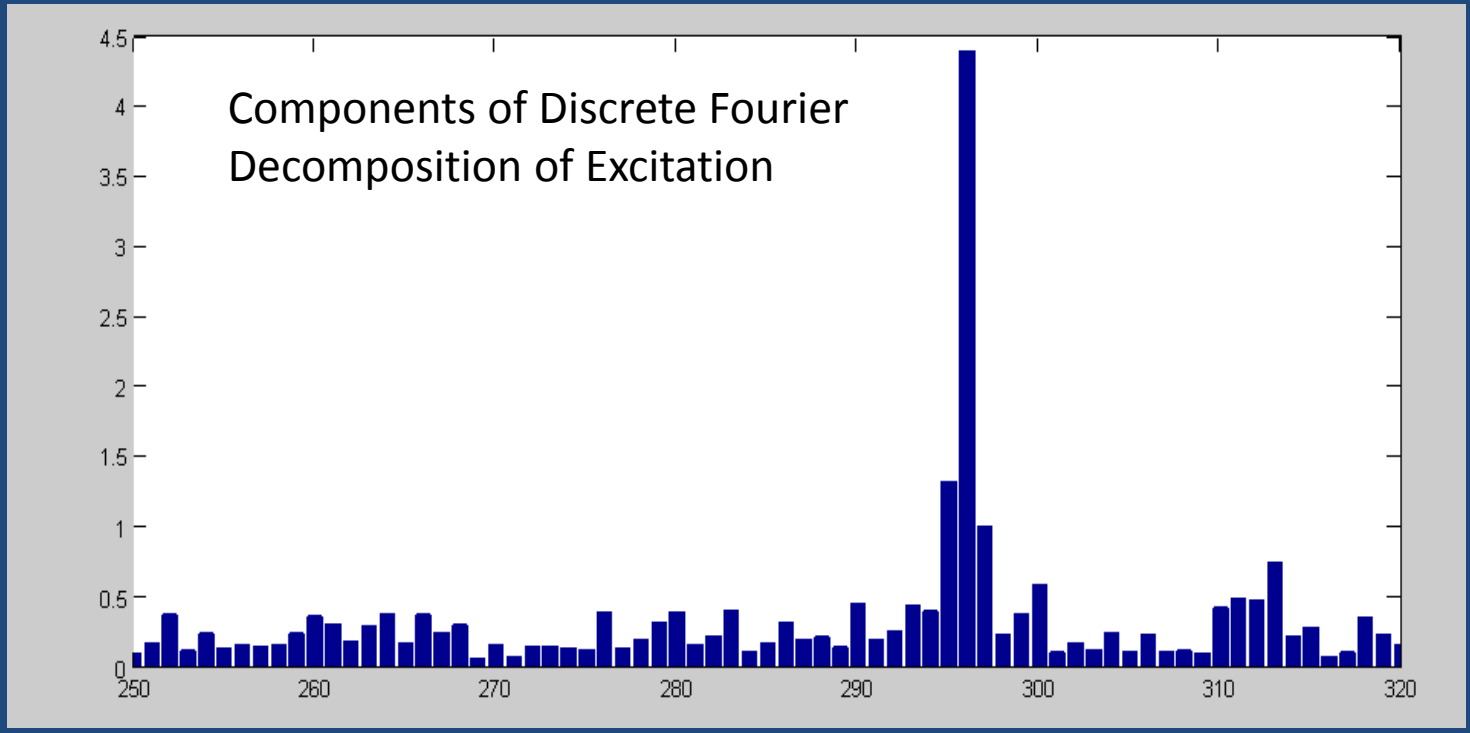
Transient Response Analysis 5ND Mode

- Time Marching numerical integration, CPU intensive, not usually tractable.
- Time histories for all nodes on every blade assembled, somewhat non-narrow band.
- Process to identify nodal comparison metrics:
  1) plot time history of blade tip node responses for a 1/5 sector of the bladed-disk
  2) Identify which node has the highest response.
  3) Subtract out mean response
  4) Calculate the statistics of the peaks of the response
  5) Apply 2σ value as value for comparison since sinusoid of this amplitude will produce equivalent damage as full Rayleigh distribution of narrow-band random signal.



