Evaluating Pressure Pulsation in Piping Systems with Caesar II

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CAU2014

Abstract:

Designing piping systems based on the forced vibration response due to pulsation-induced shaking forces is risky business. Pulsation control is the primary design tool. However, in cases where a forced response analysis is specified or otherwise deemed necessary, the simplified harmonic frequency sweep available in CAESAR II can be used to evaluate "worst-case" scenarios and satisfy this requirement.

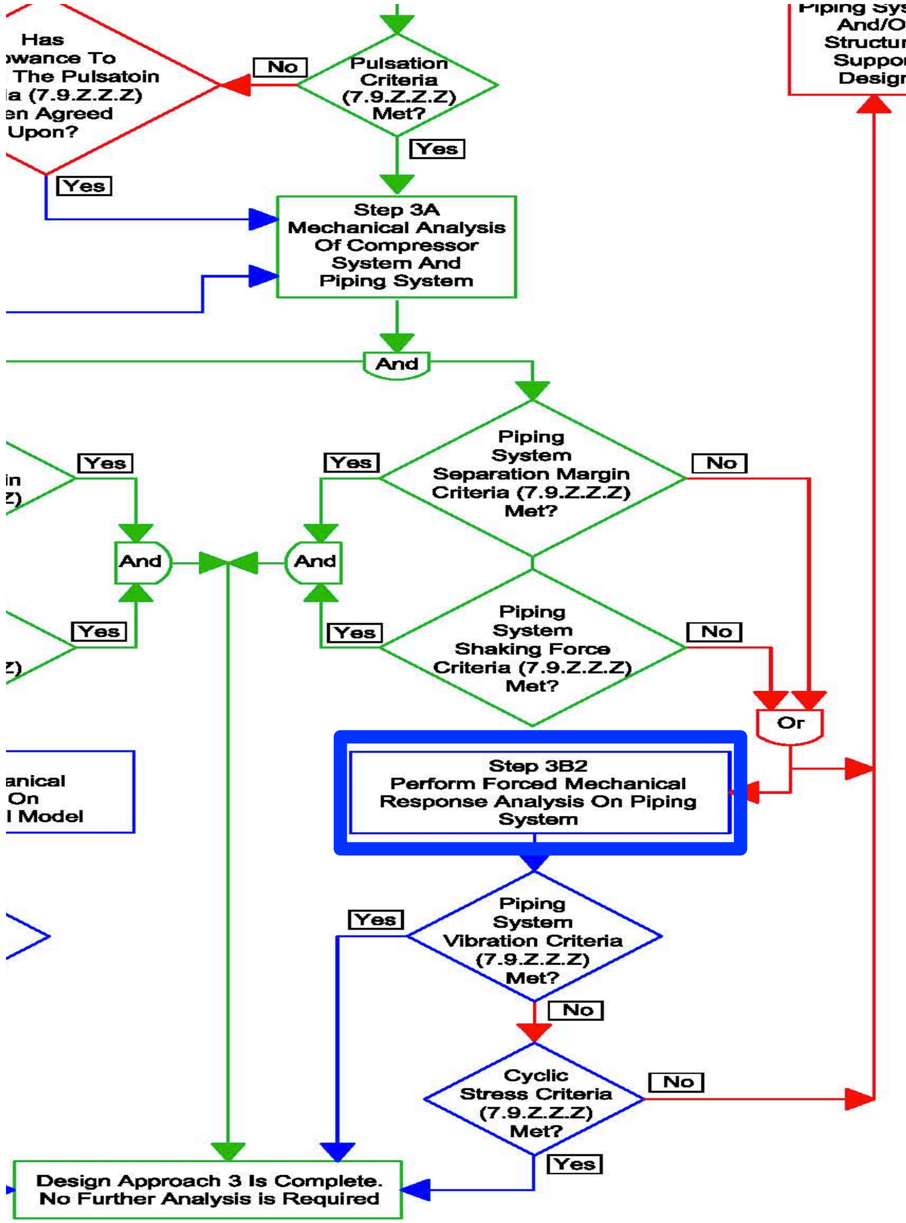
INTERGRAPH

Review / Context

Guidelines for Design of Reciprocating Machinery Piping Systems (API 618, 688)

- API 618 6th Edition will be issued soon
- API 688 2nd Edition Task Force is active
- Will cover all positive displacement machinery
  - Recip. Compressors, PD Pumps,
  - Screw compressors and pumps

Design Approach 3 Flow Chart



INTERGRAPH

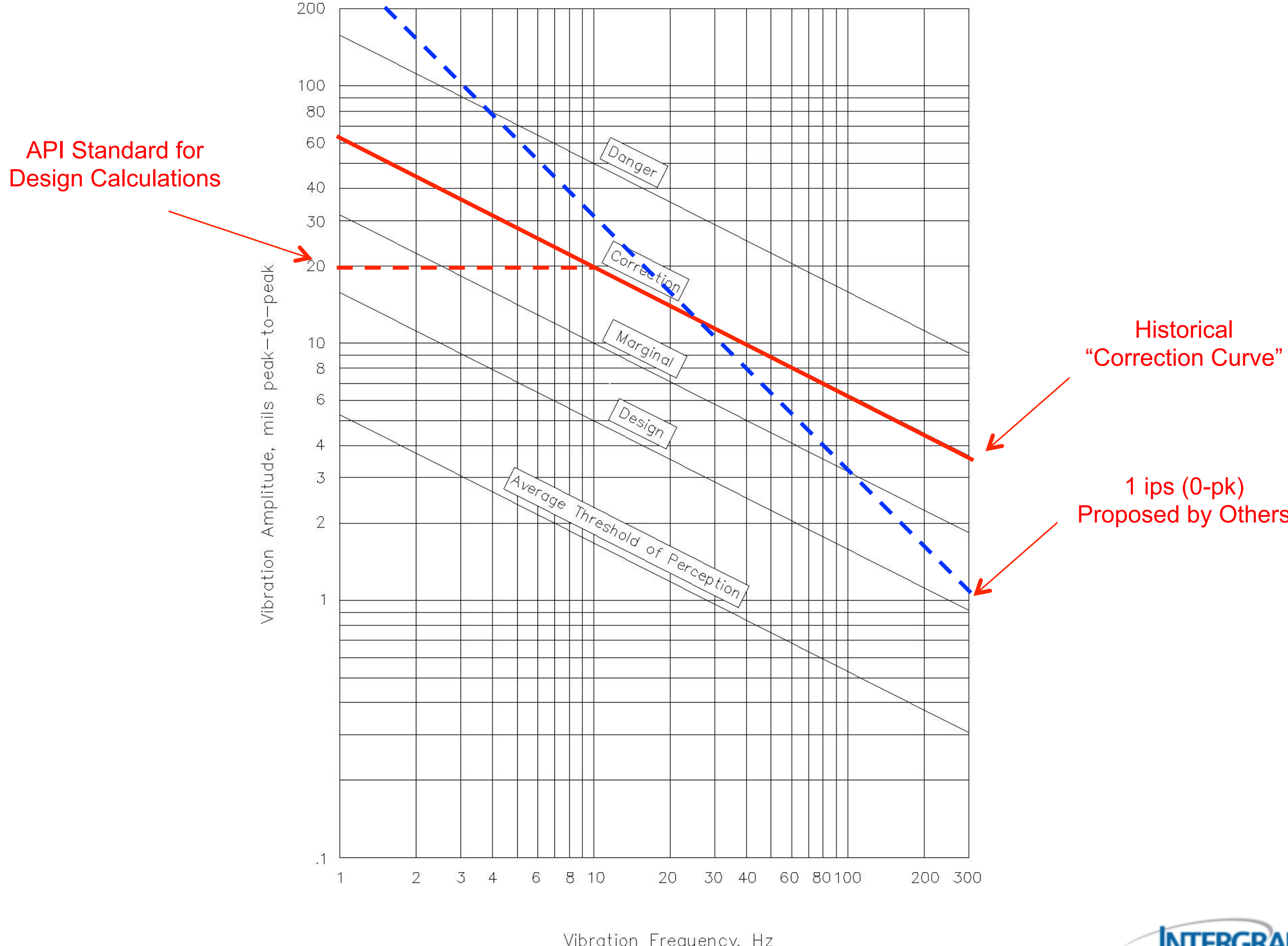
API 688 Guidelines

- Maintain separation margin between piping natural frequencies and significant shaking force frequencies.
- What is "significant" shaking force:

100 x NPS (lbs, p-p)

(non-resonant)

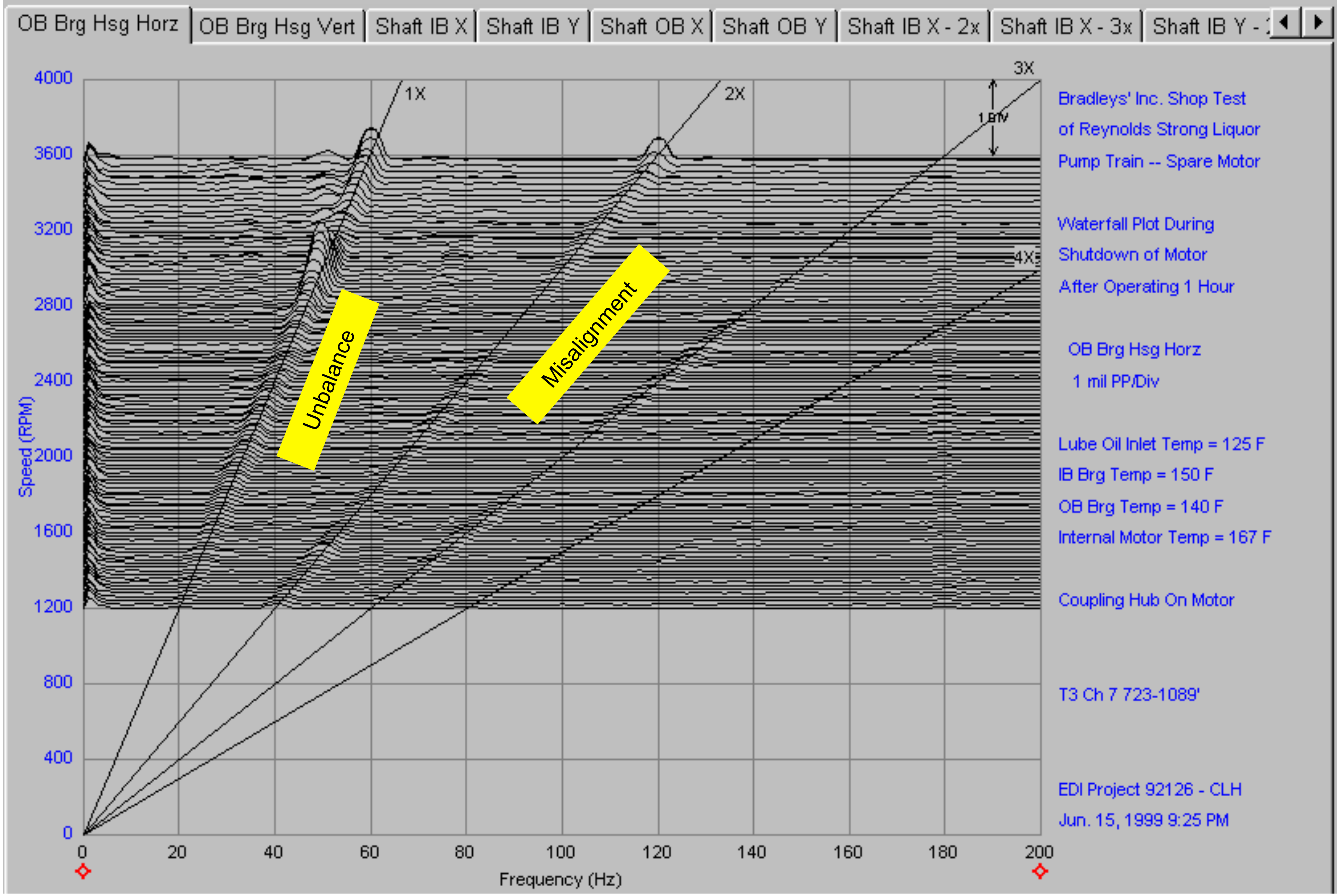
Vibration Screening Criteria for Reciprocating Compressor Piping Systems



