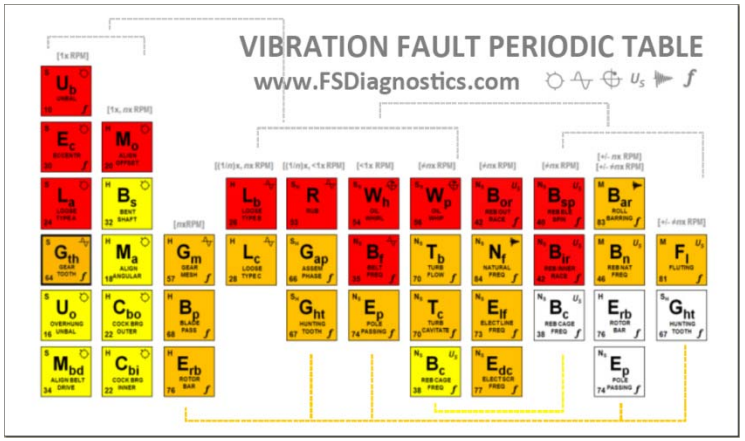
VIBRATION ANALYSIS CASE HISTORY



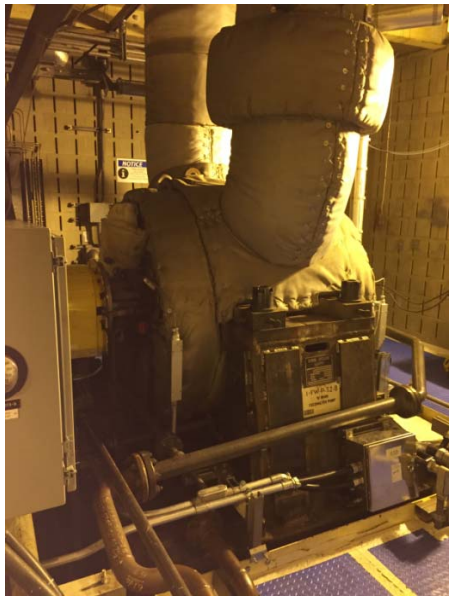
Dan Ambre is the founder of Full Spectrum Diagnostics, (June of 2000) providing the finest in Machinery Condition Monitoring, Specialized Analyses, and Vibration Training for Industrial, Manufacturing, Aerospace, and Automotive applications.

Dan is a graduate of ***The University of Iowa*** with a Bachelor's degree in Mechanical Engineering, and has completed additional graduate level course work in Engineering Dynamics from ***The University of Illinois at Chicago***, and ***Florida Atlantic University***.

Dan has over 30 years experience in the aviation and aerospace industries with a background in Vibration & Acoustic testing, Dynamic analysis of high speed rotor systems, Experimental Modal, and Finite Element Analysis. His consulting vibration experience base comes from positions at Sundstrand Aviation Corporation, Pratt & Whitney (United Technologies Corporation), and Technical Associates of Charlotte.

Dan is a Certified Level III / CAT IV. Vibration Training Instructor and a registered Professional Engineer in Minnesota.

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

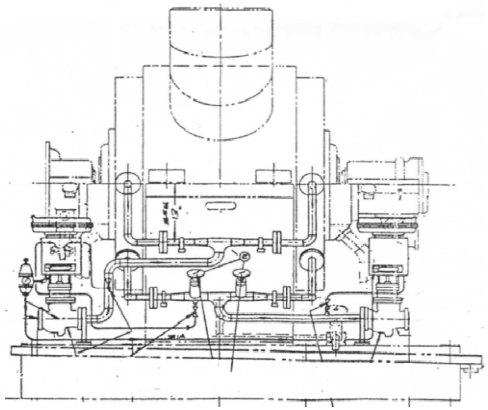


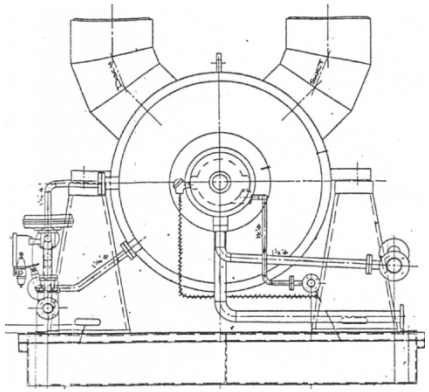
PROBLEM STATEMENT:

This machine was experiencing Elevated Vibration response at 1x RPM. The dominant response was in the Vertical Direction on the outboard bearing support.

PRELIMINARY ASSESSMENT:

1. Unbalance
2. Coupling Alignment Error (Vertical Offset)
3. Bearing Assembly Alignment Error
4. Natural Frequency excited by Pump 1x RPM response.
5. Amplified Piping Response





FINAL CONCLUSIONS:

1. Natural Frequency excited by Pump
   Residual 1x RPM response.

RECOMMENDATIONS / OPTIONS:

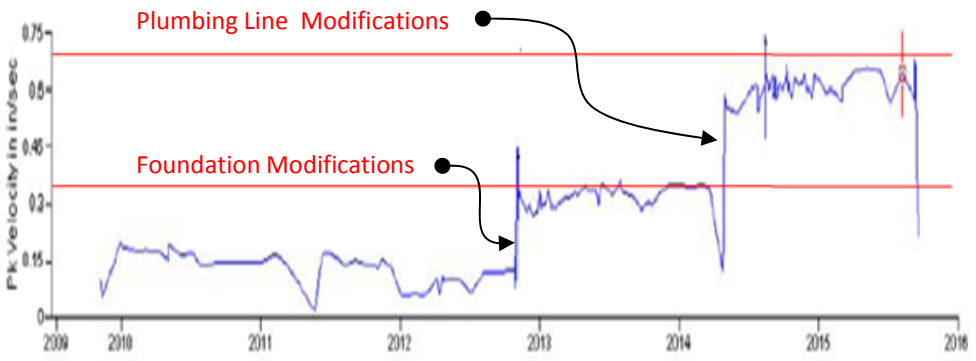
- Change Rotor Speed to Avoid Resonance
- Add Mass: Reduce Natural Frequency
- Remove Mass: Increase Natural Frequency
- Add Stiffness: Increase Natural Frequency
- Remove Stiffness: Reduce Natural Frequency
- Add Damping: Reduce Resonance Amplification

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

OVERALL RESPONSE:

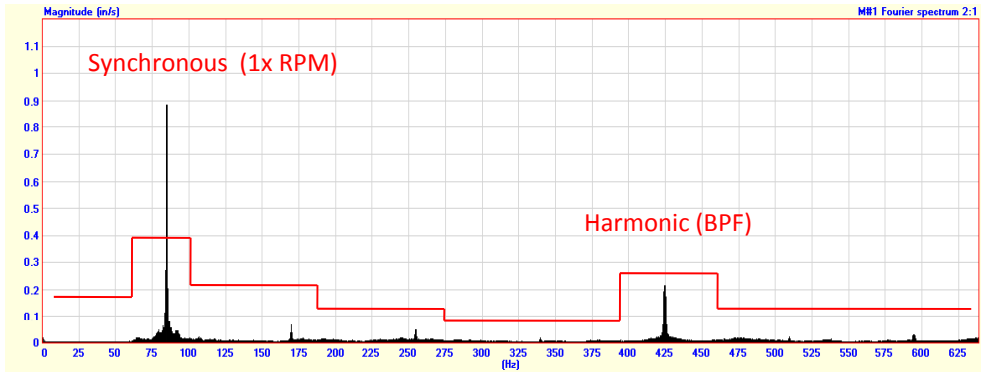
Overall response showed “step” changes in response in the Vertical Vibration levels at the pump outboard bearing housing. The step changes were associated with maintenance outage unit restarts.

Notations indicate significant structural modifications to this unit. There appears to be a shift in amplitude that is associated with each recent change.