Transient Response and Sideband Frequency Response

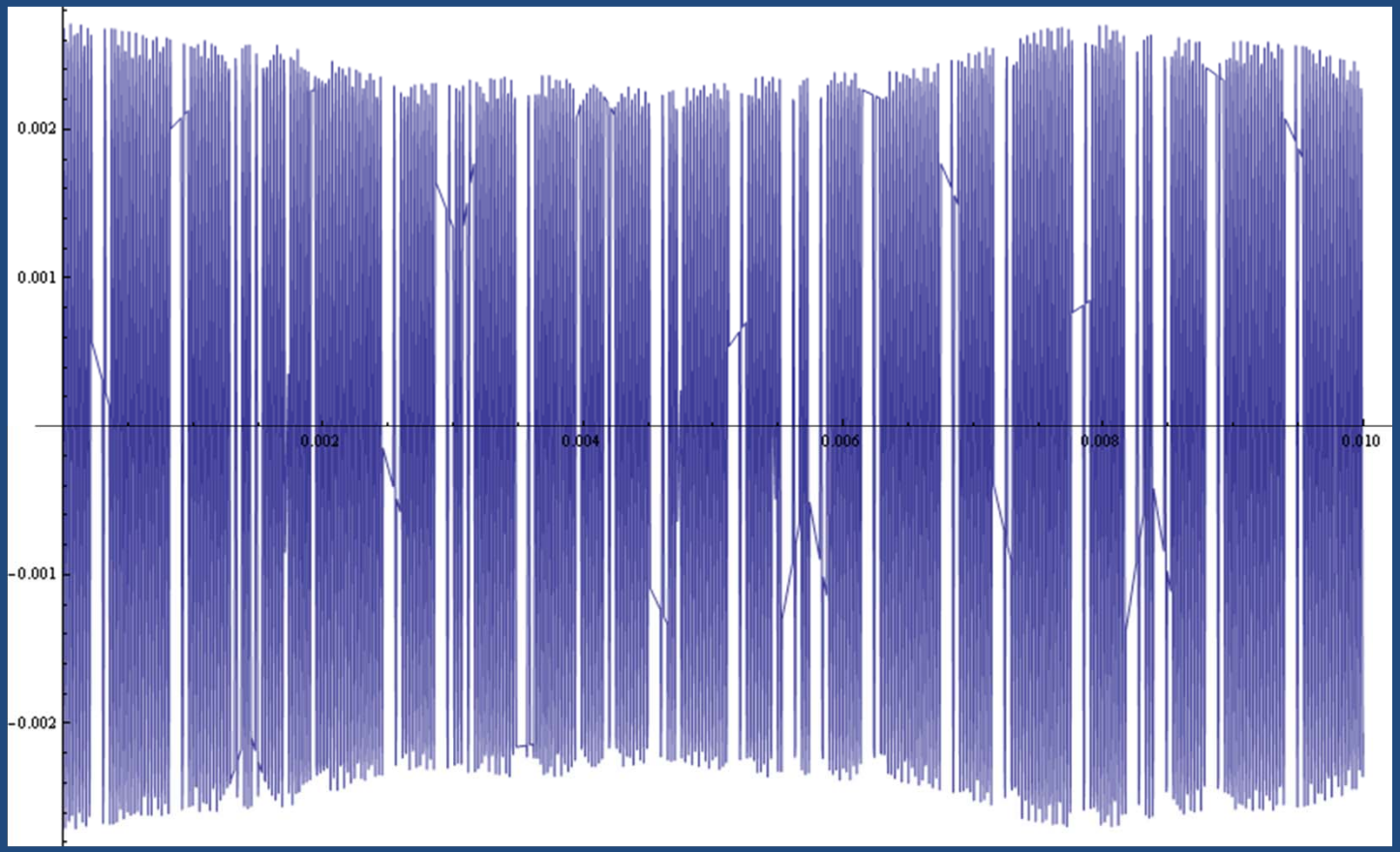
- Peak nodal transient = .00345", mean+ 2σ = .0032".
- Freq response=.0024 underpredicts by 25% (opposite of hypothesis).
- Potential source of error – contribution of non-integer multiples of running speed excitation close to 74N ("sidebands").
- Since 4 revs of CFD performed, ΔF=N/4, so 74N will be 296'th bin.
  - Non-trivial amplitudes in bins 294=73.5N, 295=73.75N, 297=74.25N



Add sidebands numerically

Perform Freq. Response Analysis at sideband frequencies using sideband amplitude, sum total:

$$x(t) = 0.000361\,\mathrm{Cos}\left[\frac{\pi}{6} - 238200.6\,t\right] + 0.000369\,\mathrm{Cos}[236596.6\,t] + 0.0024\,\mathrm{Sin}[237398.66\,t] + 0.0000458\,\mathrm{Sin}\left[\frac{\pi}{4} + 240606.7\,t\right]$$