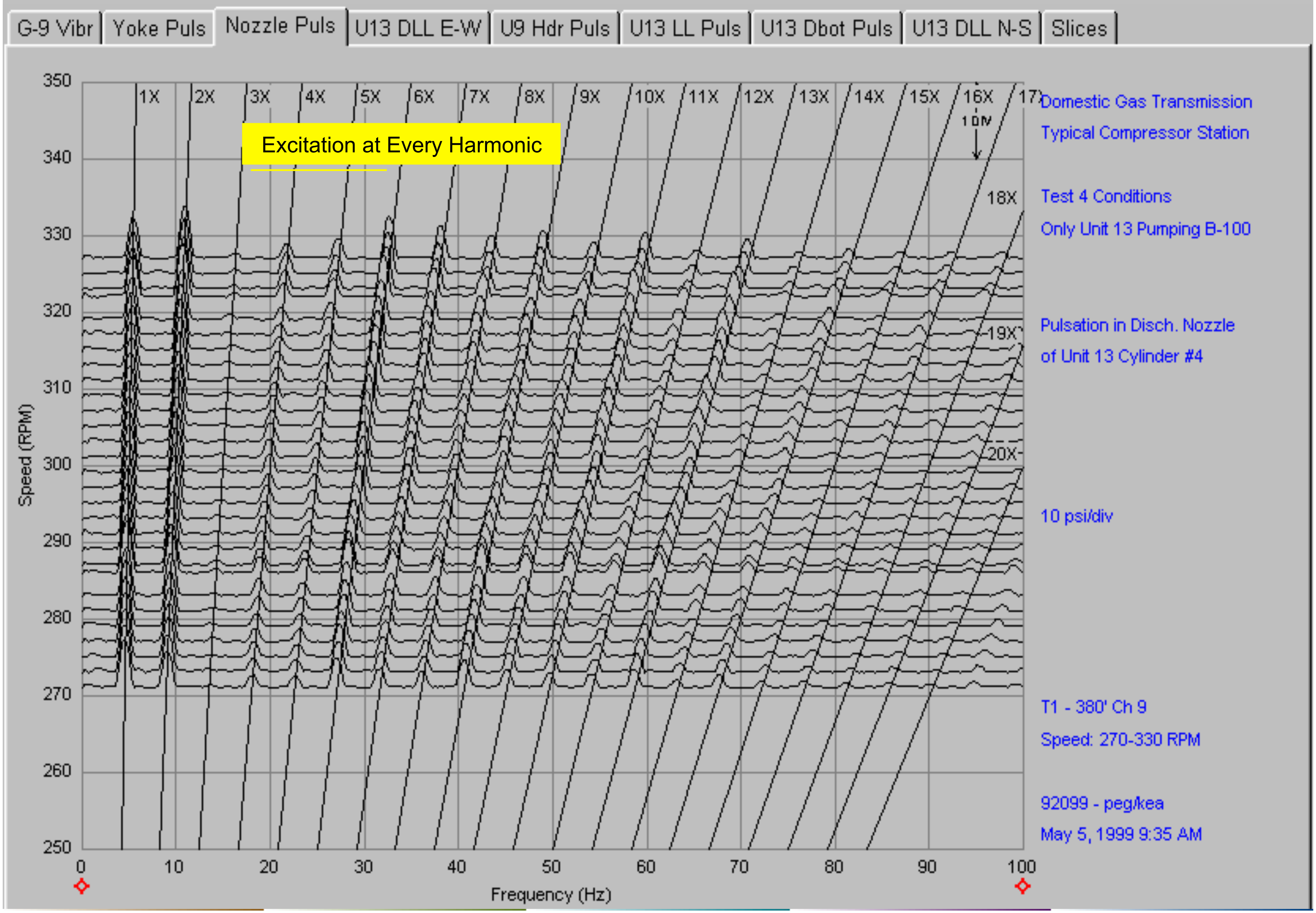
What is the excitation?

- Pulsation is generated at *every* harmonic of running speed
- Every elbow, diameter change, closed valve, etc. can couple pressure pulsation into a shaking force
- Pulsation is important!

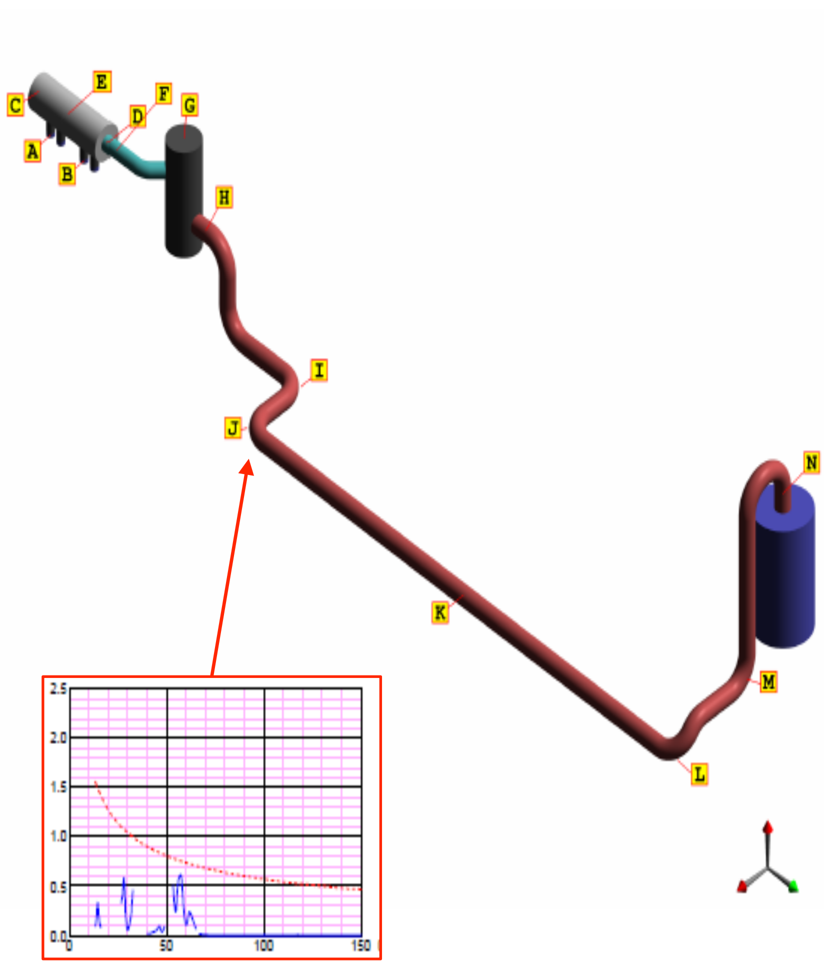
Typical Vibration Spectra From Turbomachine