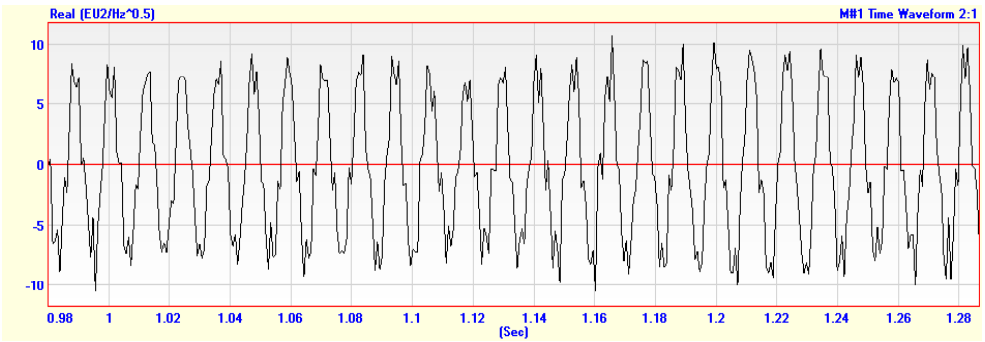
SPECTRUM RESPONSE:

The Spectrum response shown indicates a dominant 1x rotor speed (5,100 RPM / 85 Hz) vertical vibration level at the pump outboard bearing location. Also shown is the Blade Passing Frequency (BPF) at 5x RPM.



TIME WAVEFORM RESPONSE:

The Time Waveform shows a dominant synchronous response with a slight higher frequency distortion due to the 5x RPM blade passing frequency.



The VIBRATION FAULT PERIODIC TABLE

HARMONIC

SYNCHRONOUS

[1x RPM]

- S U_b UNBAL 10 *f*
- S E_c ECCENTR 30 *f*
- S L_a LOOSE TYPE A 24 *f*
- S G_{th} GEAR TOOTH 64 *f*
- S U_o OVERHUNG UNBAL 16 *f*
- S M_{bd} ALIGN BELT DRIVE 34 *f*

[1x, nx RPM]

- H M_o ALIGN OFFSET 20
- H B_s BENT SHAFT 32
- H M_a ALIGN ANGULAR 18
- H C_{bo} COCK BRG OUTER 22
- H C_{bi} COCK BRG INNER 22

[nx RPM]

- H G_m GEAR MESH 57 *f*
- H B_p BLADE PASS 68 *f*
- H E_{rb} ROTOR BAR 76 *f*

NON-SYNCHRONOUS

SUB-HARMONIC / SUB-SYNCHRONOUS

[(1/n), nx RPM]

- H L_b LOOSE TYPE B 26 *f*
- H L_c LOOSE TYPE C 28 *f*

[(1/n), <1x RPM]

- S_H R RUB 53 *f*
- S_H G_{ap} ASSEM PHASE 66 *f*
- S_H G_{ht} HUNTING TOOTH 67 *f*

[<1x RPM]

- S_S W_h OIL WHIRL 54 *f*
- N_S B_f BELT FREQ 35 *f*
- N_S E_p POLE PASSING 74 *f*

[≠nx RPM]

- S_S W_p OIL WHIP 56 *f*
- N_S T_b TURB FLOW 70 *f*
- N_S T_c TURB CAVITATE 70 *f*
- N_S U_S B_c REB CAGE FREQ 38 *f*

[≠nx RPM]

- N_S U_S B_{or} REB OUT RACE 42 *f*
- N_S N_f NAT FREQ 84 *f*
- N_S E_{lf} ELECT LINE FREQ 73
- N_S U_S E_{dc} ELECT SCR FREQ 77

MODULATION / SIDEBANDS

[≠nx RPM]

- N_S U_S B_{sp} REB ELE SPIN 40 *f*
- N_S U_S B_{ir} REB IN RACE 42 *f*
- N_S B_c REB CAGE FREQ 38 *f*

[+/- nx RPM] [+/- ≠nx RPM]

- M B_{ar} ROLL BARRING 83 *f*
- M U_S B_n REB NAT FREQ 46
- H E_{rb} ROTOR BAR 76 *f*
- N_S E_p POLE PASSING 74 *f*

[+/- nx RPM] [+/- ≠nx RPM]

- M U_S F_l FLUTING 81 *f*
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ELEMENTS INTERACTIVE TRAINING

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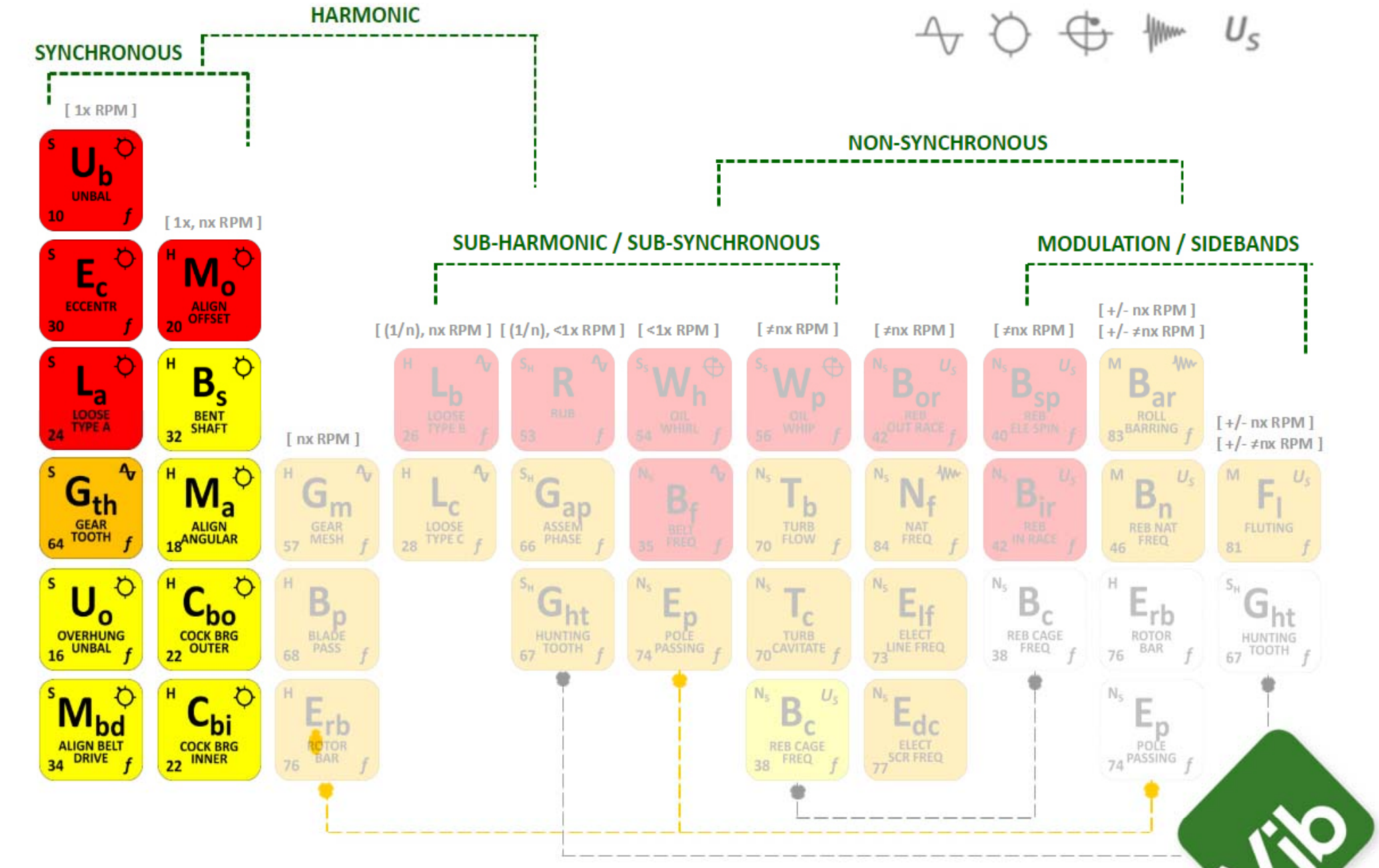