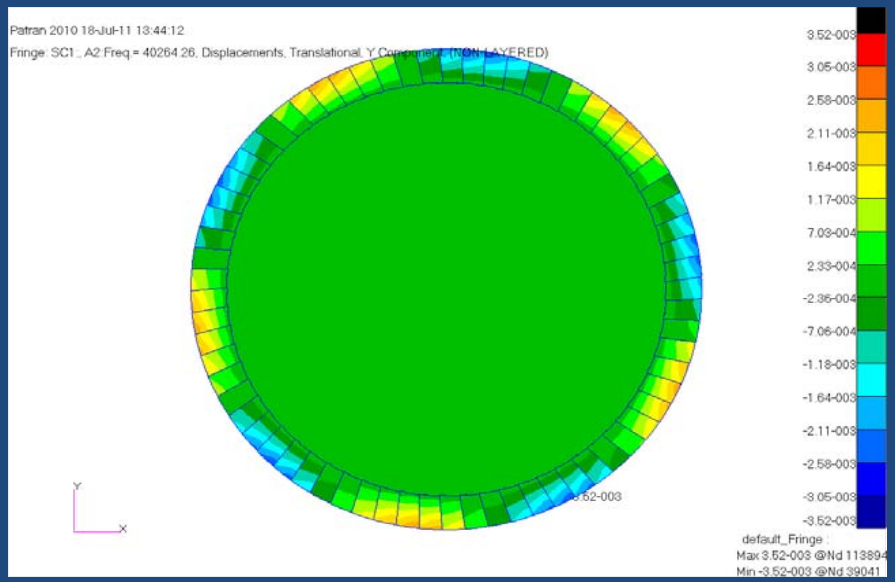


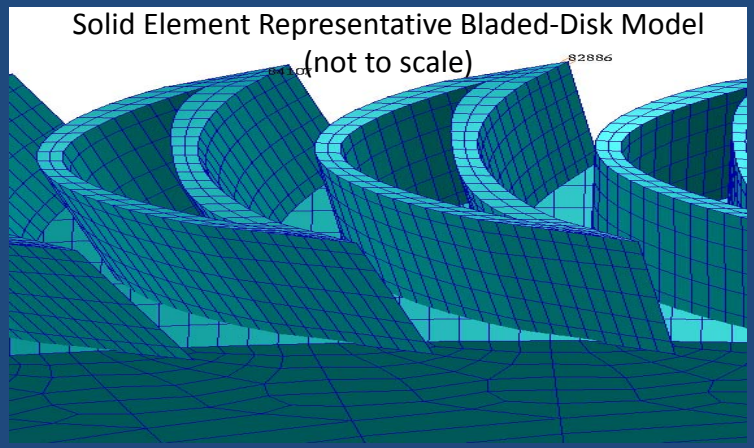
Note: Gaps in plot due to graphical error, not real

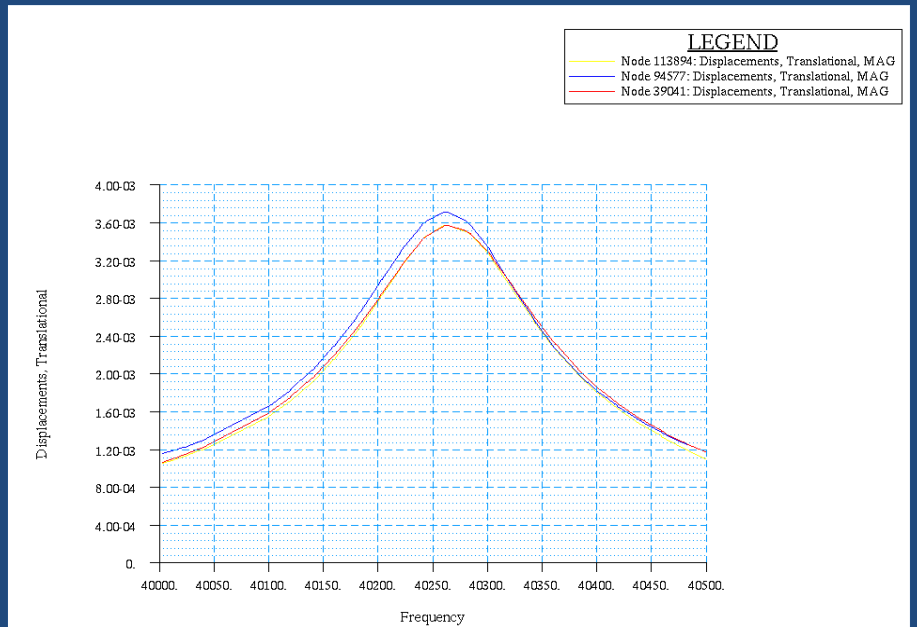
- Numerically determine Peak=0.00266” ➡ error improves to -18.6%

Realistic Airfoil Solid Model

- 2nd phase of Study – what would effect of non-periodic components be on blade-dominated modes?
- Used more realistic solid model of disk, same diameter as J2-X, and solid model of blades using airfoil shapes from J2-X.
- 5ND mode at 40264hz identified.
- Frequency response for 74N excitation performed for peak responding nodes.