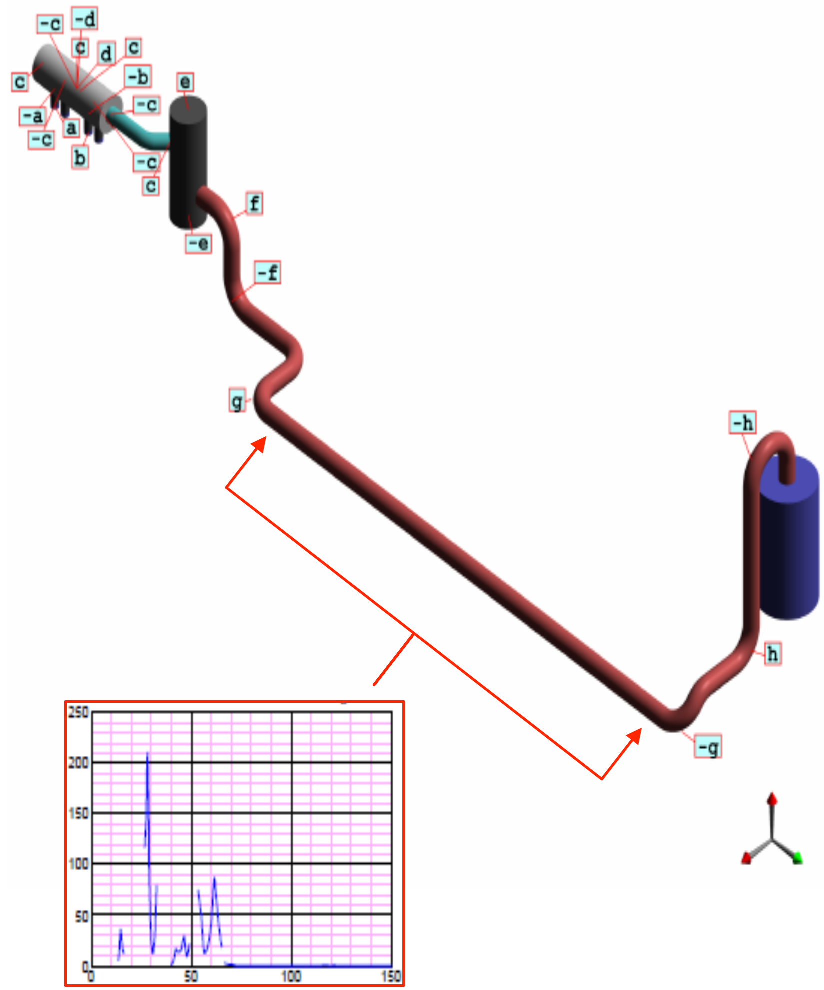


Typical Pulsation Spectra from Recip

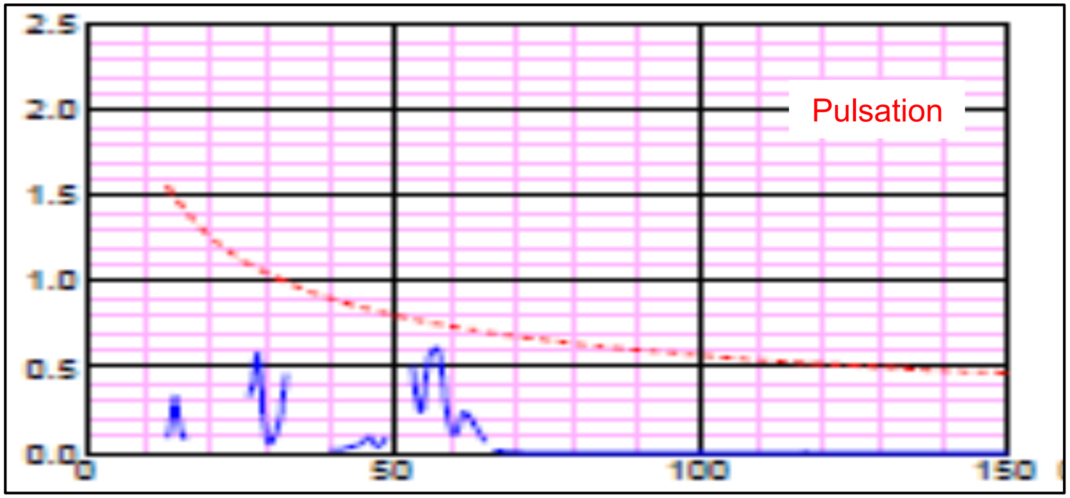


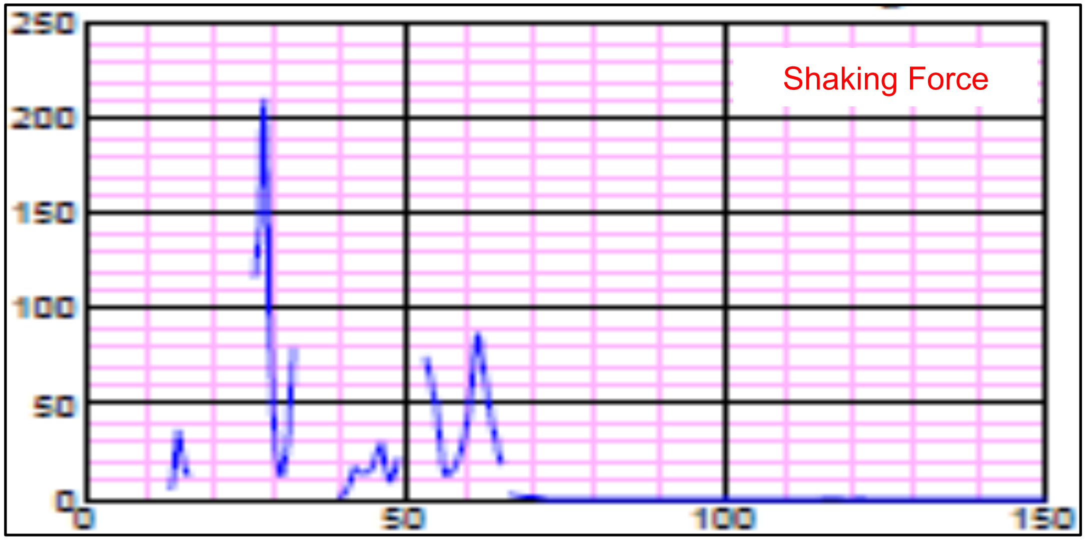
Typical Piping System Acoustical Model





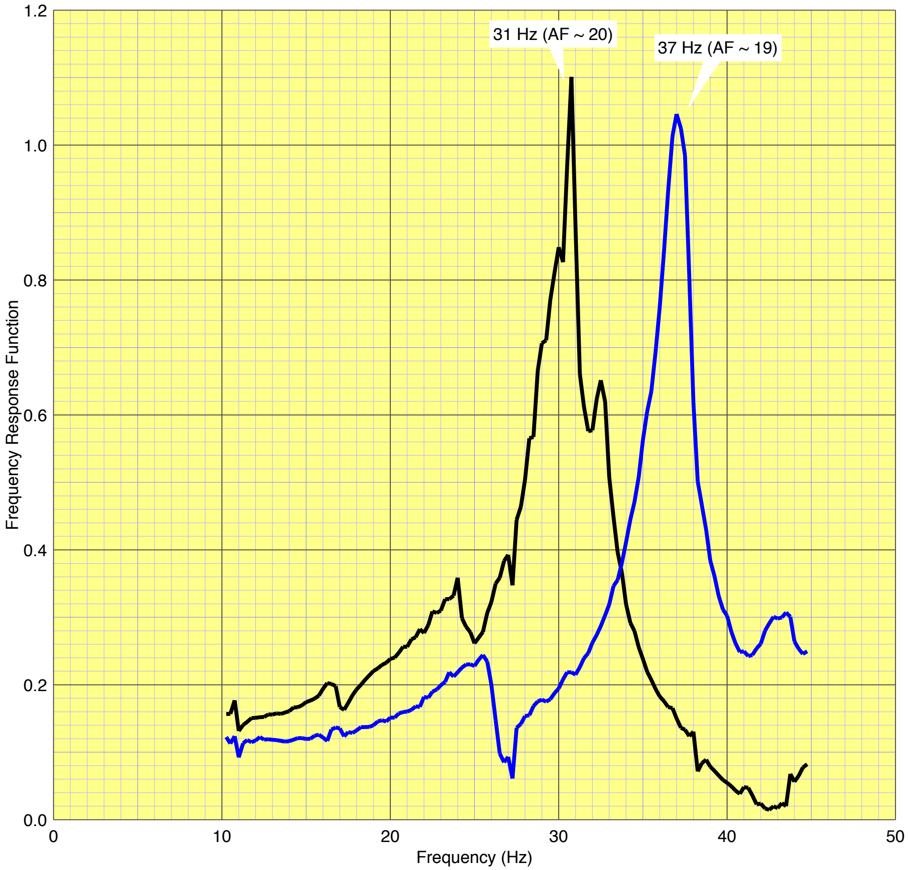
Sample Data: Variable Speed





This is the forcing function
to be considered

Sample Data: Measured Piping MNFs



Example of Measured Piping Mechanical Natural Frequency

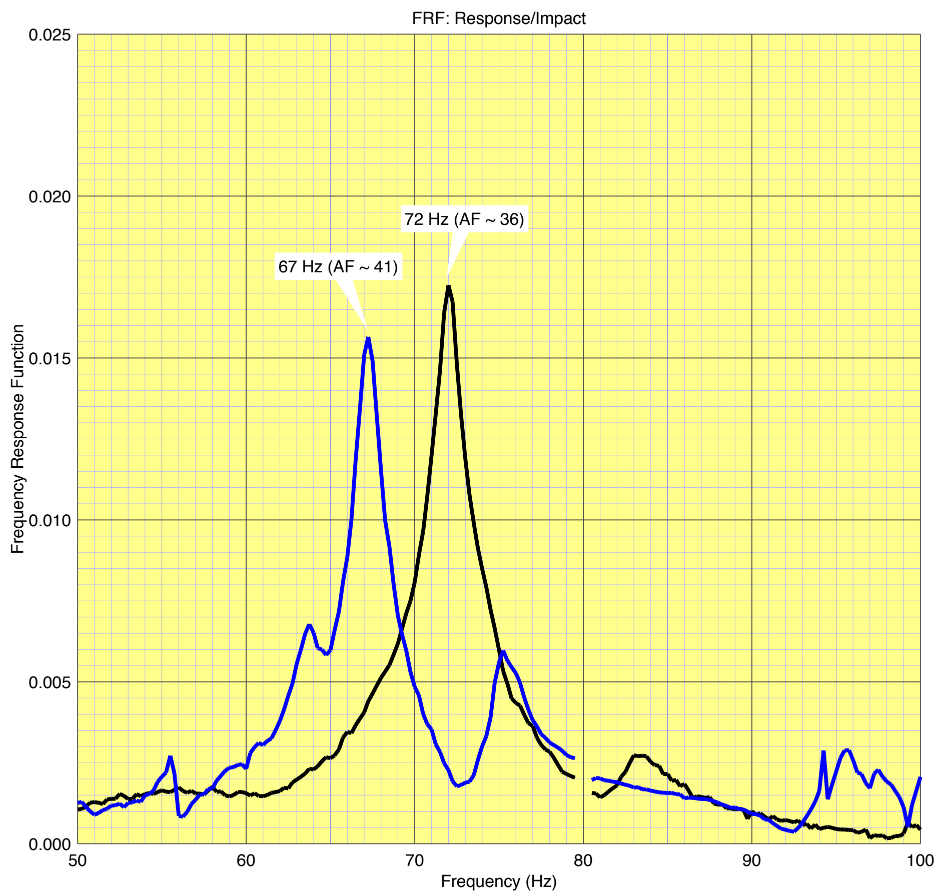
Impact Test of Discharge Piping.

Impact and Measure Z Axis

17% Variation in MNF of "Identical" Systems (Typical of Piping Systems) Damping Ratio ~ 2.5%

Illustrates that forced response predictions of vibration and stress are very dependent on factors that cannot be controlled by the design.

Sample Data: Measured Piping MNFs



Example of Measured Piping Mechanical Natural Frequency

Impact Test of Discharge Piping. Midspan Elbow

Impact and Measure N-S

7% Variation in MNF of "Identical" Systems (Larger Spread is Common)

Damping Ratio ~ 1.3%

Magnitude of Response Varies By Factor of 4 - 8 at the Two Peak Frequencies

Illustrates that forced response predictions of vibration and stress are very dependent on factors that cannot be controlled by the design.

Concepts:

- Uncertainty of Piping MNFs is high (+/- 20%)
- Forced response results are dependent on proximity to resonance and damping
- Avoiding resonance is the preferred approach

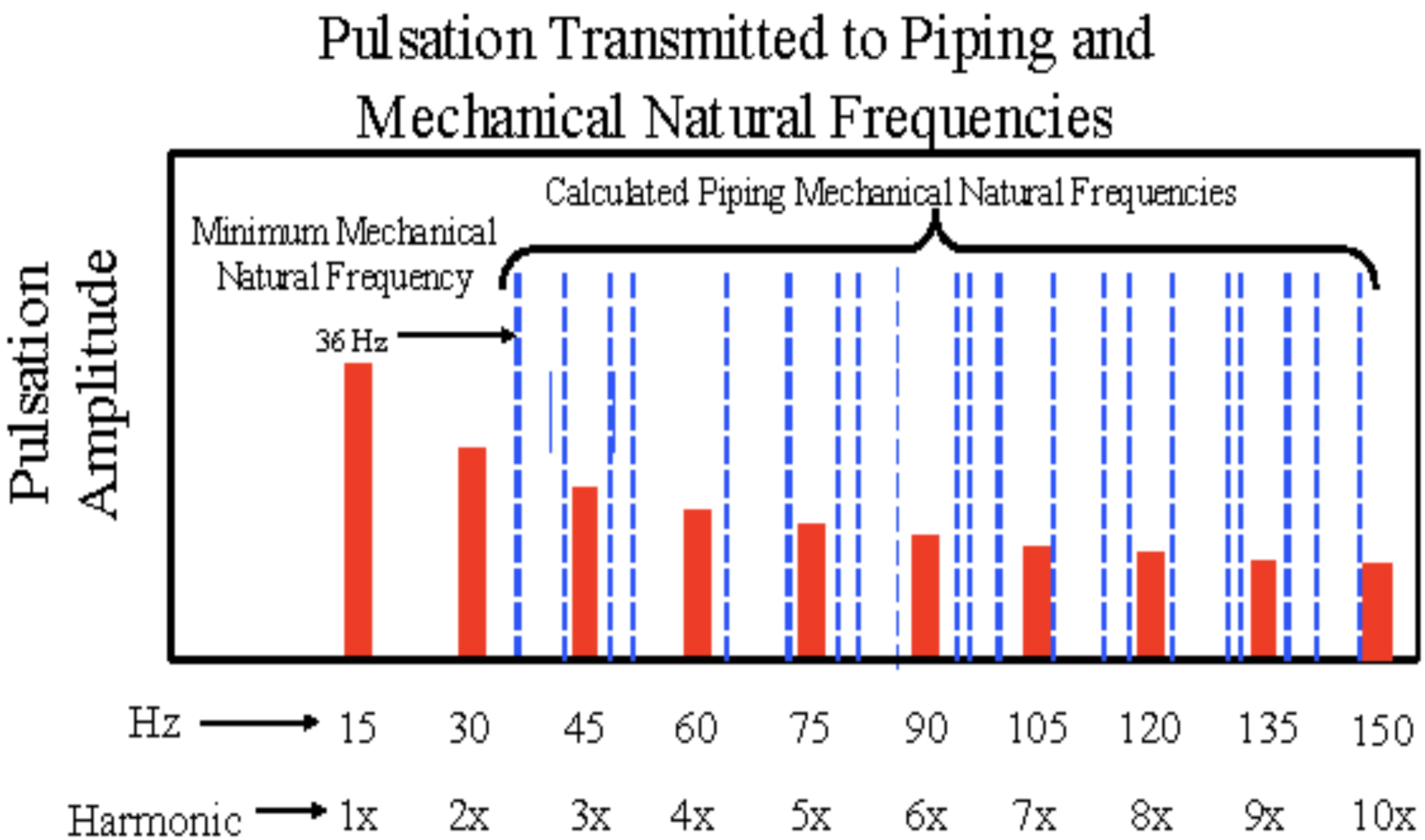


Figure 10. Pulsation Characteristics without Acoustic Filtering: Calculated Mechanical Natural Frequencies Superimposed

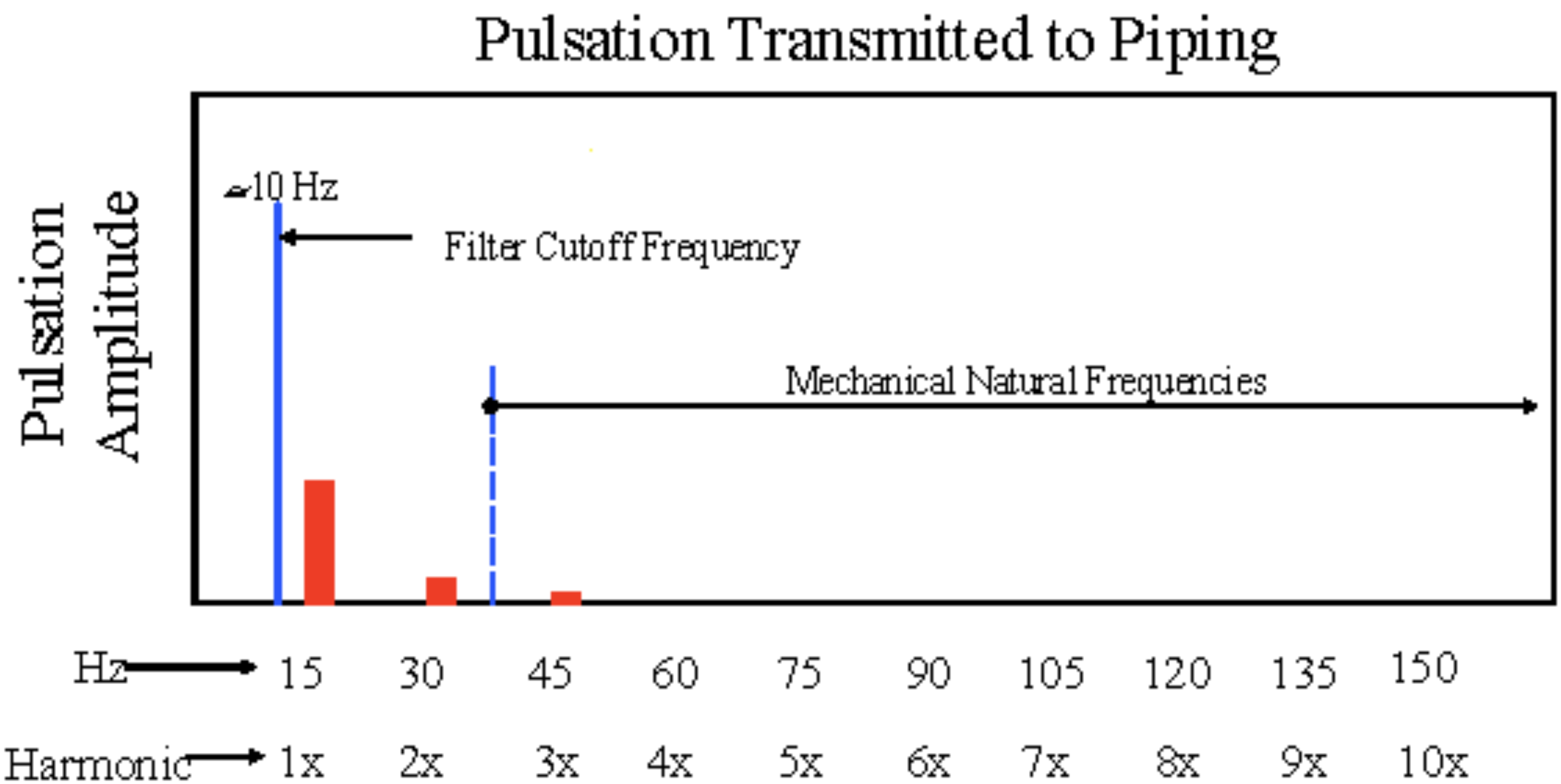


Figure 16. Pulsation Characteristics with Acoustic Filtering

"Old School" (from CAU2012)