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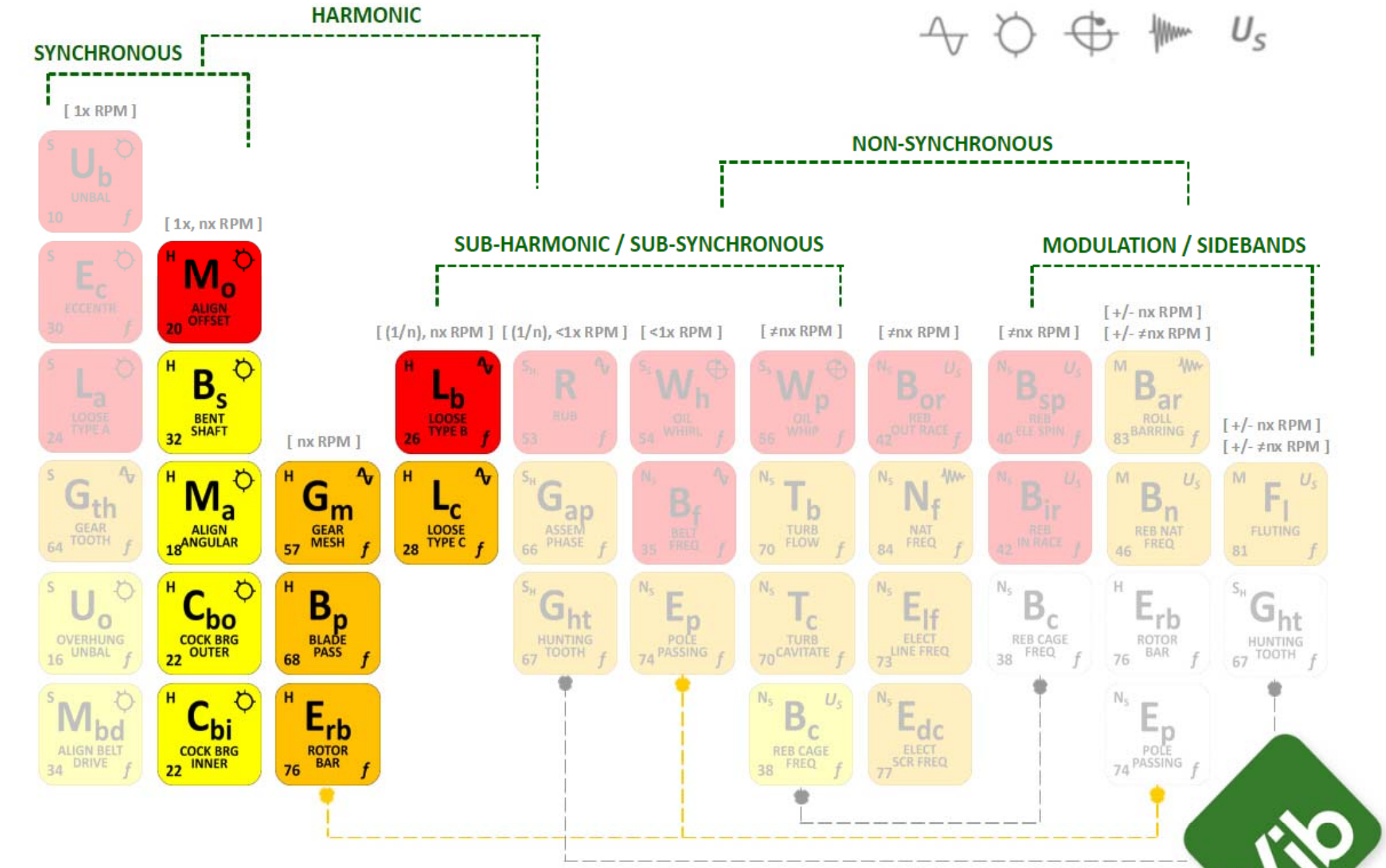

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[1x, nx RPM]

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- H C_{bi} COCK BRG INNER 22 *f*

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[(1/n), nx RPM]

- H L_b LOOSE TYPE B 26 *f*
- H L_c LOOSE TYPE C 28 *f*

[(1/n), <1x RPM]

- S_H R RUB 53 *f*
- S_H G_{ap} ASSEM PHASE 66 *f*
- S_H G_{ht} HUNTING TOOTH 67 *f*

[<1x RPM]

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[≠nx RPM]

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[≠nx RPM]

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MODULATION / SIDEBANDS

[≠nx RPM]

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[+/- nx RPM]
[+/- ≠nx RPM]

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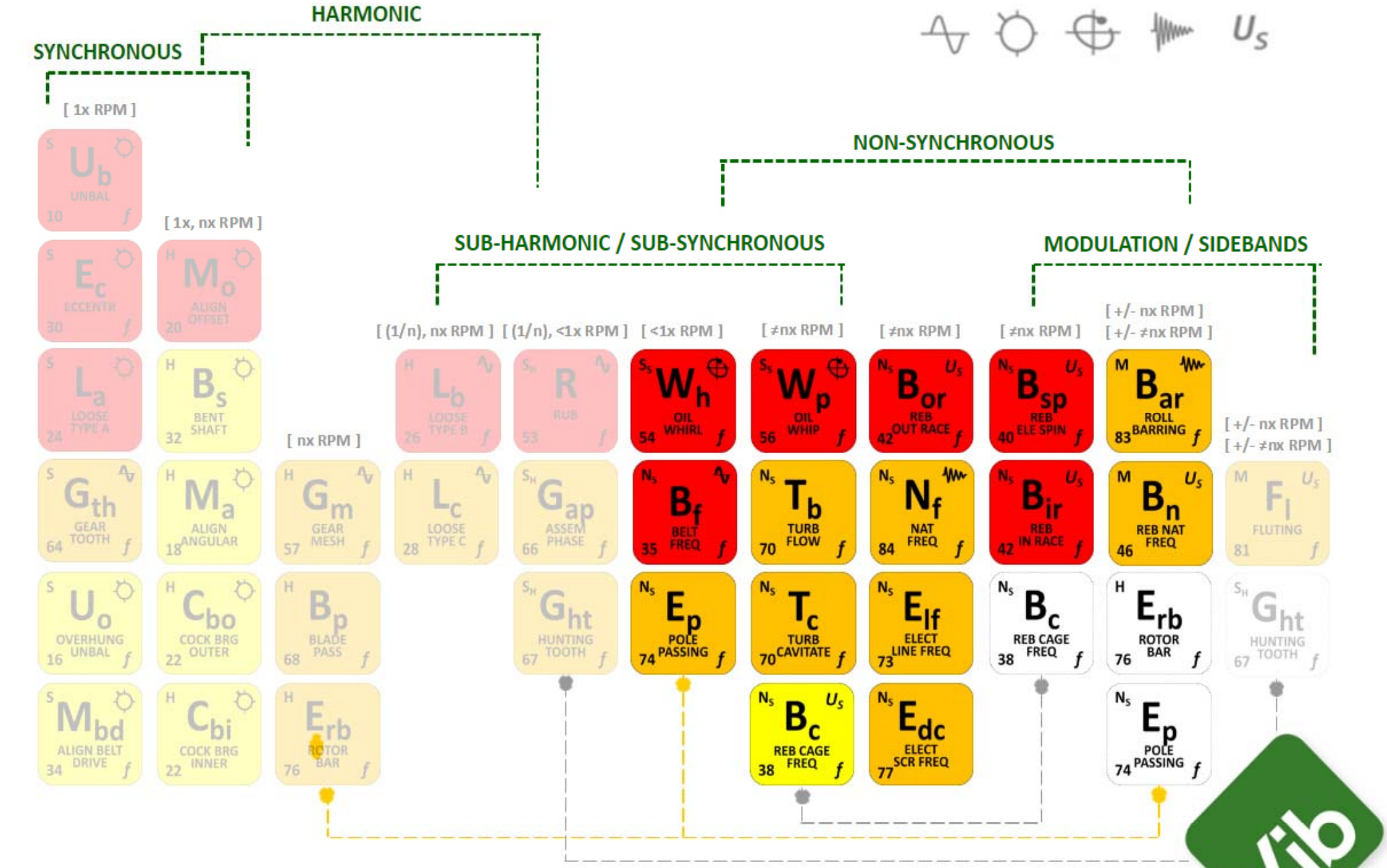