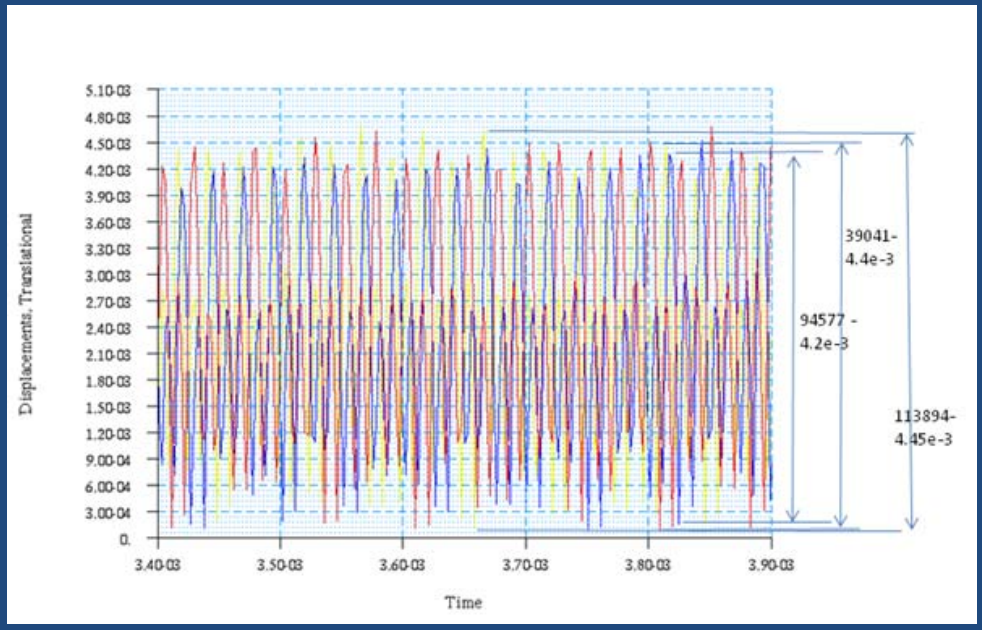






5ND Response Analysis

- Transient analysis required 52,000 point time history on each of 29,000 nodes, took 84 clock hours.
- Good Agreement achieved by adding in sidebands.

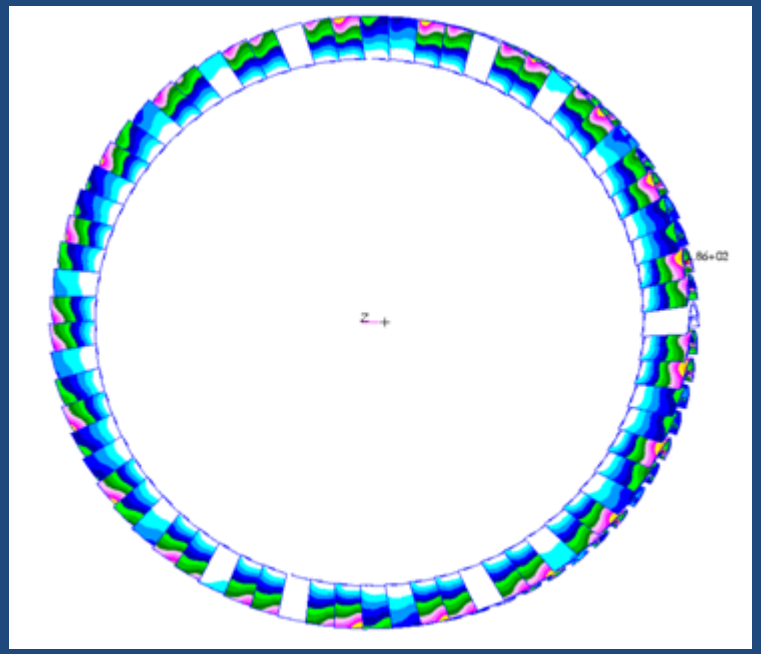


Node	Transient Response Theta Displacement	74N Frequency Response Theta	Error 74N Freq Resp from Transient Theta	73.8N Frequency Response Theta	74.2N Frequency Response Theta	Peak of sum of 74N, 73.8N,74.2N	Error sum Freq Resp from Transient Theta
113894	.00380	.00358	-6%	.000658	.000732	.00415	9%
94577	.00403	.00366	-9%	.000606	.000668	.00421	5%
39041	.00398	.00353	-11%	.000694	.000772	.00414	4%
52320	.004	.00357	-11%	.000666	.000740	.00415	4%
83711	.0042	.00352	-16%	.000695	.000664	.00409	-3%