Guidelines for Design of Reciprocating Machinery Piping Systems (API 618, 688)

- Minimize Bends
- Provide Clamp Near Each Bend
- Provide Clamp Near Each Concentrated Weight
- Space Clamps According to Expected Excitation Frequency

"Old School"

Guidelines for Design of Reciprocating Machinery Piping Systems *(continued)*

- Ensure $K_{support}$ > 2x K_{span}
- Use Good Clamp Designs

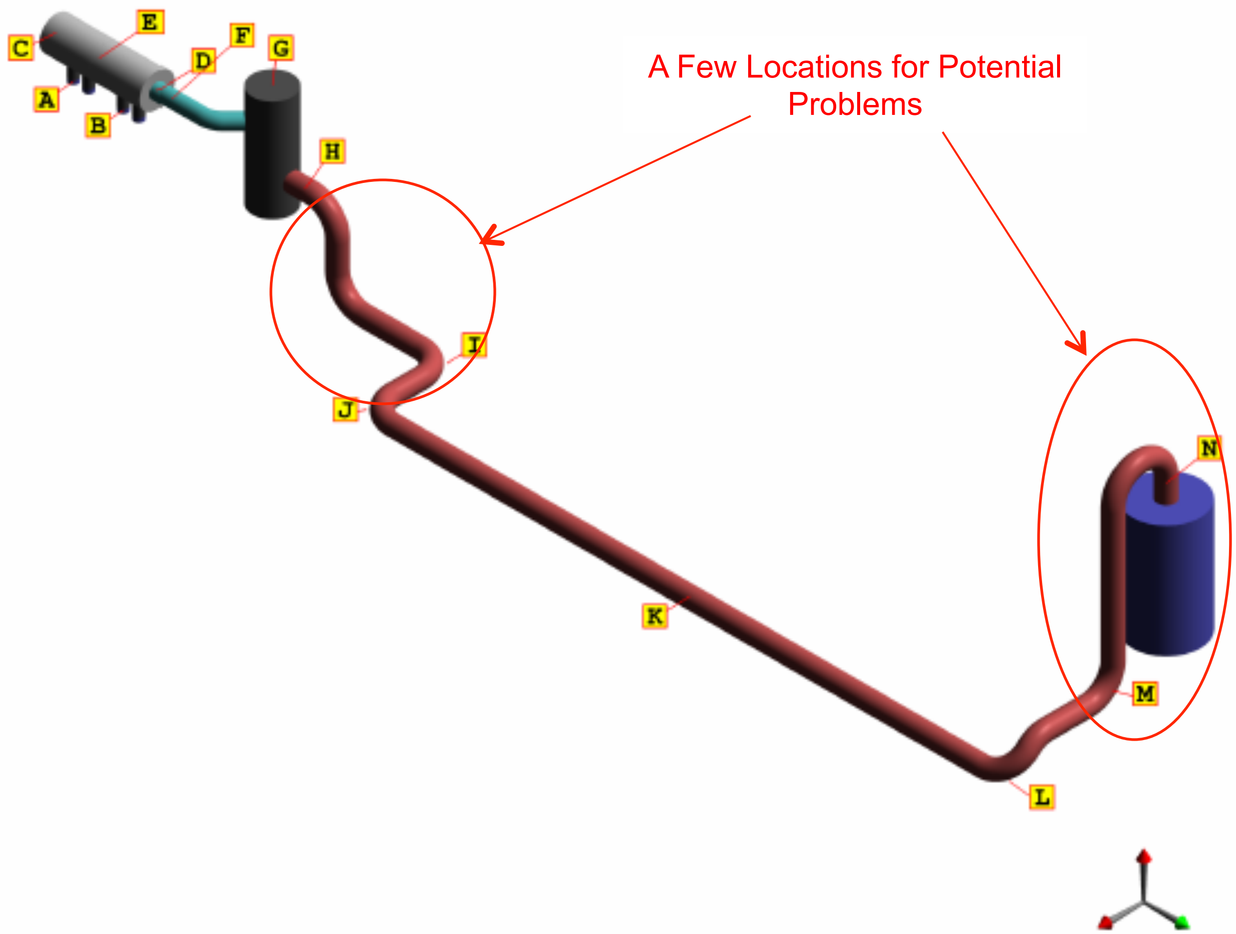
INTERGRAPH

Natural Frequency of Simply-Supported Span ($\lambda = 9.87$)

Natural Freq. (Hz)	*Nominal Pipe Size / Outside Diameter*							
	6 6.625	8 8.625	10 10.75	12 12.75	14 14.00	16 16.00	18 18.00	20 20.00
25	14.1	16.1	17.9	19.5	20.5	21.9	23.2	24.5
30	12.9	14.7	16.4	17.8	18.7	20.0	21.2	22.3
35	11.9	13.6	15.2	16.5	17.3	18.5	19.6	20.7
40	11.1	12.7	14.2	15.4	16.2	17.3	18.4	19.3
45	10.5	12.0	13.4	14.6	15.3	16.3	17.3	18.2
50	10.0	11.4	12.7	13.8	14.5	15.5	16.4	17.3
55	9.5	10.8	12.1	13.2	13.8	14.8	15.6	16.5
60	9.1	10.4	11.6	12.6	13.2	14.1	15.0	15.8
65	8.7	10.0	11.1	12.1	12.7	13.6	14.4	15.2
70	8.4	9.6	10.7	11.7	12.2	13.1	13.9	14.6
75	8.1	9.3	10.4	11.3	11.8	12.6	13.4	14.1
80	7.9	9.0	10.0	10.9	11.4	12.2	13.0	13.7

INTERGRAPH

Piping Model



Using Caesar II for Dynamics

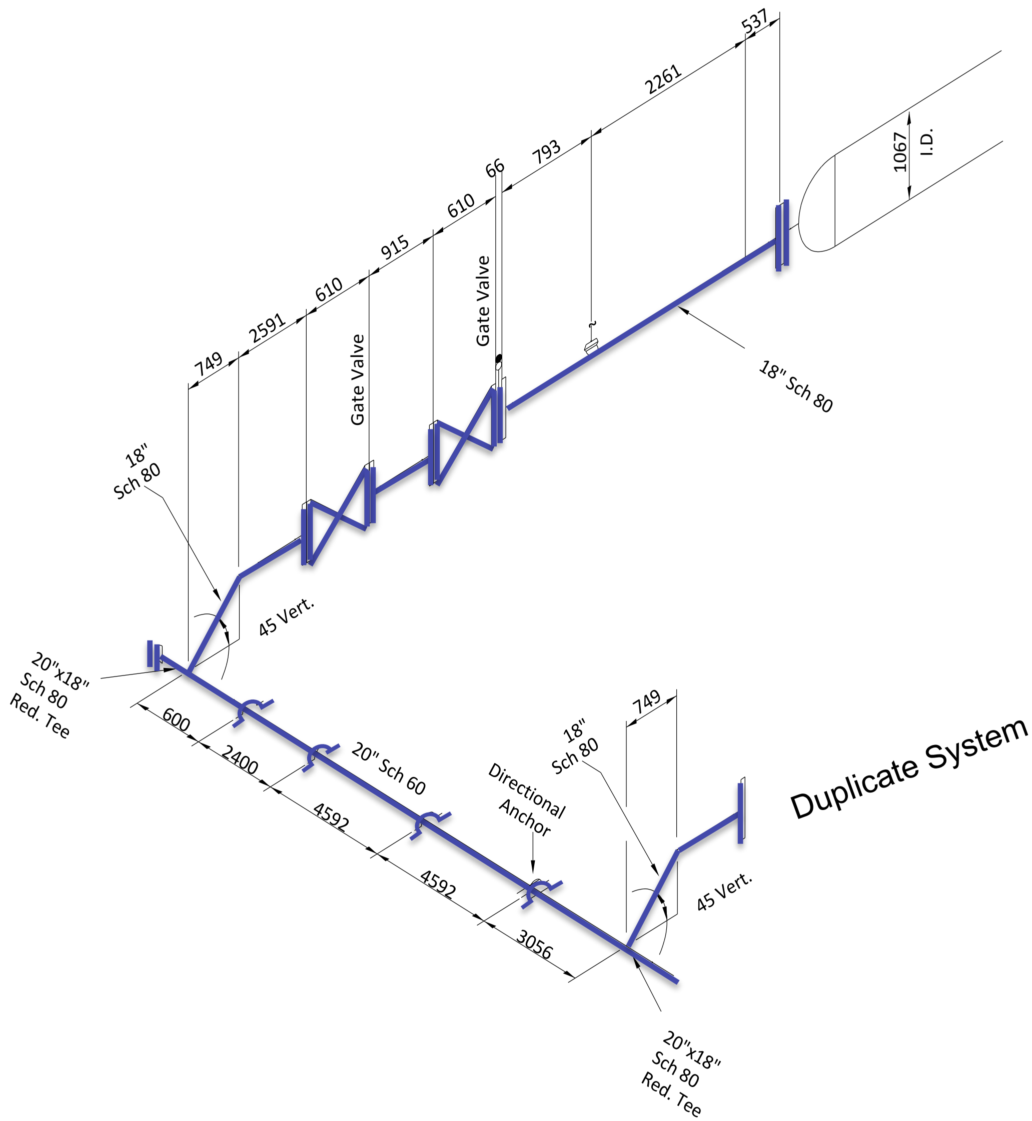
Caesar II Pipe Models

- Able to handle complex, non-deal spans that do not lend themselves to hand calculations
- Boundary conditions are the key. Assumptions that may be conservative from a thermal growth standpoint often lead to inaccuracies in natural frequency predictions
- If the guidelines for designing the system are followed, natural frequencies should be within the expected range

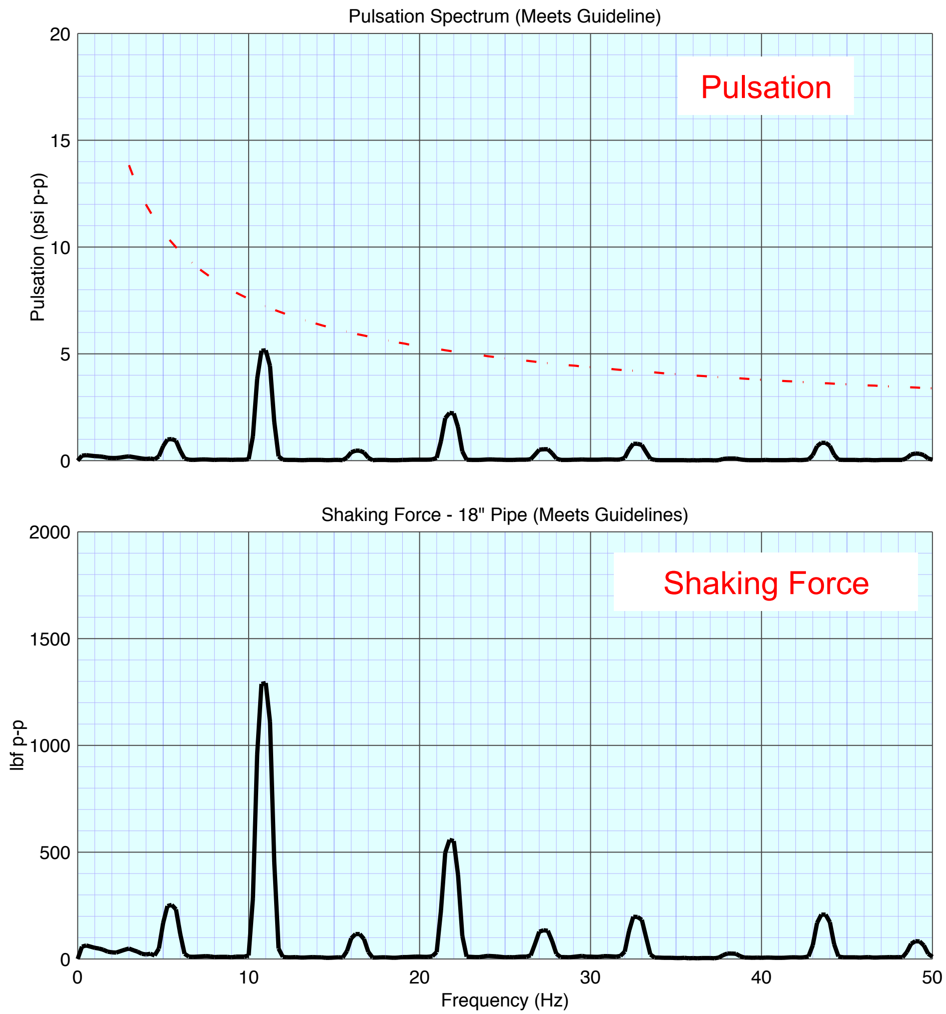
Concepts:

- Many times it is impractical to consider every force, every mode.
- Using constant force vs frequency is conservative
- Must understand mode shapes and forces

Sample Piping System



Sample Data: Constant Speed Unit



Design Goal:

Lowest MNF > 25 Hz

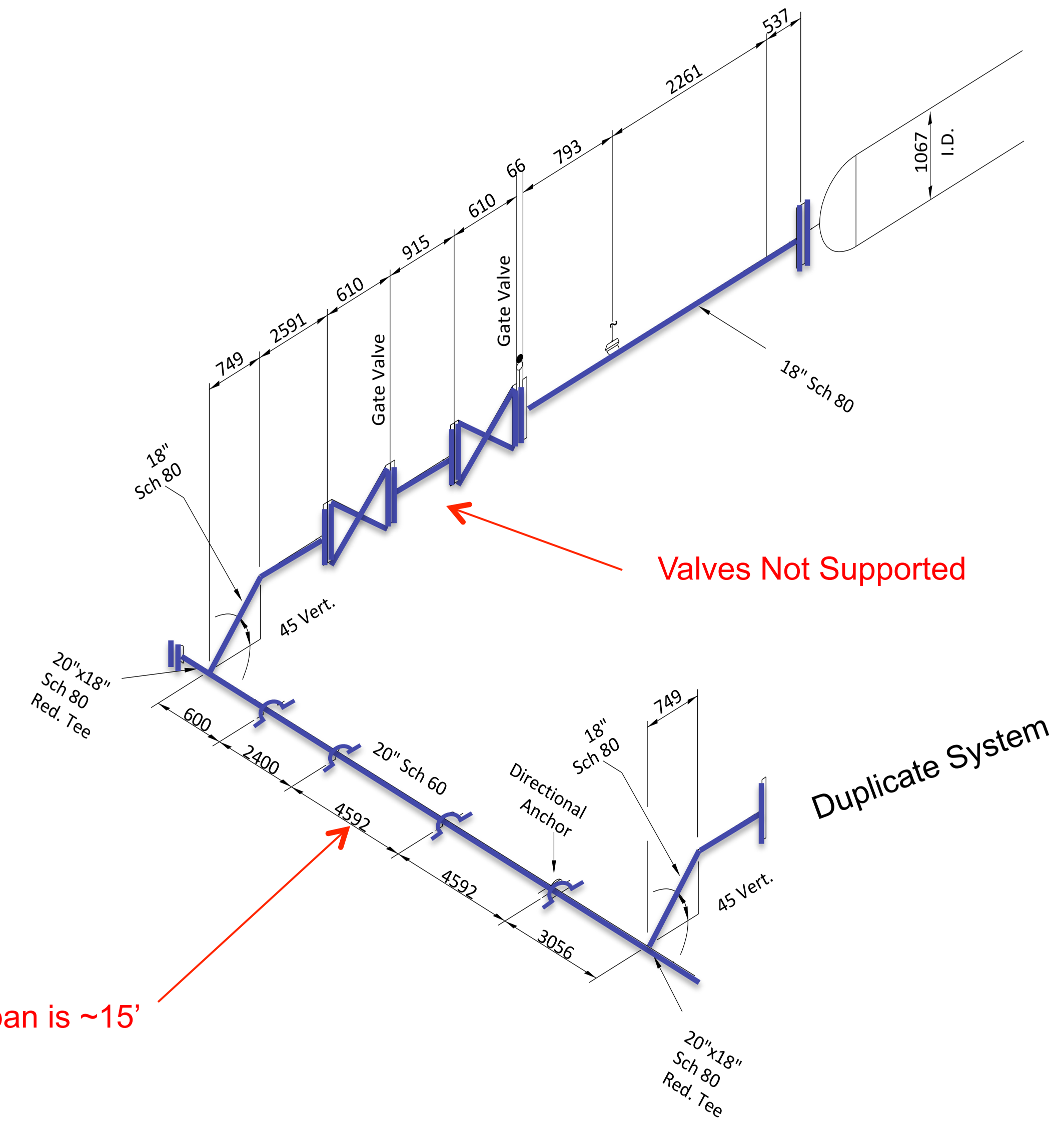
(No Significant Forces Above 25 Hz)

This is the forcing function to be considered

Natural Frequency of Simply-Supported Span (λ = 9.87)

Natural Freq. (Hz)	*Nominal Pipe Size / Outside Diameter* 6 6.625	8 8.625	10 10.75	12 12.75	14 14.00	16 16.00	18 18.00	20 20.00
25	14.1	16.1	17.9	19.5	20.5	21.9	23.2	24.5
30	12.9	14.7	16.4	17.8	18.7	20.0	21.2	22.3
35	11.9	13.6	15.2	16.5	17.3	18.5	19.6	20.7
40	11.1	12.7	14.2	15.4	16.2	17.3	18.4	19.3
45	10.5	12.0	13.4	14.6	15.3	16.3	17.3	18.2
50	10.0	11.4	12.7	13.8	14.5	15.5	16.4	17.3
55	9.5	10.8	12.1	13.2	13.8	14.8	15.6	16.5
60	9.1	10.4	11.6	12.6	13.2	14.1	15.0	15.8
65	8.7	10.0	11.1	12.1	12.7	13.6	14.4	15.2
70	8.4	9.6	10.7	11.7	12.2	13.1	13.9	14.6
75	8.1	9.3	10.4	11.3	11.8	12.6	13.4	14.1
80	7.9	9.0	10.0	10.9	11.4	12.2	13.0	13.7

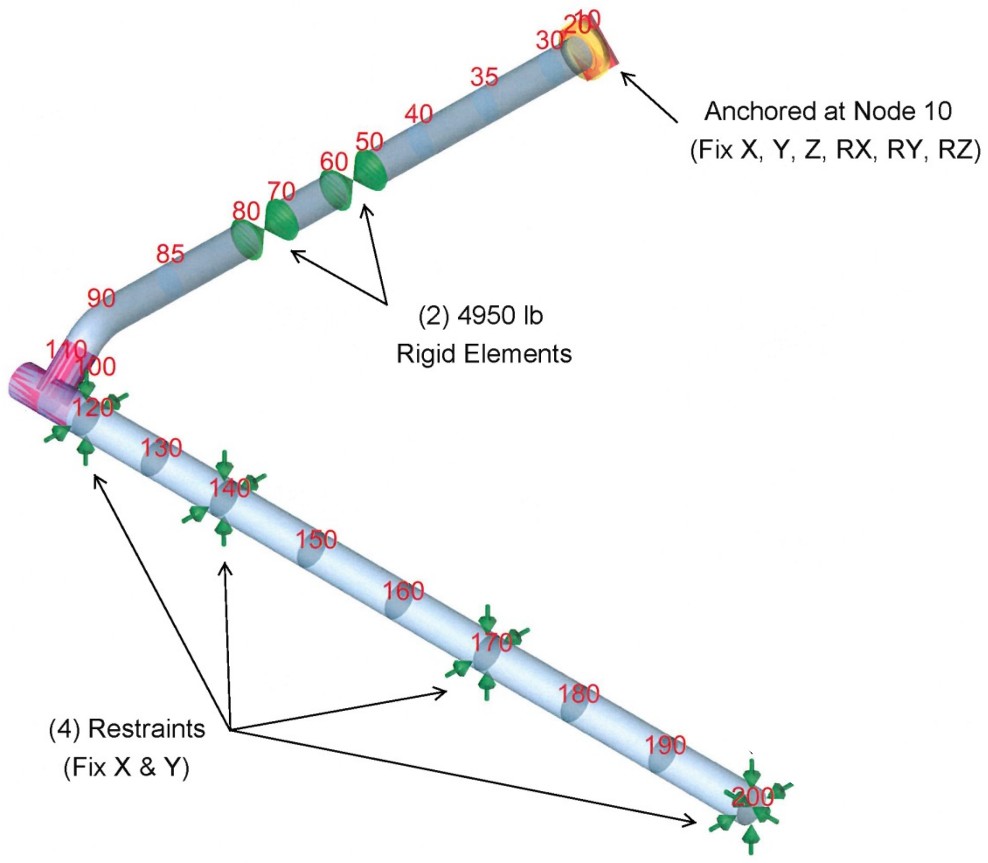
Sample Piping System



But….

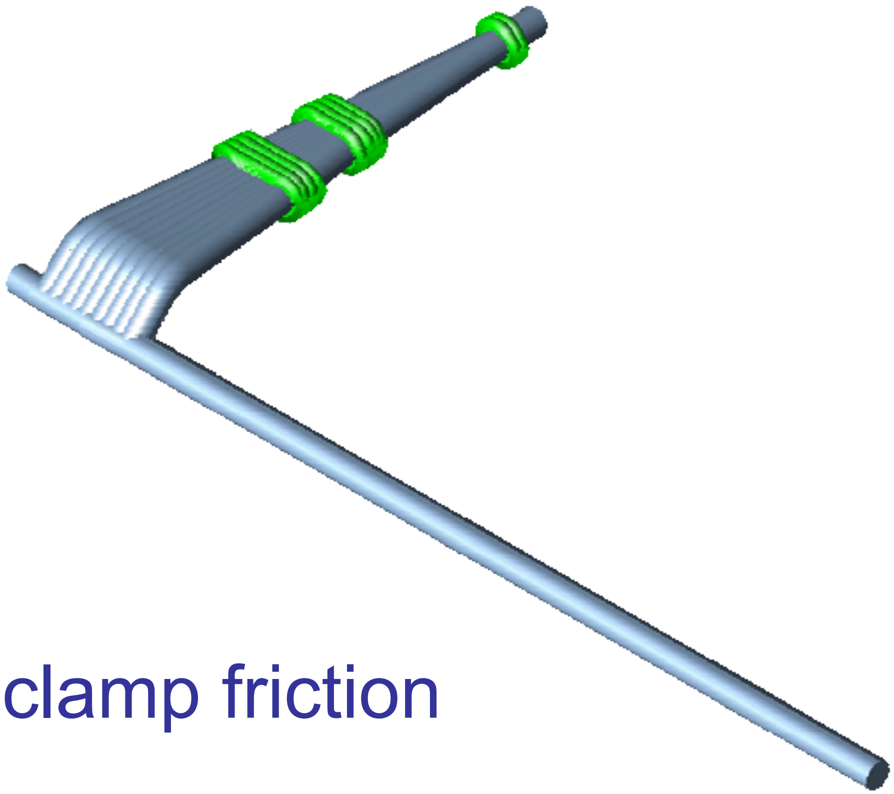
Caesar II Model

CAESAR Model

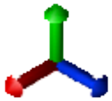


Suction Line (Header to Bottle)

Without axial restraint, F = 2.7 Hz

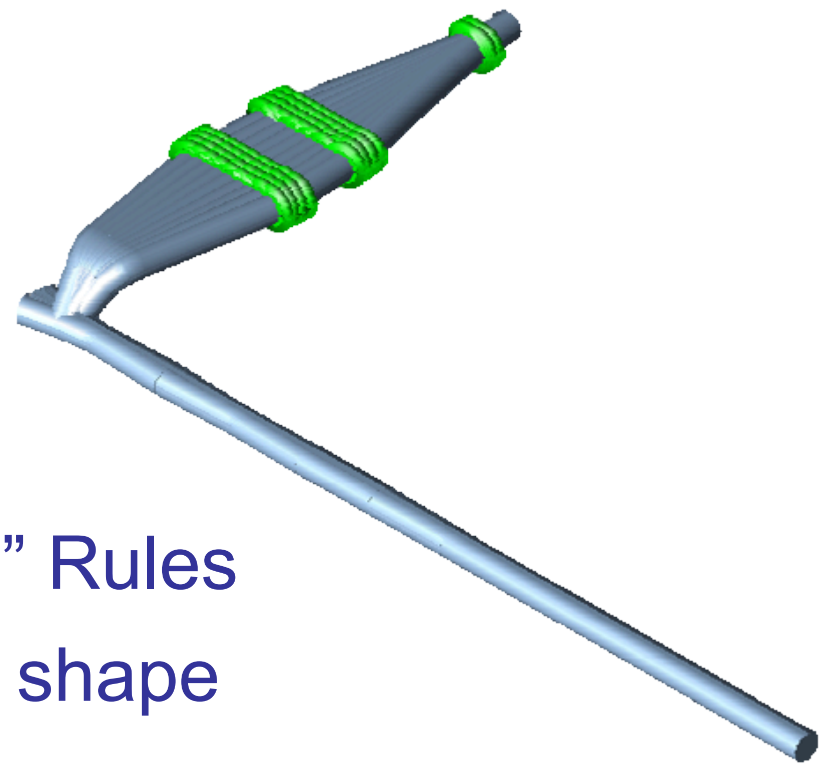


Oops!
Not realistic due to clamp friction



Suction Line (Header to Bottle)