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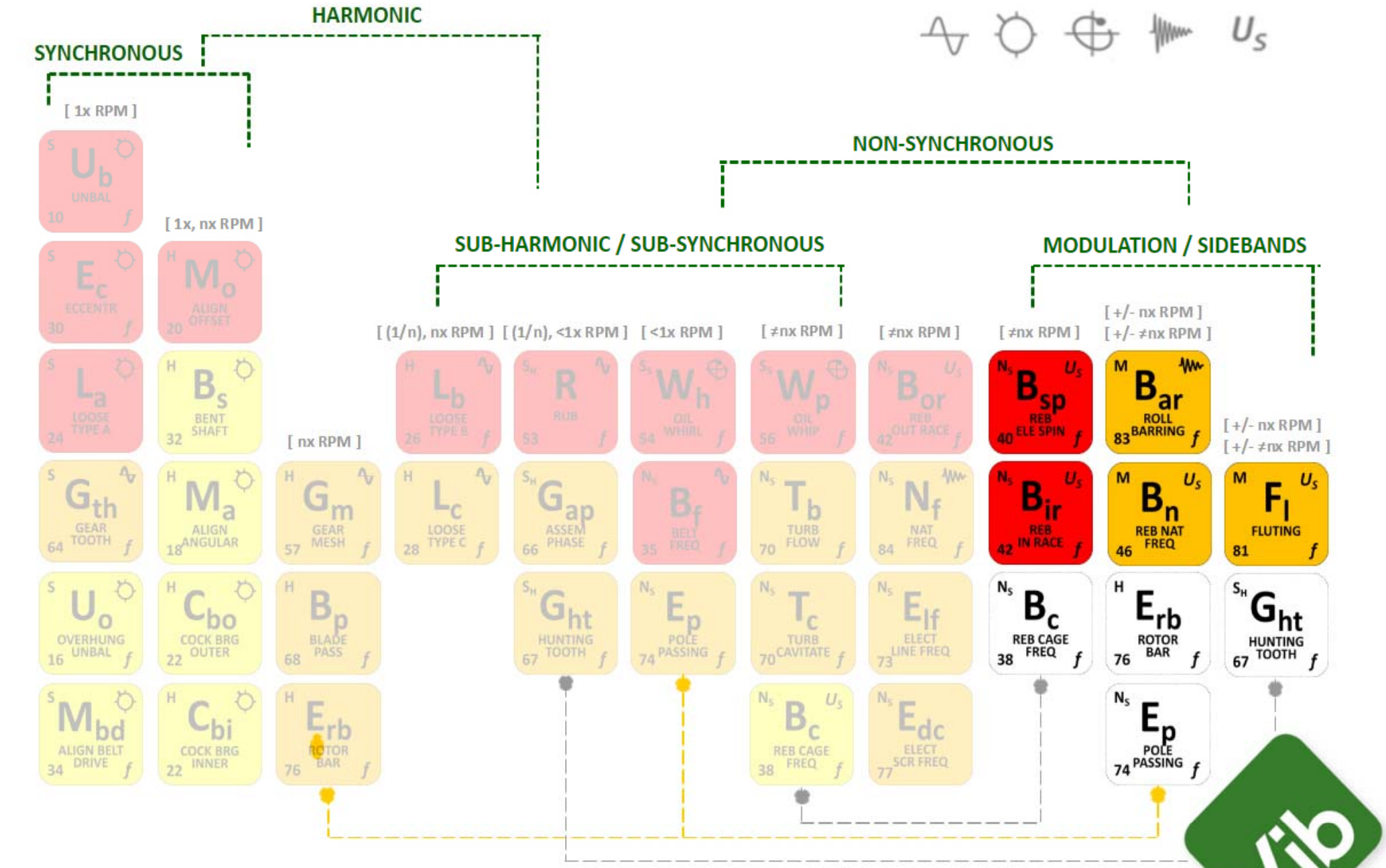

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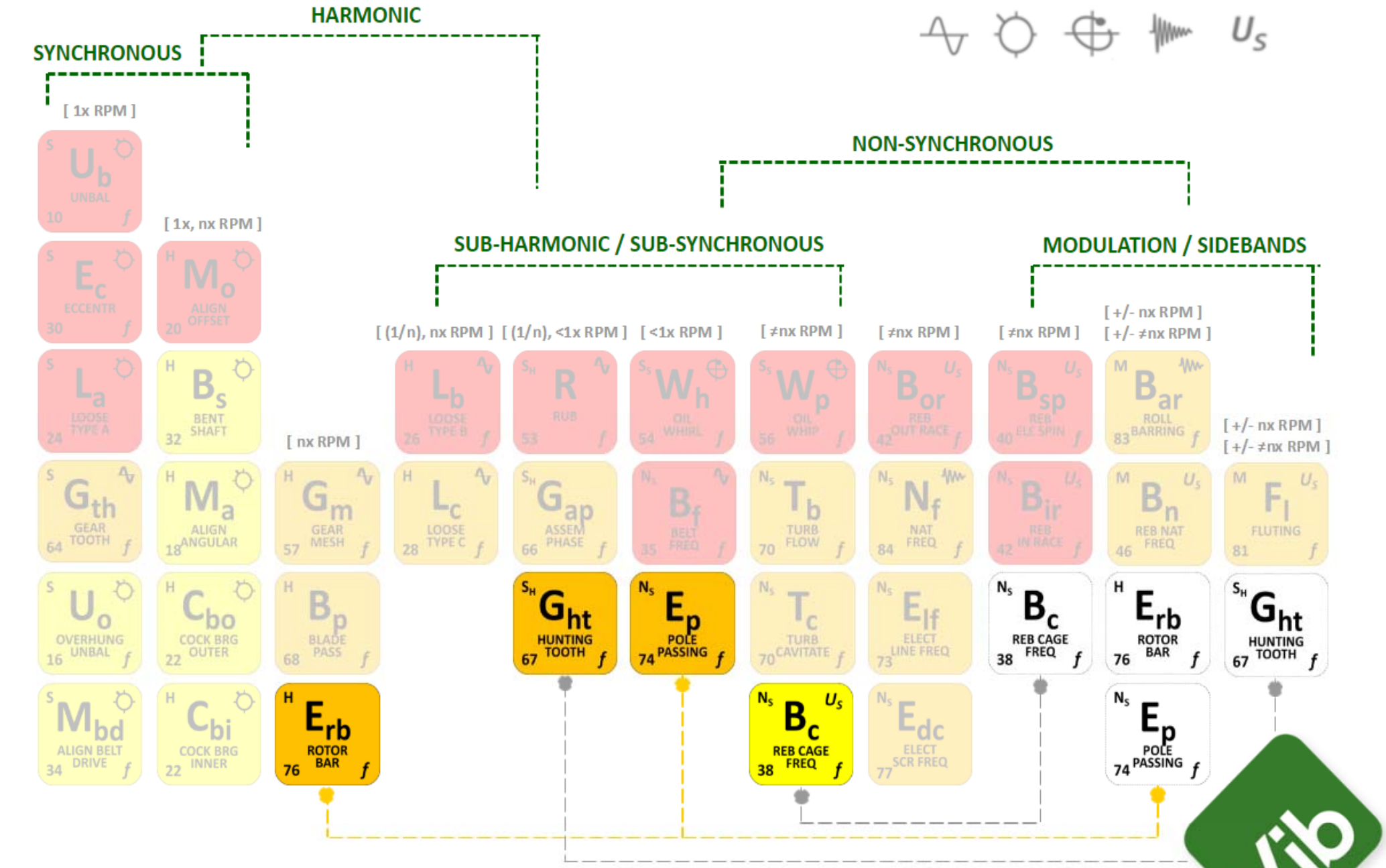

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[1x RPM]

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- S **M_{bd}** ALIGN BELT DRIVE 34 *f*

[1x, nx RPM]

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- H **C_{bo}** COCK BRG OUTER 22
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[nx RPM]

- H **G_m** GEAR MESH 57 *f*
- H **B_p** BLADE PASS 68 *f*
- H **E_{rb}** ROTOR BAR 76 *f*

NON-SYNCHRONOUS

SUB-HARMONIC / SUB-SYNCHRONOUS

[(1/n), nx RPM]

- H **L_b** LOOSE TYPE B 26 *f*
- H **L_c** LOOSE TYPE C 28 *f*

[(1/n), <1x RPM]

- S_H **R** RUB 53 *f*
- S_H **G_{ap}** ASSEM PHASE 66 *f*
- S_H **G_{ht}** HUNTING TOOTH 67 *f*

[<1x RPM]

- S_S **W_h** OIL WHIRL 54 *f*
- N_S **B_f** BELT FREQ 35 *f*
- N_S **E_p** POLE PASSING 74 *f*

[≠nx RPM]

- S_S **W_p** OIL WHIP 56 *f*
- N_S **T_b** TURB FLOW 70 *f*
- N_S **T_c** TURB CAVITATE 70 *f*
- N_S **B_c** REB CAGE FREQ 38 *f*