- However, don't need sidebands if using Transient Mean + 2σ, e.g., for node 83711 =.00381", 6.8% < summed frequency response of .00409"

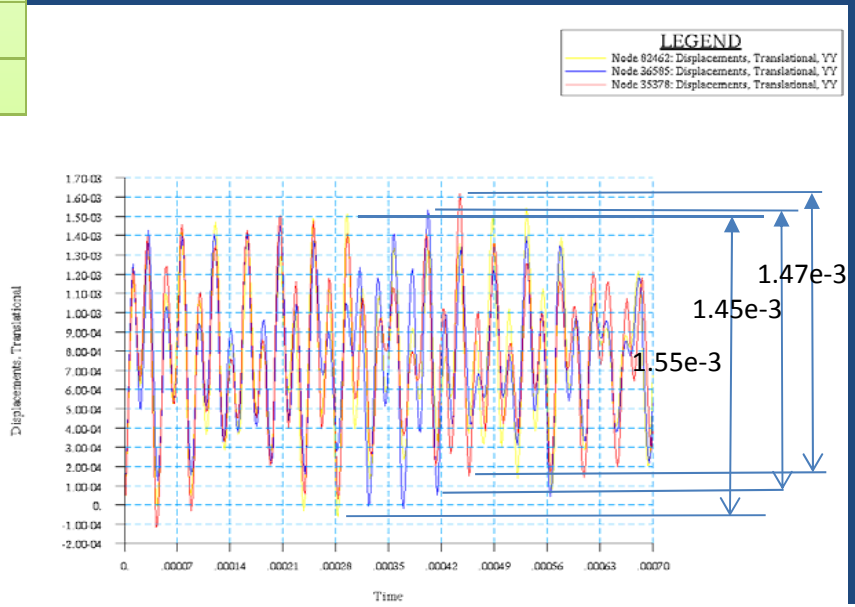
57N Excitation of 12ND Mode, Solid Airfoil Model

- 12ND mode at 40883 hz identified, freq. response & trans response analyses performed.



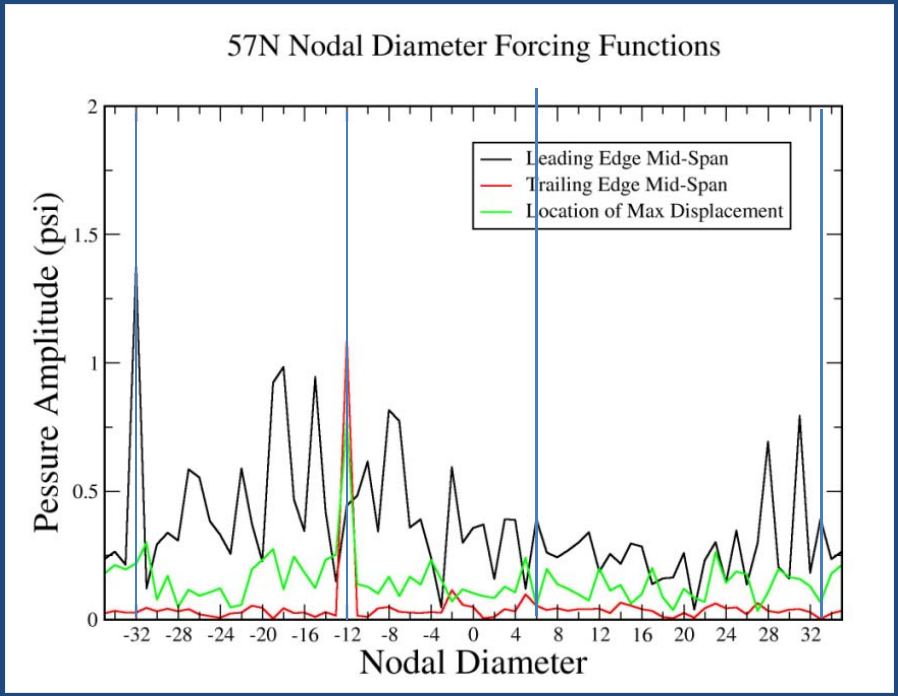
node	transient, theta, 5 revs, excitation at 40882.5hz	57N freqresp, 5 revs, 285th bin (5*57N)	error from transient	57N freqresp, 1 rev, 57th bin	error from transient
35378	1.45E-03	2.02E-04	-618%	5.10E-04	-184%
36585	1.47E-03	2.00E-04	-635%	5.48E-04	-168%
82462	1.55E-03	3.20E-04	-384%	2.65E-04	-485%
110229	1.47E-03	2.80E-04	-425%	2.73E-04	-438%