With axial restraint, lowest MNF = 13.3 Hz

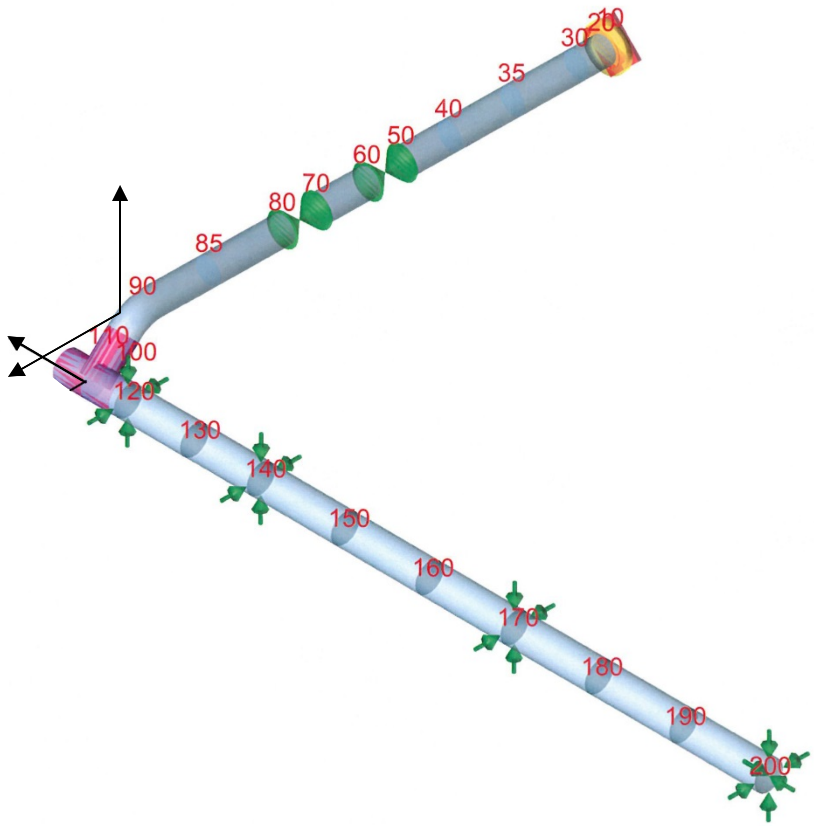


Violated “Old School” Rules

Understand mode shape

Case 1: Forced Response

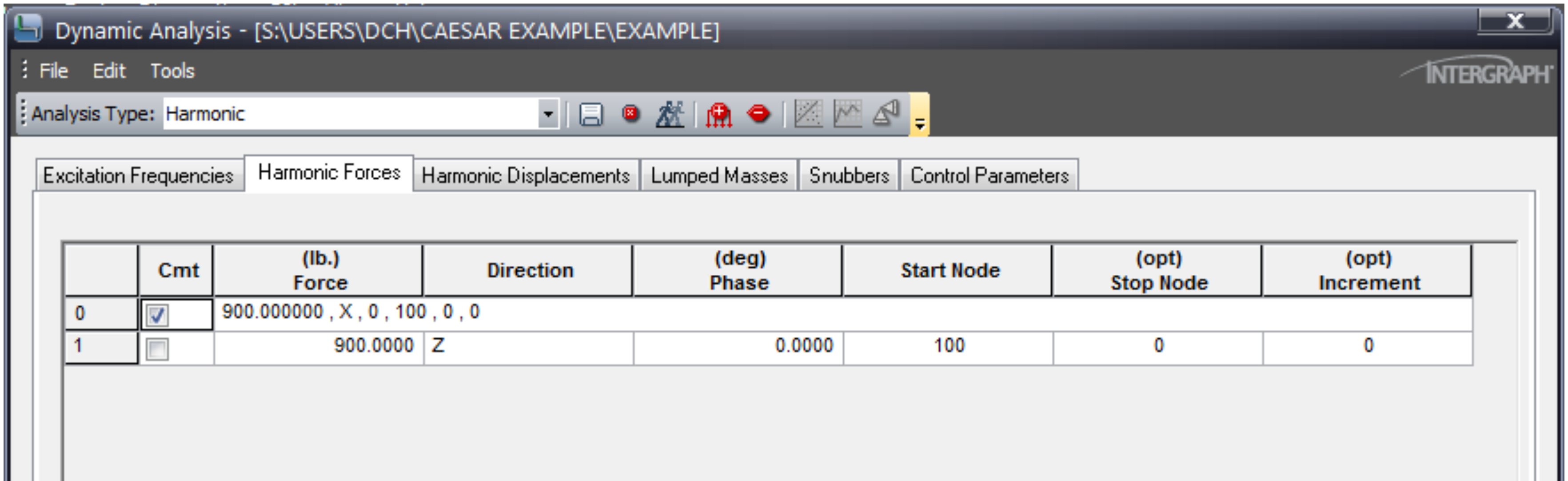
Apply Forces to excite mode shape of interest



Evaluate System in Context of API

- Case 1: Separation margins not met, but forces are low
- Case 2: Separation margins not met, forces are high
- Case 3: Both separation margins and force guidelines are met

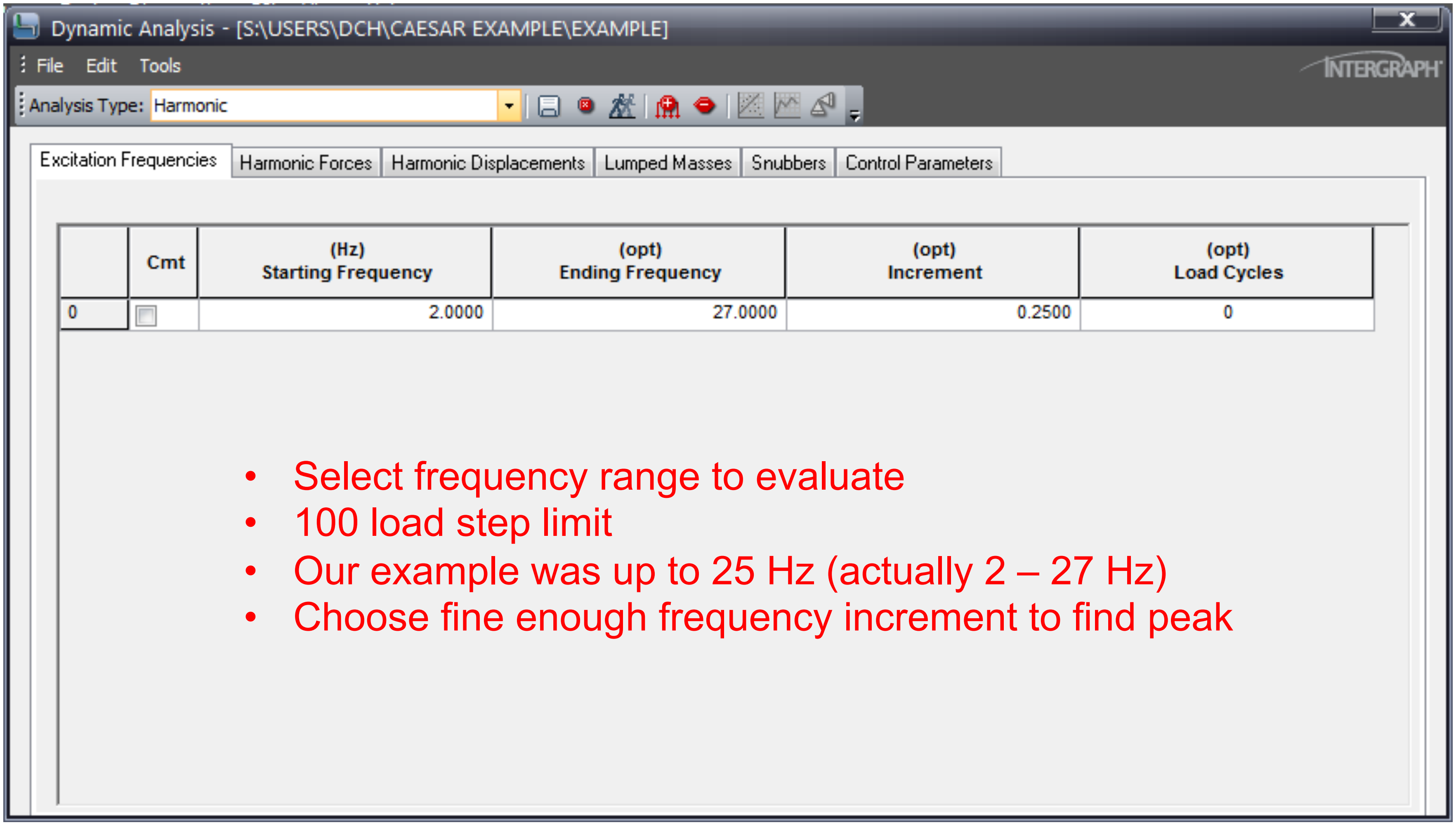
Cases 1 and 2: Forced Response



- Force applied is 0-pk. Enter 900 lbs for 1800 lbs p-p.
- Calculate response to force each direction separately.
- Comment-out direction not considered.
- Response will be linear with force.

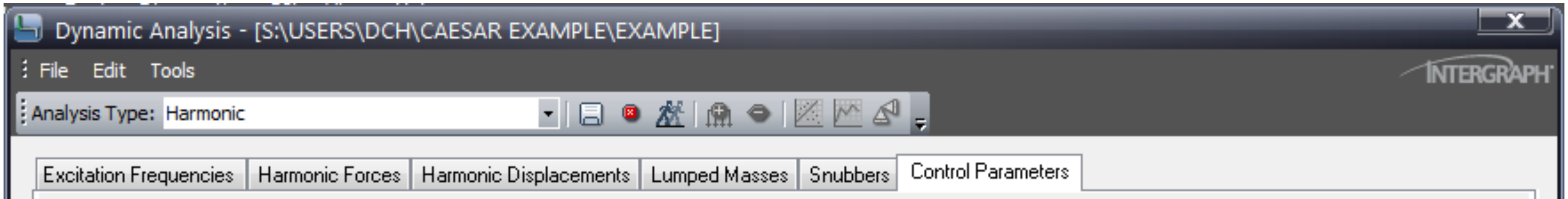
INTERGRAPH

Forced Response



- Select frequency range to evaluate
- 100 load step limit
- Our example was up to 25 Hz (actually 2 – 27 Hz)
- Choose fine enough frequency increment to find peak