[≠nx RPM]

- N_S **B_{or}** U_S REB OUT RACE 42 *f*
- N_S **N_f** NAT FREQ 84 *f*
- N_S **E_{lf}** ELECT LINE FREQ 73
- N_S **E_{dc}** ELECT SCR FREQ 77

MODULATION / SIDEBANDS

[≠nx RPM]

- N_S **B_{sp}** U_S REB ELE SPIN 40 *f*
- N_S **B_{ir}** U_S REB IN RACE 42 *f*
- N_S **B_c** REB CAGE FREQ 38 *f*

[+/- nx RPM] [+/- ≠nx RPM]

- M **B_{ar}** ROLL BARRING 83 *f*
- M **B_n** U_S REB NAT FREQ 46
- H **E_{rb}** ROTOR BAR 76 *f*
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[1x, nx RPM]

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ELEMENTS INTERACTIVE TRAINING

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Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

THE VIBRATION FAULT PERIODIC TABLE

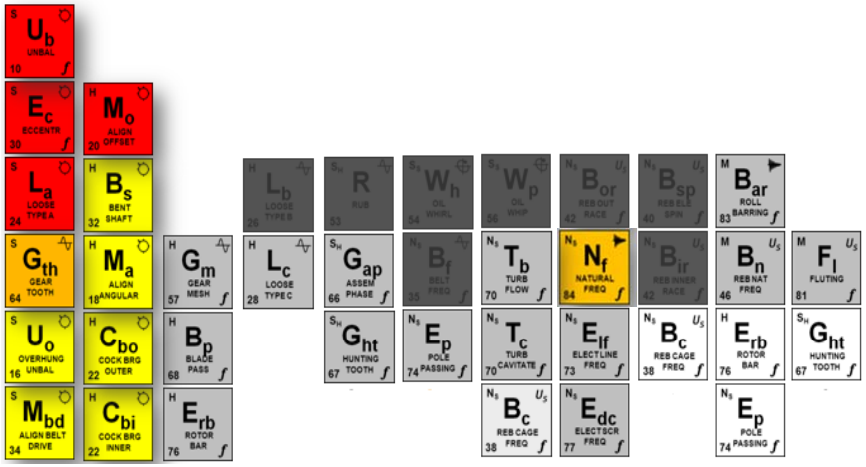
ANALYSIS & TESTING

SYNCHRONOUS VIBRATION [1x RPM]
Potential Causes:

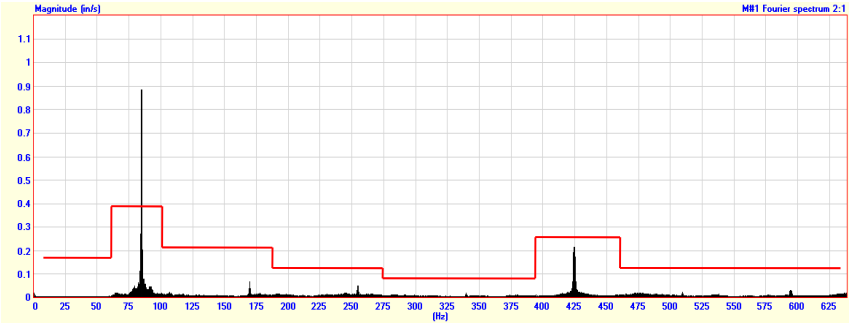
U_b **Unbalance**
E_c **Eccentricity**
L_a **Mechanical Looseness Type A**
G_{th} **Gear Tooth Fault**
U_o **Overhung Rotor Unbalance**
M_{bd} **Belt Drive Misalignment**

M_o **Offset Coupling Misalignment**
B_s **Bent / Bowed Shaft**
M_a **Angular Coupling Misalignment**
C_{bo} **Cocked Bearing Outer Race**
C_{bi} **Cocked Bearing Inner Race**

N_f **Natural Frequency / Resonant Amplification**



SOURCES of SYNCHRONOUS VIBRATION



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~~U_o Overhung Rotor Unbalance~~
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M_o **Offset Coupling Misalignment**
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C_{bo} **Cocked Bearing Outer Race**
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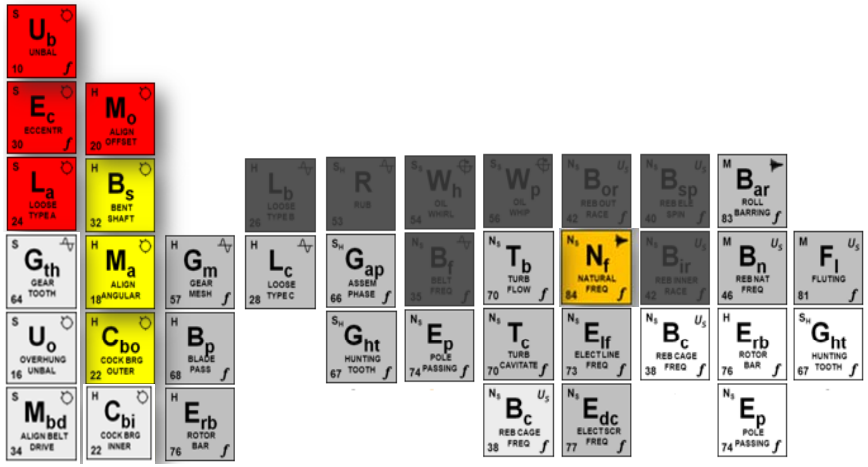
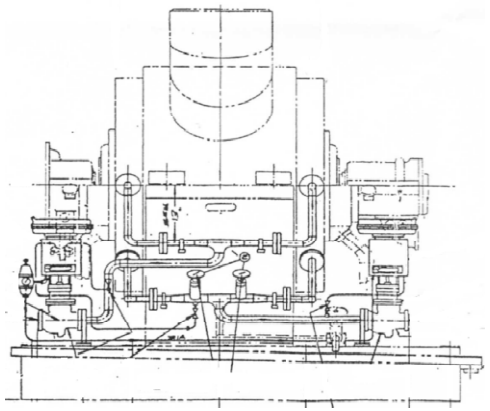
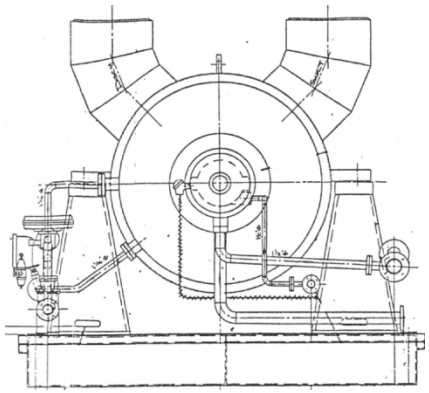


BY DESIGN SOME FAULTS ARE RULED-OUT





Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

THE VIBRATION FAULT PERIODIC TABLE

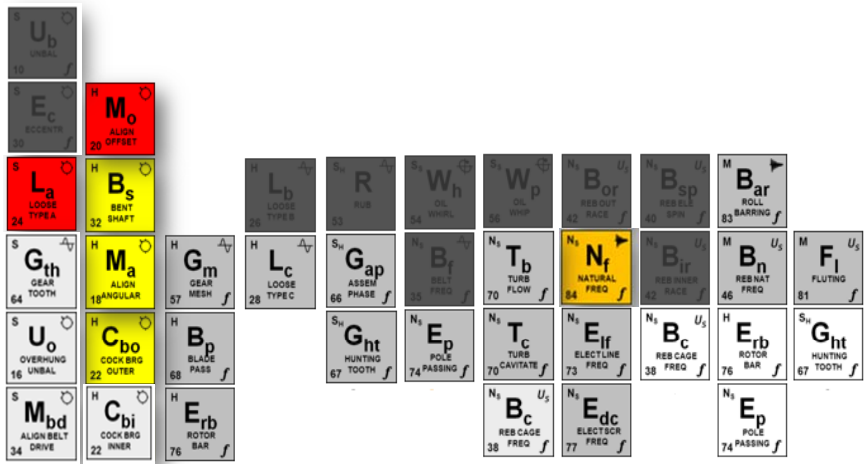
ANALYSIS & TESTING

SYNCHRONOUS VIBRATION [1x RPM]
Potential Causes:

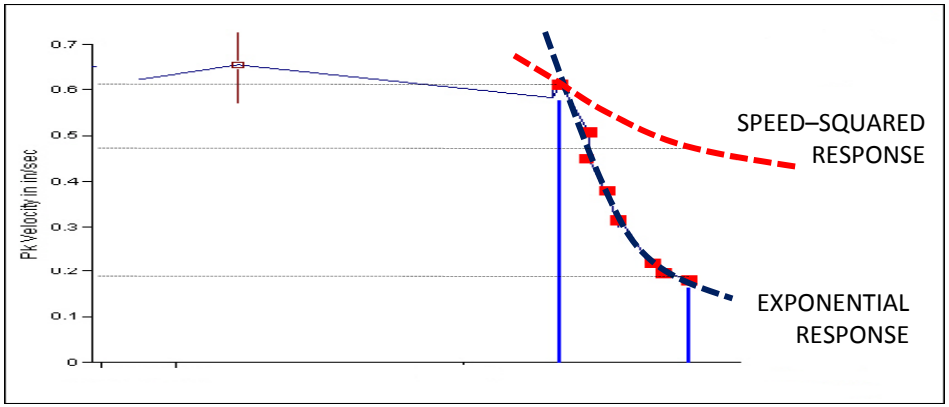
~~U_b Unbalance~~
~~E_c Eccentricity~~
L_a Mechanical Looseness Type A
~~G_{th} Gear Tooth Fault~~
~~U_o Overhung Rotor Unbalance~~
~~M_{bd} Belt Drive Misalignment~~

M_o Offset Coupling Misalignment
B_s Bent / Bowed Shaft
M_a Angular Coupling Misalignment
C_{bo} Cocked Bearing Outer Race
~~C_{bi} Cocked Bearing Inner Race~~

N_f Natural Frequency / Resonant Amplification



SOME FAULTS ARE RULED-OUT BY TRANSIENT BEHAVIOR



Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

THE VIBRATION FAULT PERIODIC TABLE

ANALYSIS & TESTING

SYNCHRONOUS VIBRATION [1x RPM]
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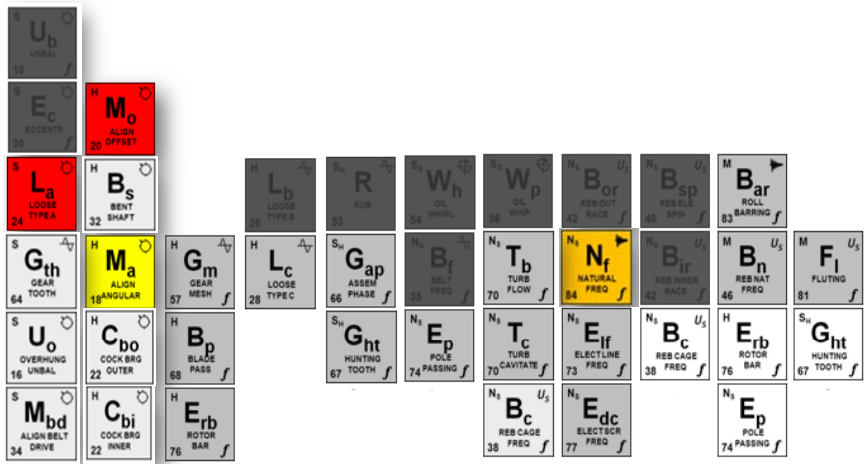
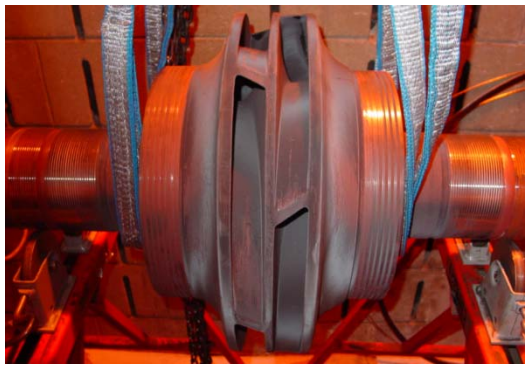
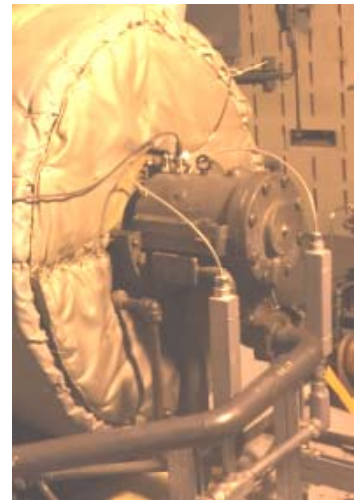


SOME FAULTS ARE RULED-OUT BY INSPECTION

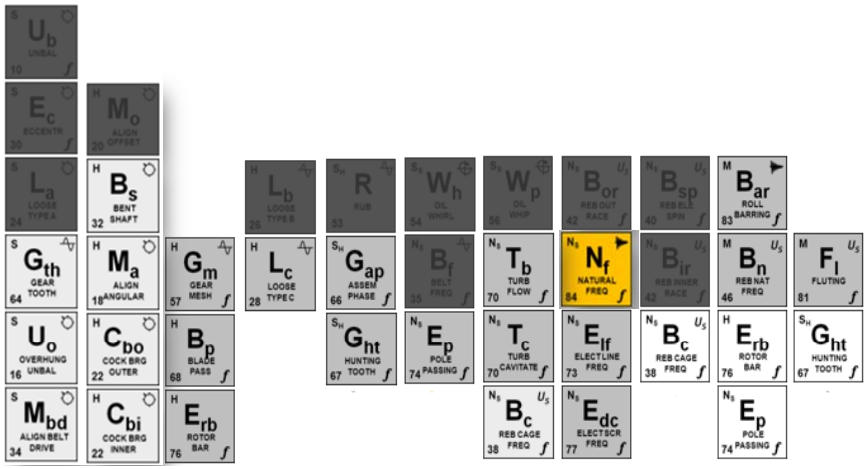




Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

THE VIBRATION FAULT PERIODIC TABLE

ANALYSIS & TESTING



SYNCHRONOUS VIBRATION [1x RPM]
Potential Causes:

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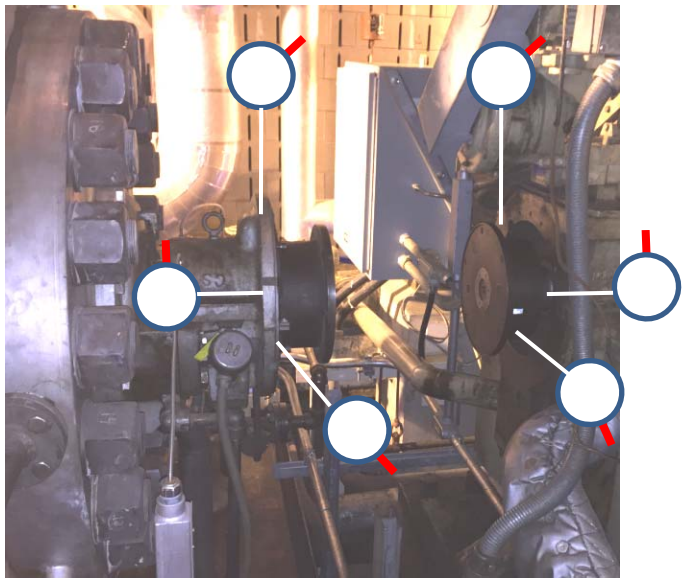
N_f Natural Frequency / Resonant Amplification

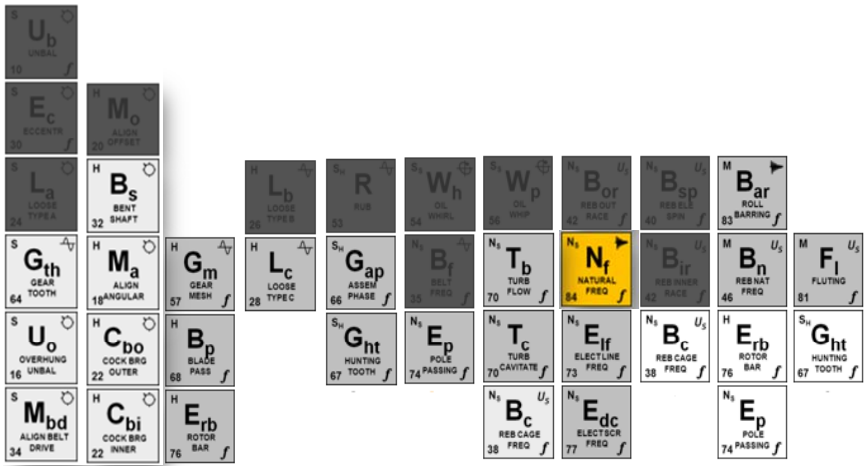
SOME FAULTS ARE RULED-OUT BY PHASE ANALYSIS



Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

THE VIBRATION FAULT PERIODIC TABLE

ANALYSIS & TESTING



SYNCHRONOUS VIBRATION [1x RPM]
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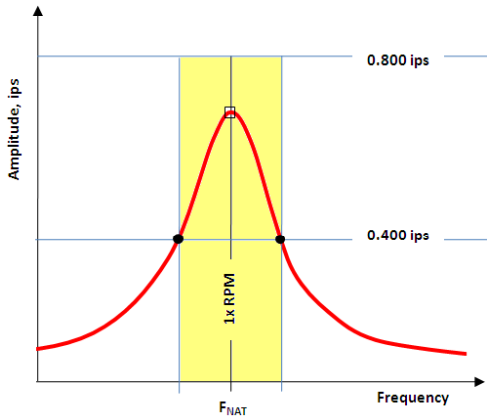
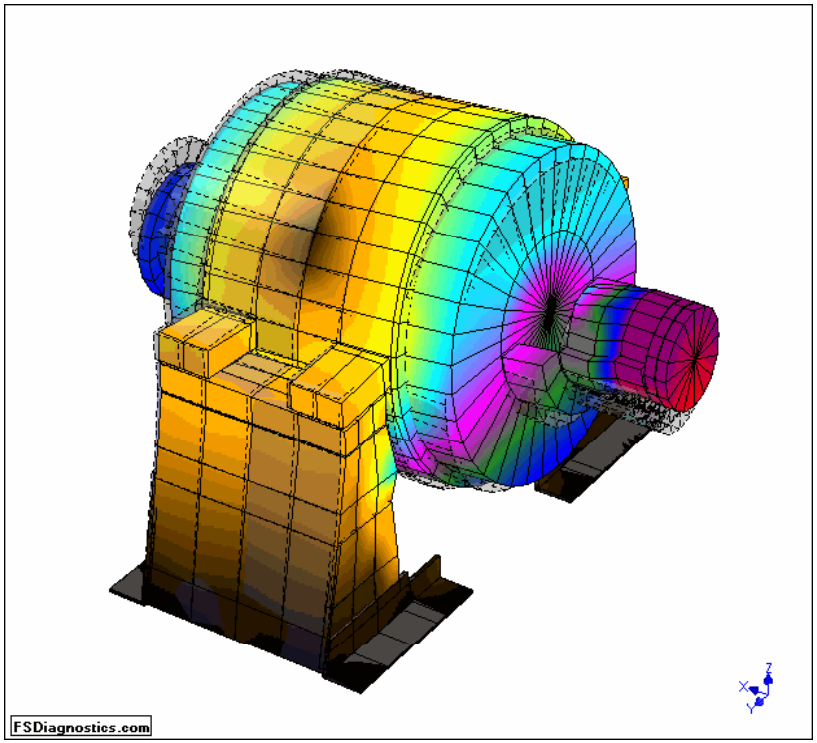
N_f Natural Frequency / Resonant Amplification

MOST LIKELY FAULT is IDENTIFIED



Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

FEED WATER PUMP HISTORY

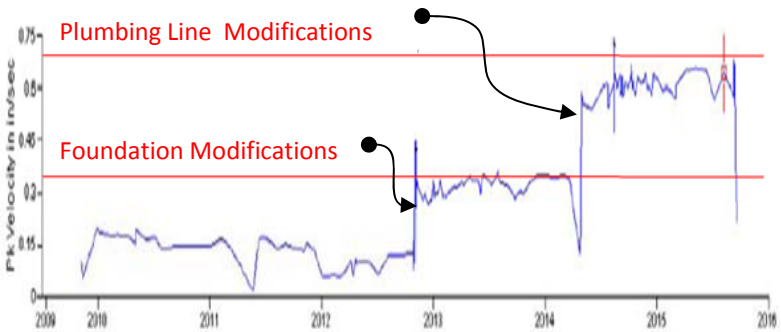


SYNCHRONOUS VIBRATION [1x RPM]
Potential Causes:

Natural Frequency / Resonant Amplification
Current Motion Indicates Vertical Pitching Mode

2005
EMA defined HORIZONTAL Torsional Mode @ 5,112 RPM [1x]. This Resonance is Resolved by Structural Modification

2005
EMA defined a VERTICAL PITCHING MODE @ 4,200 CPM [>20% Resonance Margin] Recommended Pedestal Structural Modification is NOT expected to alter this mode.



2015
The 2005 Vertical Pitching Mode at 4,200 CPM is suspected to be stiffened into the Operating Speed Range due to Large Piping Line (2014) and/or Foundation Modifications (2012) associated with the shifts in Vertical Overall Vibration response.

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

ANALYSIS & TESTING PROPOSAL

REVIEW 2005 Experimental Modal Analysis
Data / Analysis / Methodologies / Assumptions / Conclusions

PERFORM Operating Modal Analysis (OMA) on FW-P-32B
Determine Current Natural Frequencies, Mode Shapes

CONTRUCT Finite Element Analysis (FEA) Model of Pump
Use 2005 EMA and 2015 OMA Analyses for Correlation of Modes and Mode Shapes

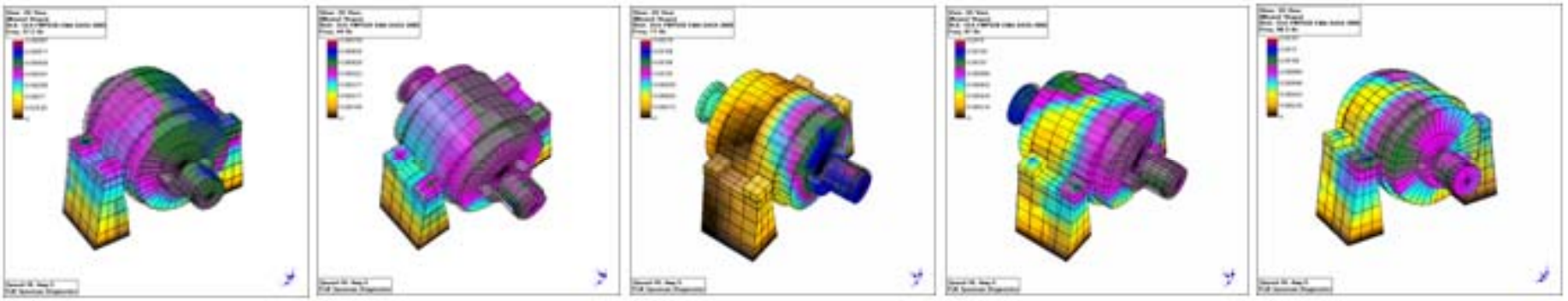
Use FEA Model to **DEFINE** Structural Modifications to Eliminate or Reduce 1x RPM Vibration Response
Stiffness / Mass / Damping / Phase Cancellation

VERIFY Natural Frequencies and Mode Shapes during Maintenance Outage (OR17)
Shutdown Experimental Modal Analysis
Post-Modification EMA

PERFORM Start-up Operating Modal Analysis (OMA) on FW-P-32B
Monitor Natural Frequencies, Mode Shapes
Verify Modification Results

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2005 EXPERIMENTAL MODAL ANALYSIS



REVIEW 2005 Experimental Modal Analysis
Data / Analysis / Methodologies / Assumptions / Conclusions