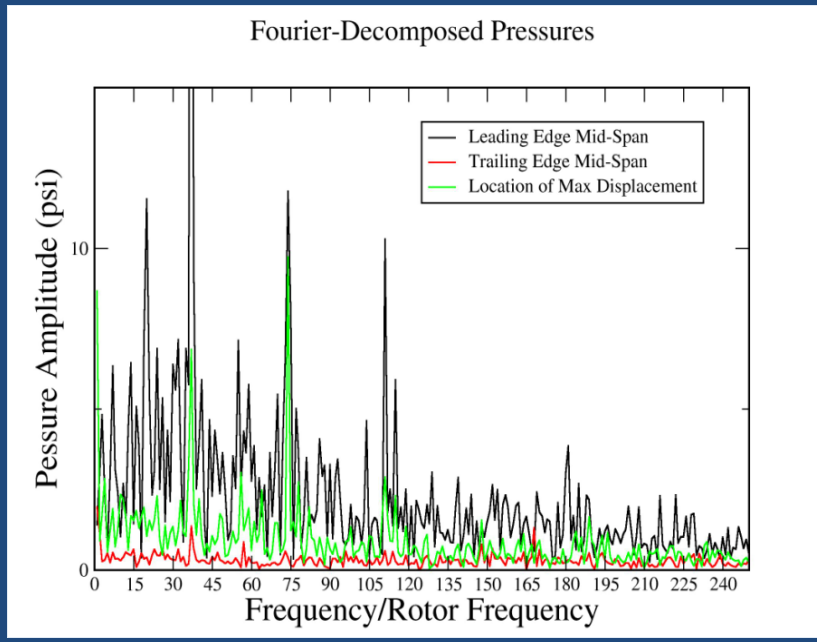
- Huge Error in Frequency Response Result Compared with Transient.
- Transient not narrow-banded.



Investigation of Huge Discrepancy

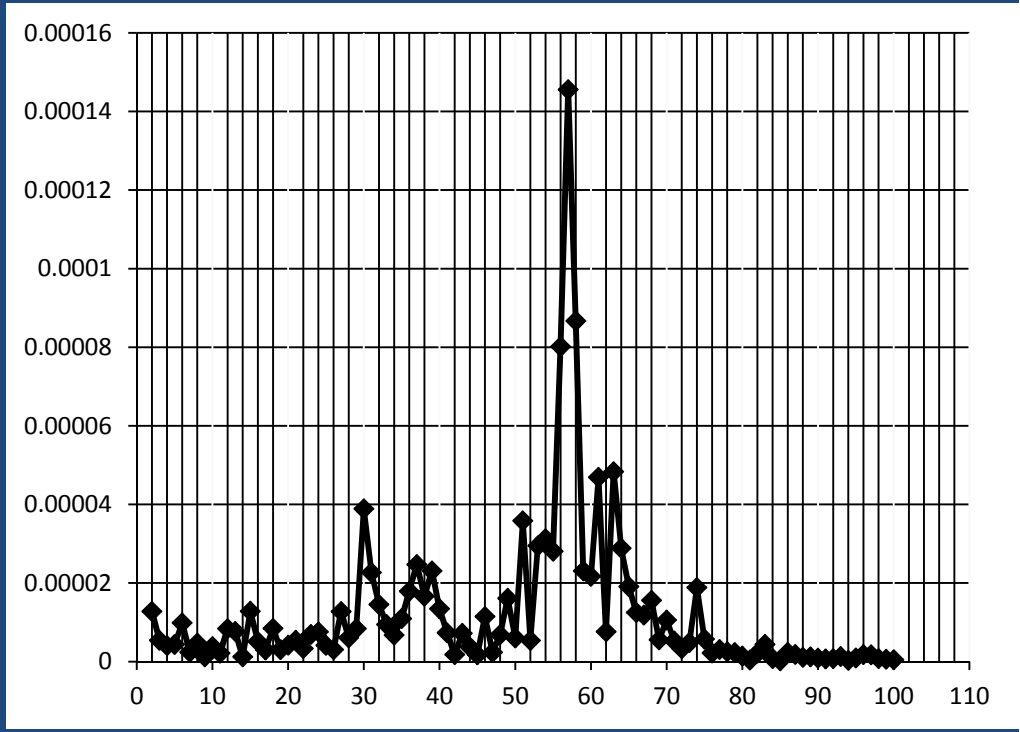
- Energy on LE>> energy on TE, even at 57N
- Fourier 2D (Spatial) Decomposition shows high spatial density.