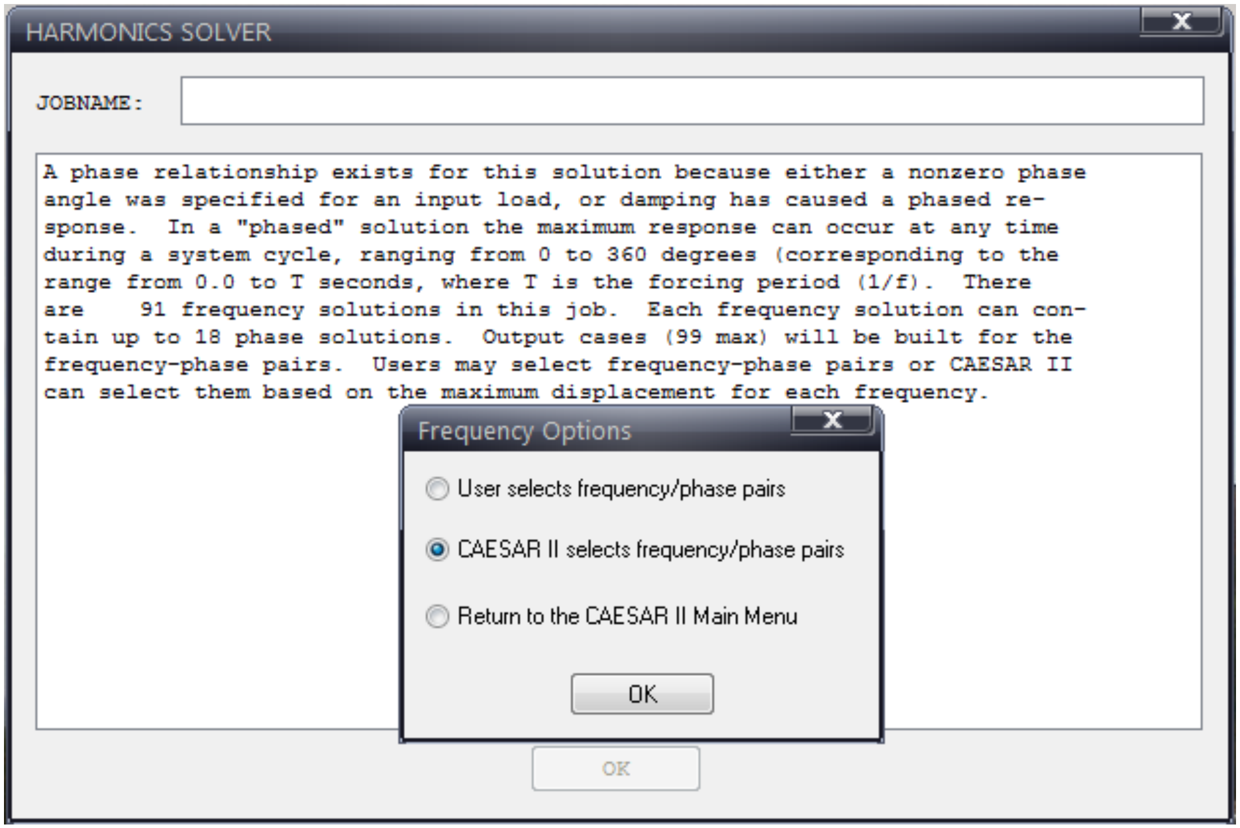
Forced Response



	Def	Setting	Parameter
1		1	Static Load Case for Nonlinear Restraint Status
2		1000	Stiffness Factor for Friction (0.0-Not Used)
3		.005	Damping (DSRSS) (ratio of critical)
4		CONSISTENT	Mass Model (LUMPED/CONSISTENT)

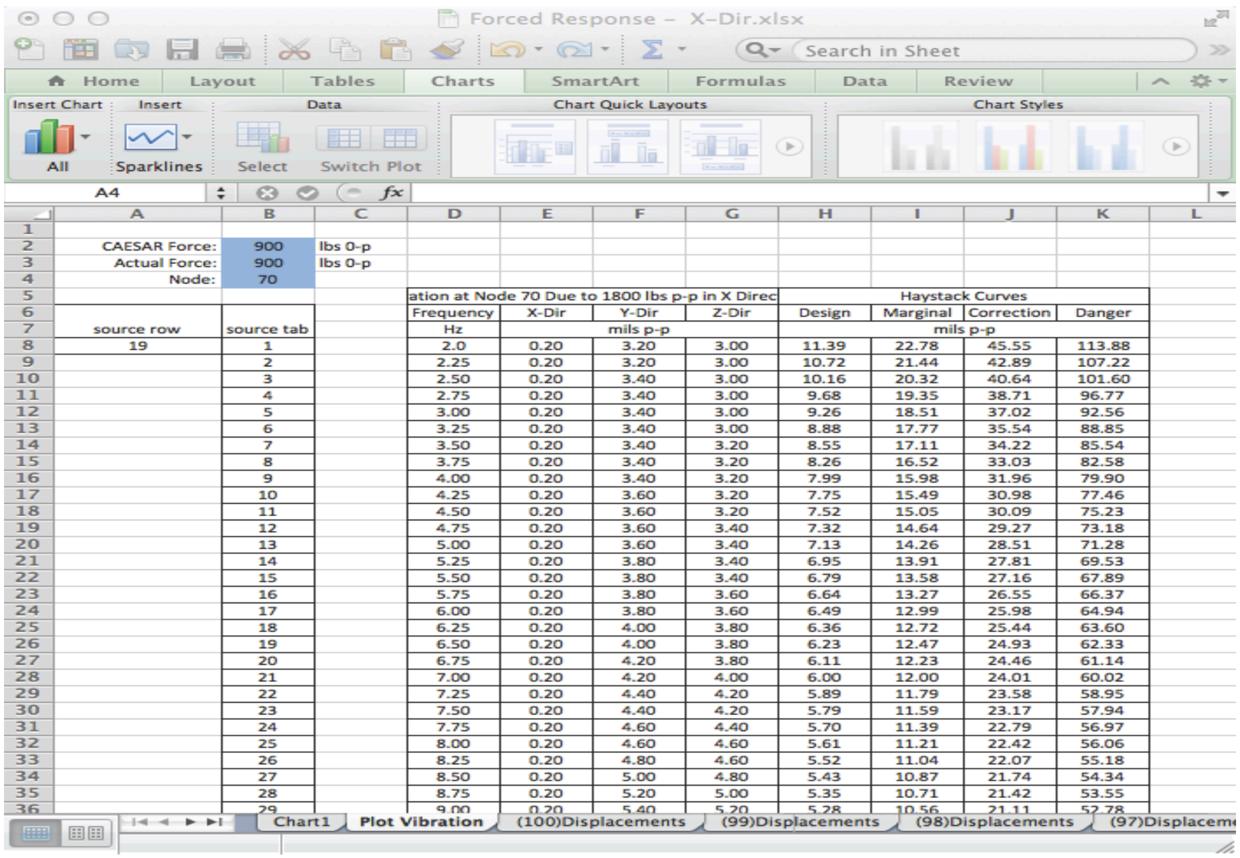
- Select appropriate load case for nonlinear or single-direction restraints.
- Stiffness in friction direction =
  Force × mu × Stiffness Factor (0 if axial restraints used)
- DSRSS = ζ (damping ratio, 0.005 = ½%, conservative)
- Consistent model includes more terms in mass matrices but uses more memory. Recommend tighter node spacing for lumped model.

Forced Response



- Allow CAESAR to chose phase angle for each frequency step that results in highest response.

Forced Response

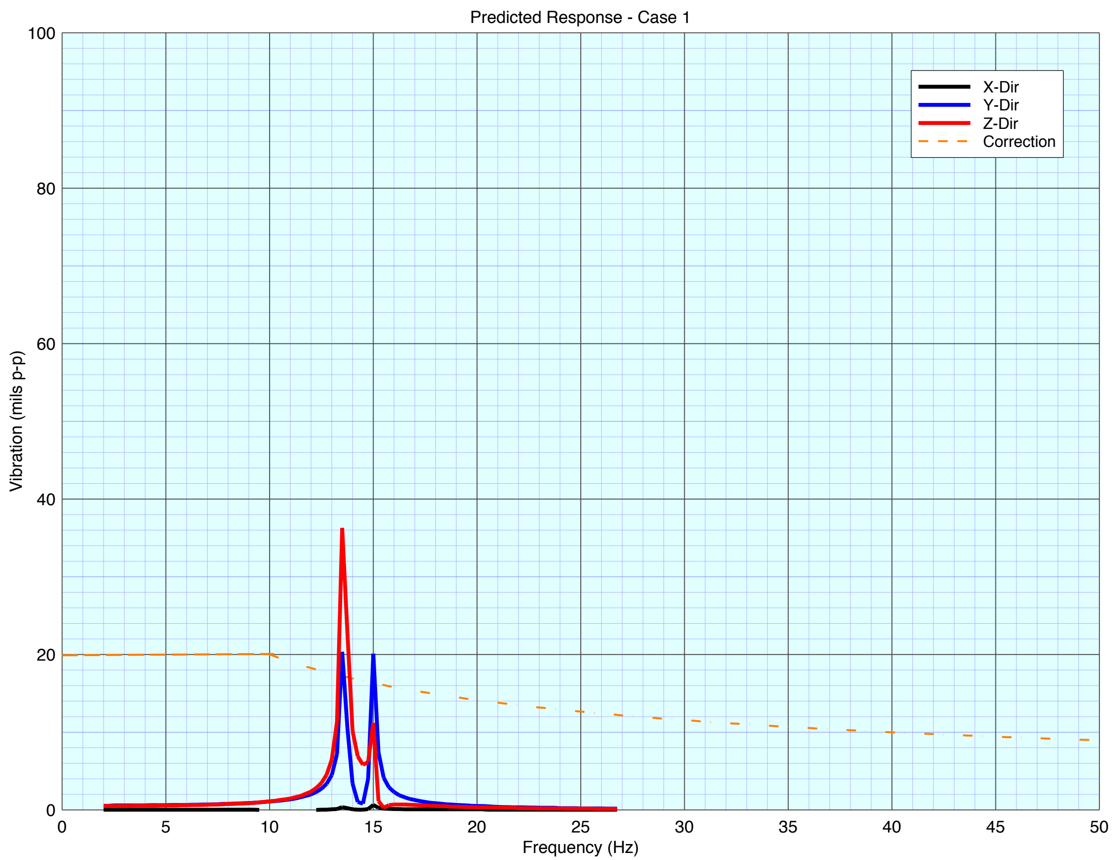


	A	B	C	D	E	F	G	H	I	J	K
1											
2	CAESAR Force:	900	lbs 0-p								
3	Actual Force:	900	lbs 0-p								
4	Node:	70									
5				ation at Node 70 Due to 1800 lbs p-p in X Direc				Haystack Curves			
6				Frequency	X-Dir	Y-Dir	Z-Dir	Design	Marginal	Correction	Danger
7	source row	source tab		Hz		mils p-p			mils p-p		
8	19	1		2.0	0.20	3.20	3.00	11.39	22.78	45.55	113.88
9		2		2.25	0.20	3.20	3.00	10.72	21.44	42.89	107.22
10		3		2.50	0.20	3.40	3.00	10.16	20.32	40.64	101.60
11		4		2.75	0.20	3.40	3.00	9.68	19.35	38.71	96.77
12		5		3.00	0.20	3.40	3.00	9.26	18.51	37.02	92.56
13		6		3.25	0.20	3.40	3.00	8.88	17.77	35.54	88.85
14		7		3.50	0.20	3.40	3.20	8.55	17.11	34.22	85.54
15		8		3.75	0.20	3.40	3.20	8.26	16.52	33.03	82.58
16		9		4.00	0.20	3.40	3.20	7.99	15.98	31.96	79.90
17		10		4.25	0.20	3.60	3.20	7.75	15.49	30.98	77.46
18		11		4.50	0.20	3.60	3.20	7.52	15.05	30.09	75.23
19		12		4.75	0.20	3.60	3.40	7.32	14.64	29.27	73.18
20		13		5.00	0.20	3.60	3.40	7.13	14.26	28.51	71.28
21		14		5.25	0.20	3.80	3.40	6.95	13.91	27.81	69.53
22		15		5.50	0.20	3.80	3.40	6.79	13.58	27.16	67.89
23		16		5.75	0.20	3.80	3.60	6.64	13.27	26.55	66.37
24		17		6.00	0.20	3.80	3.60	6.49	12.99	25.98	64.94
25		18		6.25	0.20	4.00	3.80	6.36	12.72	25.44	63.60
26		19		6.50	0.20	4.00	3.80	6.23	12.47	24.93	62.33
27		20		6.75	0.20	4.20	3.80	6.11	12.23	24.46	61.14
28		21		7.00	0.20	4.20	4.00	6.00	12.00	24.01	60.02
29		22		7.25	0.20	4.40	4.20	5.89	11.79	23.58	58.95
30		23		7.50	0.20	4.40	4.20	5.79	11.59	23.17	57.94
31		24		7.75	0.20	4.60	4.40	5.70	11.39	22.79	56.97
32		25		8.00	0.20	4.60	4.60	5.61	11.21	22.42	56.06
33		26		8.25	0.20	4.80	4.60	5.52	11.04	22.07	55.18
34		27		8.50	0.20	5.00	4.80	5.43	10.87	21.74	54.34
35		28		8.75	0.20	5.20	5.00	5.35	10.71	21.42	53.55
36		29		9.00	0.20	5.40	5.20	5.28	10.56	21.11	52.78