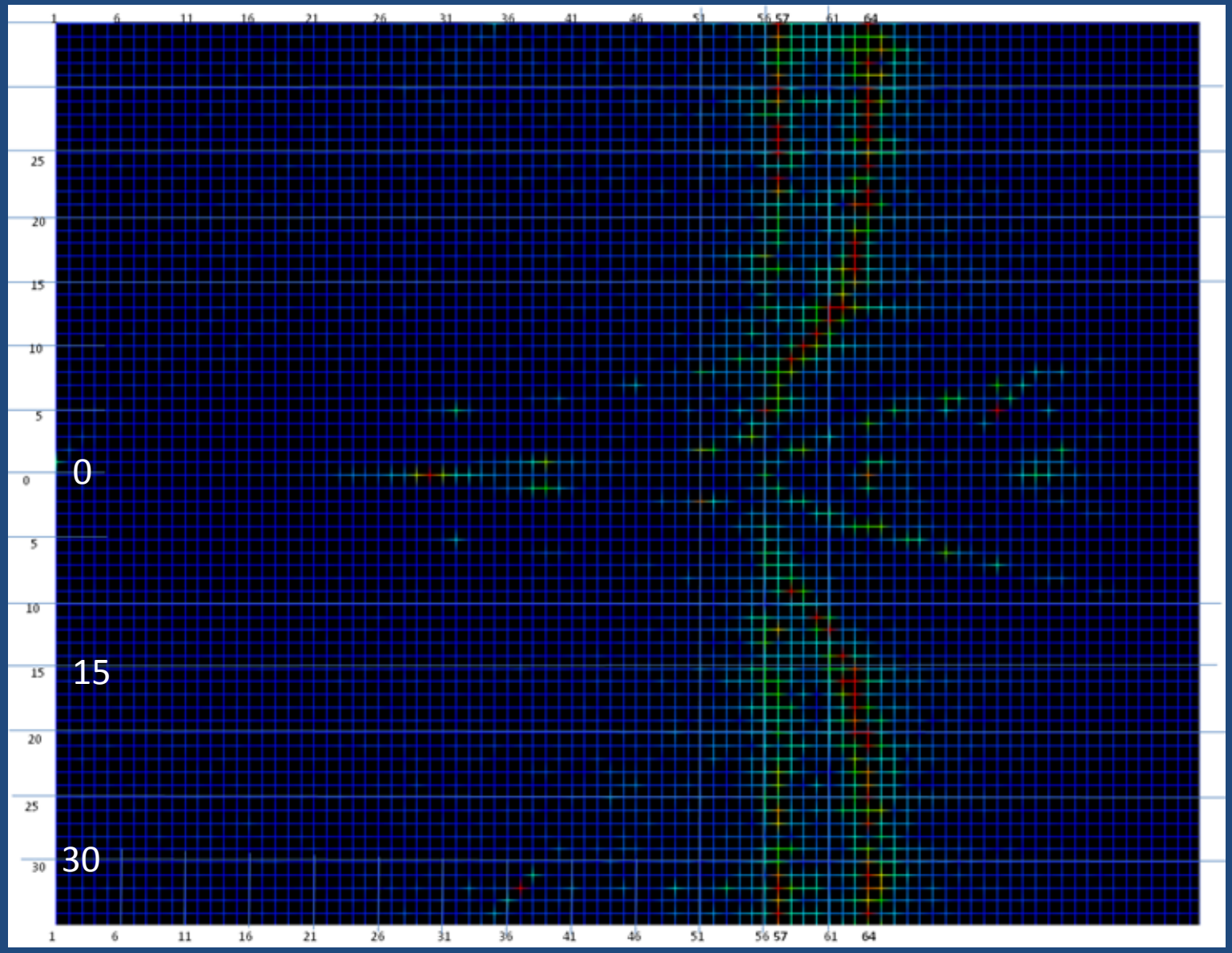
1st Hypothesis to Explain Error

- Hypothesis – high non-12ND spatial content and frequencies of excitation match a mode shape.
- Examine modal excitation due to high non-57N peaks 29N and 63N shown in temporal Fourier decomposition of transient response.
- Mode close to 29N at 21146hz, but it is concentric circle mode.
- High-order nodal diameter mode shape near 63N at 45208 hz.
  - Frequency response analysis yields response << 57N response though -????