- CAESAR Forced Response Output

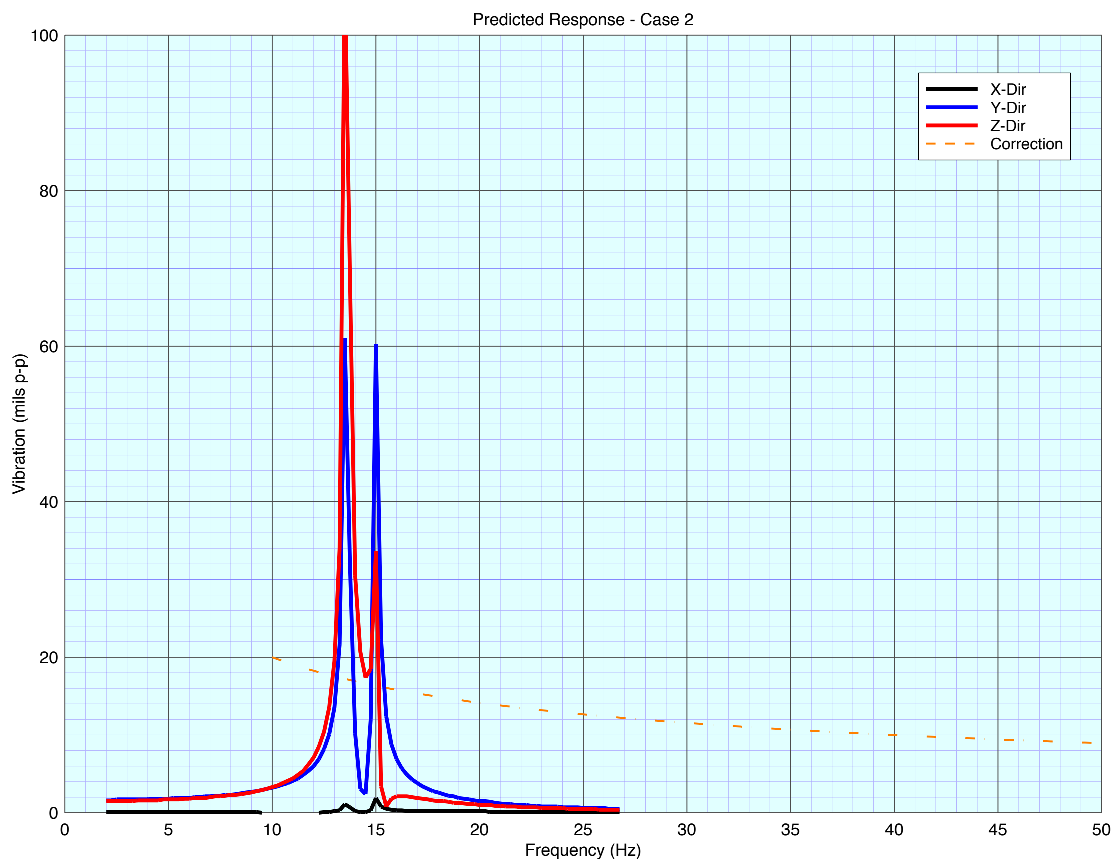
Forced Response: Case 1

- First two modes are excited with maximum response at Node 70 in the Y and Z directions.
- Response exceeds “Correction” allowable.



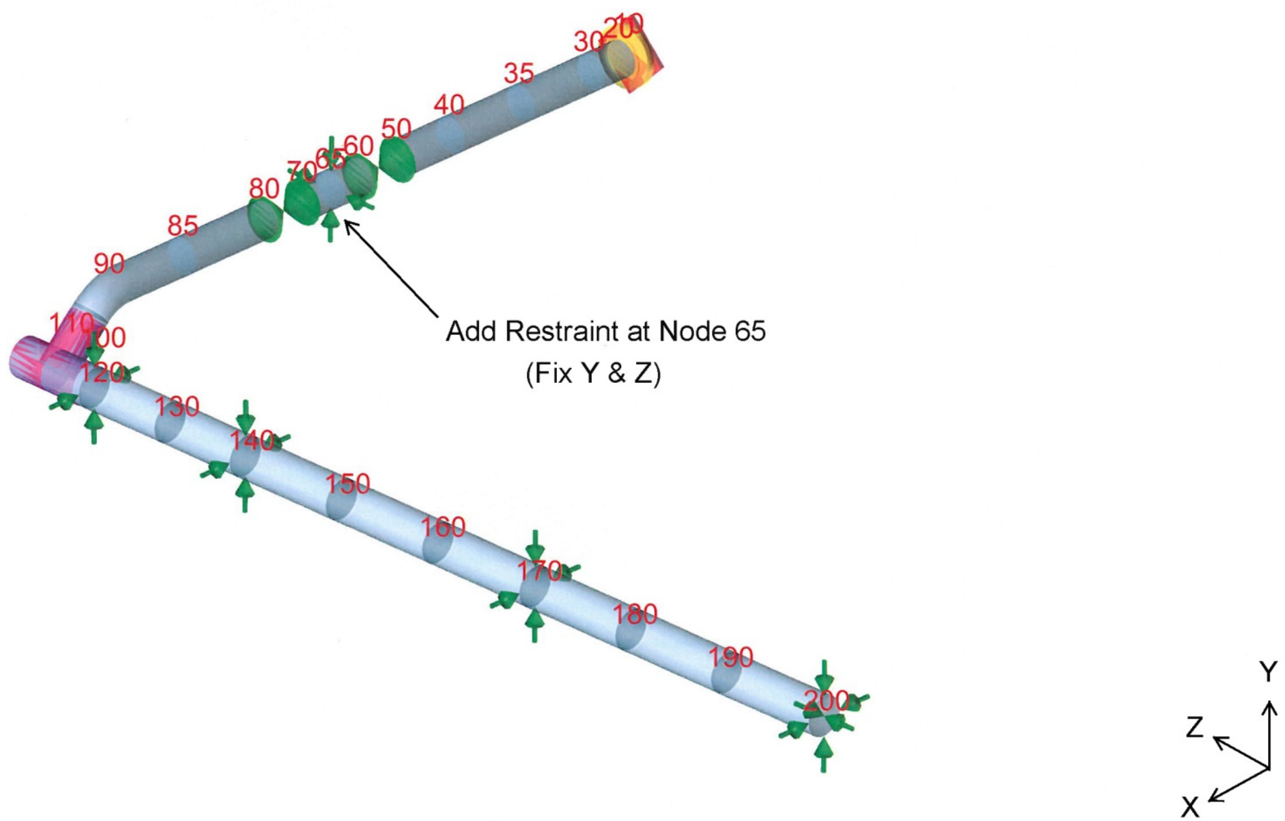
Forced Response: Case 2

- Amplitude is much higher because force is higher
- Force must be a factor of ~6 lower to meet guidelines



Forced Response: Case 3

- A better approach is to raise mechanical natural frequencies
- Add support near anti-node of first two modes.



Forced Response: Case 3

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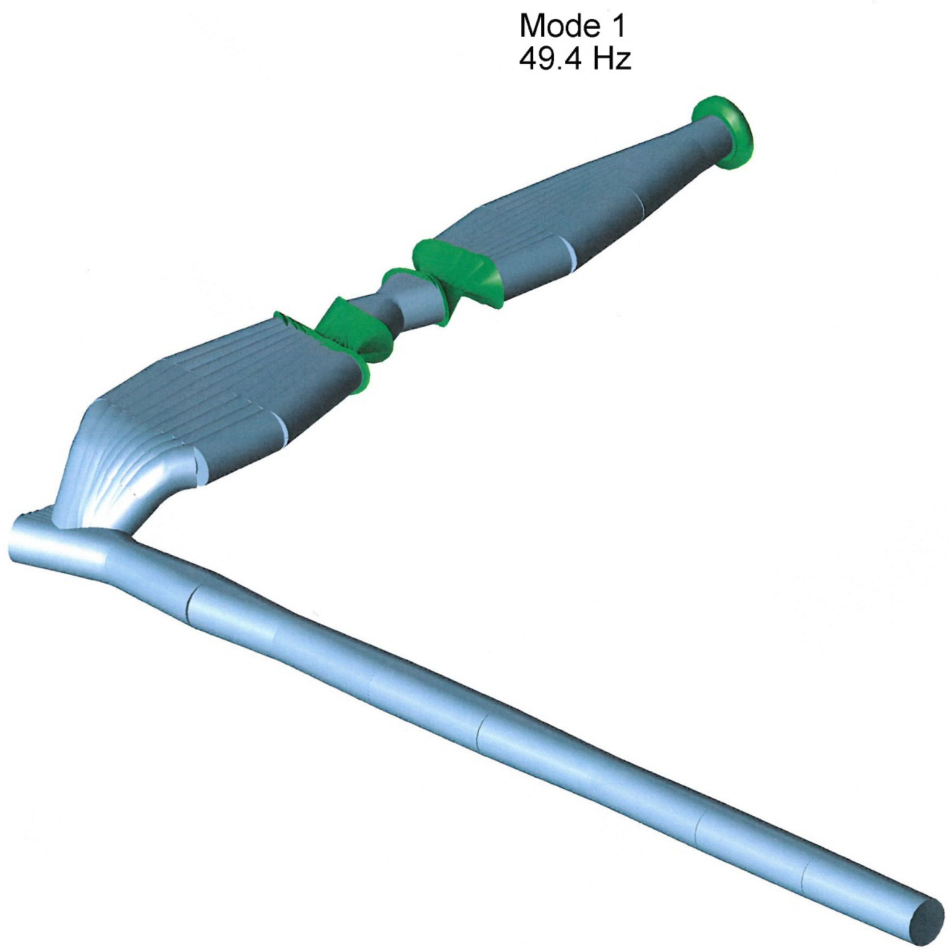
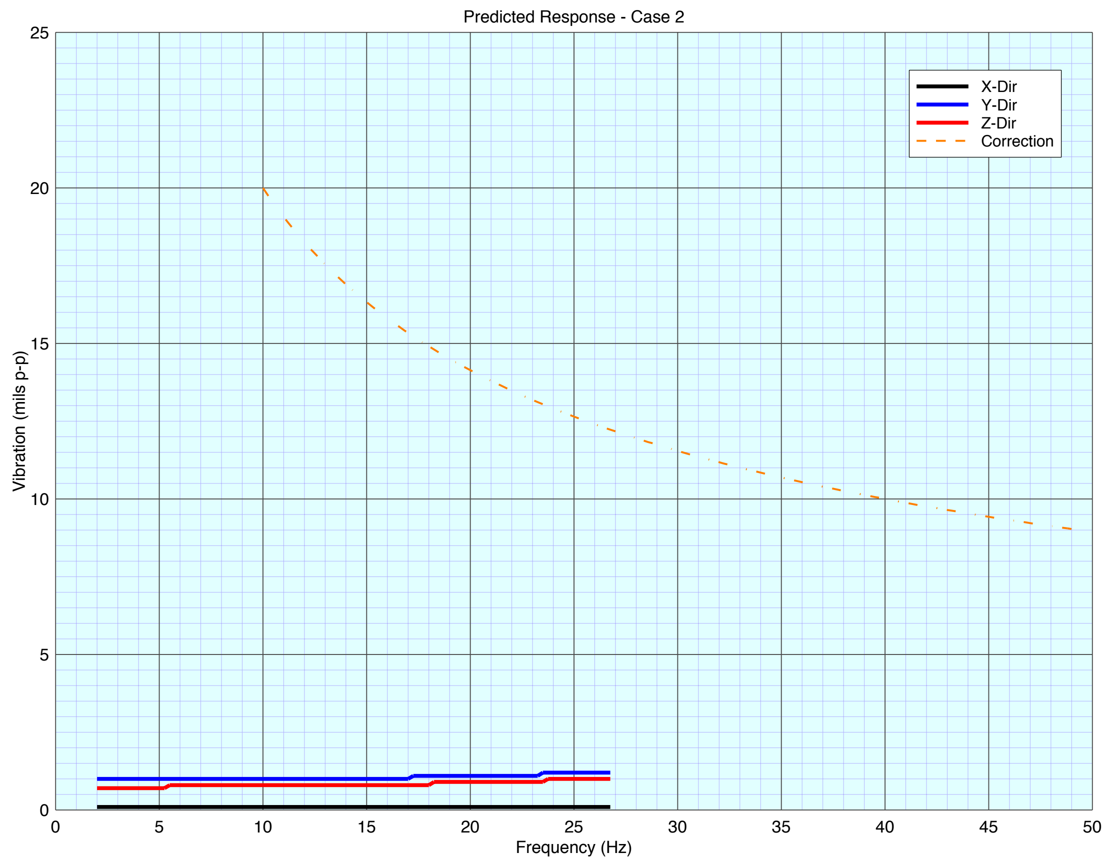


Forced Response: Case 3

- Forced response no longer needed, but…
- Results are as expected



Conclusions

- Both Thermal and Dynamic Analysis Should Be Done Simultaneously to Optimize Results
- Realistic Boundary Conditions Should Be Applied
- Remember "Old School" Rules
- Designing Based on Forced Response is Risky
  - MNFs vary widely due to fabrication and installation
  - Damping varies widely depending on support types
  - Complexity of forcing function

Conclusions

- Pulsation Control and Resonance Avoidance is Best
- Forced Response can be used to evaluate worst case scenarios
- Also useful for trouble shooting field vibration problems
  - Benchmark Model with Measured MNFs
  - Benchmark Response with Measured Vibration
  - Evaluate Potential Modifications

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Questions?

INTERGRAPH