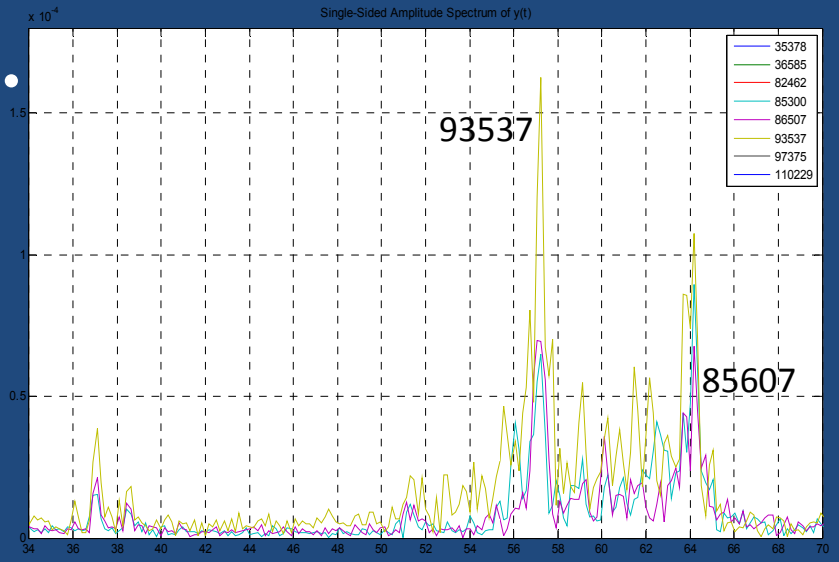


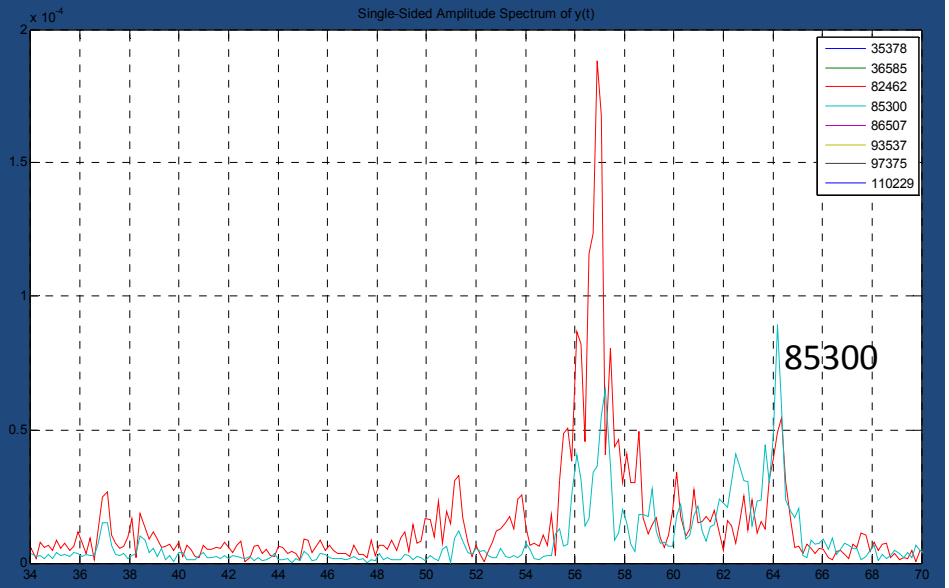
Fourier Transform of Transient Response for excitation such that 57N=40883hz

2-D Fourier Transform Shows Spatial Complexity



Focus on Mid-Chord Nodes Explains Discrepancy





- 63N response greater than 57N for selected nodes.

Location	Node	Transient Response, theta, 5 revs, at 40882 hz	Frequency Response 57N, 1 rev, 57th bin	Error from transient	Frequency Response bin 64 at 45903hz theta	Frequency Response bin 63 at 45186
close to mid-chord	93537	5.60E-04	4.09E-04	-27%	1.76E-04	3.29E-05
Mid-chord	86507	3.81E-04	2.60E-05	-93%	1.01E-04	4.30E-05
Mid-chord	85300	3.80E-04	4.84E-05	-87%	5.53E-05	3.83E-05

- Conclusion - Response in nodal diameters other than 57N forms bulk of response

Conclusions & Future Work (part 1)

- Non-periodic content in CFD motivated study to characterize possible deficiencies in standard frequency response analysis for Bladed-Disks.
- Transient, or temporal solution solved by numerical integration used as baseline.
- Two models used: simple beam-blade model and realistic solid-airfoil model.
- For cases where strong excitation mechanism exists, difference between frequency and transient response results < 10%, but sidebands may need to be added to primary frequency response results.
- Rather than using peak value of transient, may use statistical value (ie, mean +2 or 3 σ) if transient is not narrow-banded.

Conclusions & Future Work (continued)

- Cases when excitation mechanism weak (i.e. downstream drivers in middle of flow path) can exhibit errors > 100%.
  - Spatial shapes in flow other than those from vane-blade interaction and which have significant temporal fourier content interact generate significant response.
- These mechanisms don't usually drive design, but can sometimes, so accuracy of standard frequency response must be examined for accurate prediction.
- Future work: Need to identify when including sidebands in frequency response and statistical value for transient response are appropriate.