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

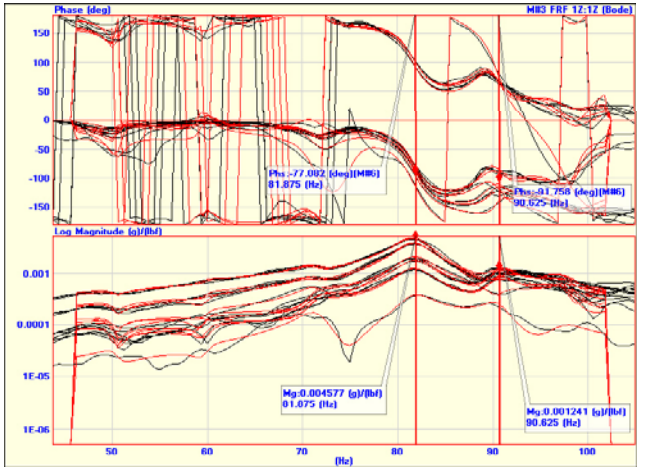
EXPERIMENTAL MODAL ANALYSIS:

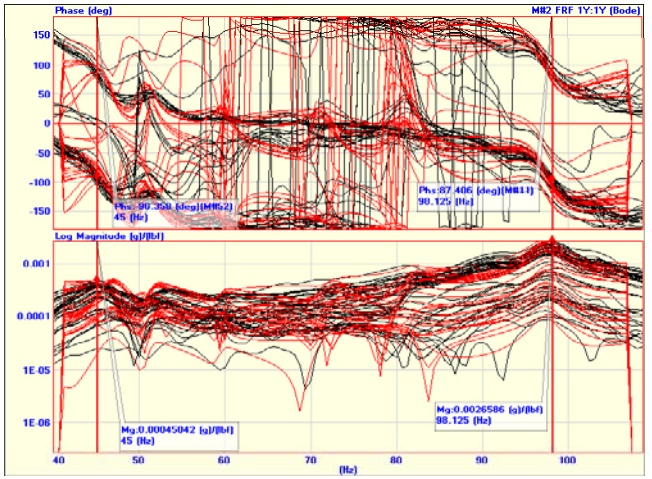
Experimental Modal Analysis (EMA) is also known as “Impact” or “Impulse” Natural Frequency Analysis. The empirical test method is a static diagnostic performed on structures to determine their natural frequencies, damping, and mode shapes. This analysis is performed with the machinery in a non-operating condition with limited background vibration from other machinery sources.

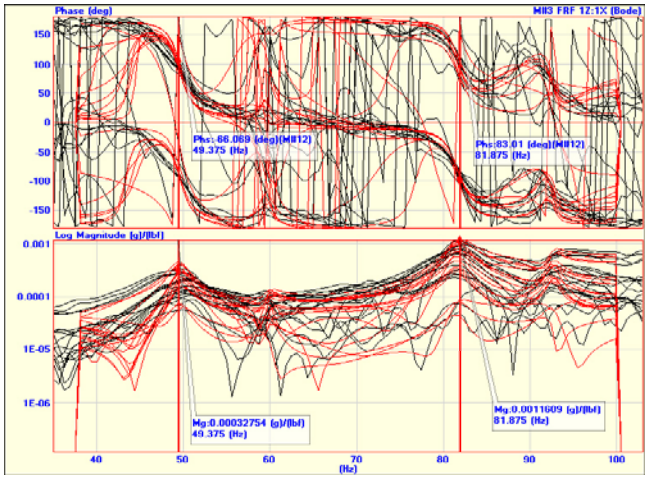
An impulse (usually a hammer blow) is applied to the structure to impart broad-band energy to the system. This energy functions to excite all of the system natural frequencies, similar to the response of a bell or tuning fork to a sharp impact. This hammer has a load cell built into the head that measures the force parted to the structure and allows this signal to be compared to the accelerometer response, via a transfer function, resulting in a measurement of the frequency response of the structure. Given enough response locations, each system natural frequency can be curve fit and its mode shape animated with specialized modal analysis software.

This testing was performed on the FW-P-32-B unit in each directional axis (x, y, z) separately to ensure that each mode in the operating range would be excited. The resulting data reflects mode shapes in these three dominant directions.

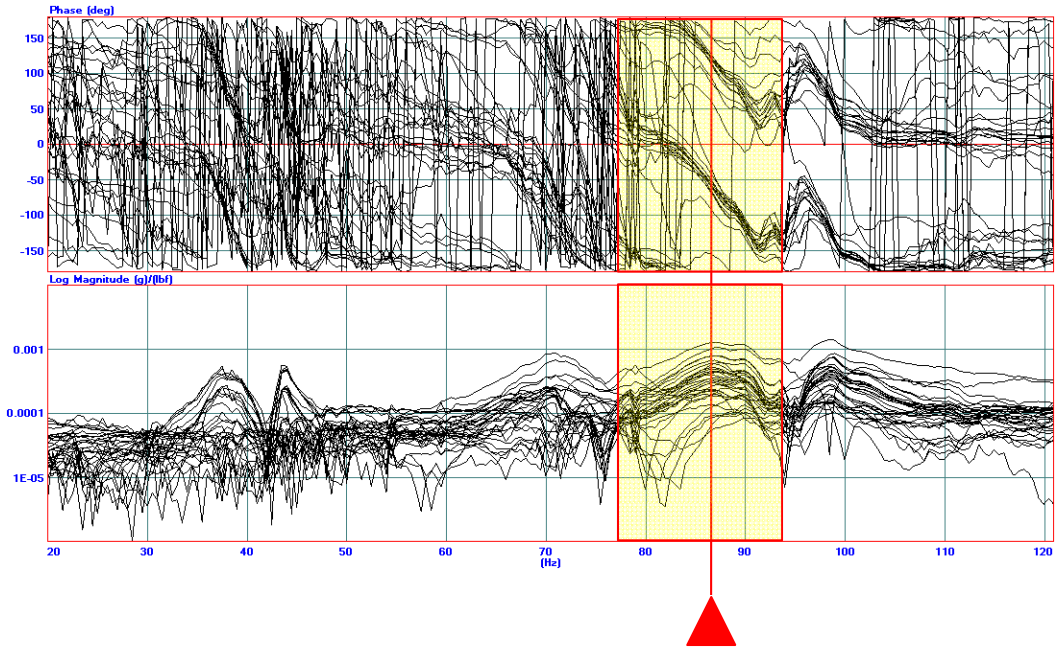
The x-axis is along the shaft centerline.
The y-axis is in the pump horizontal direction.
The z-axis is in the vertical pump direction.







Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips



2005 EMA Analysis

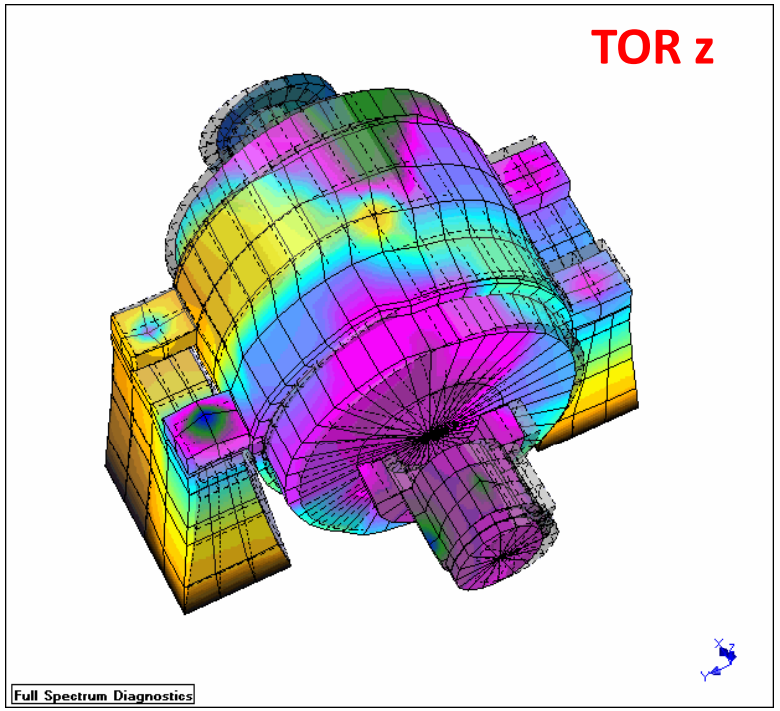
1	37.7 Hz	Rigid Body (y)
2	43.7 Hz	Rigid Body (x, y)
3	69.9 Hz	Vert Pitch (z)
4	**85.2 Hz**	**Torsion (z)**
5	98.3 Hz	Torsion (y, z)

EXPERIMENTAL MODAL ANALYSIS:

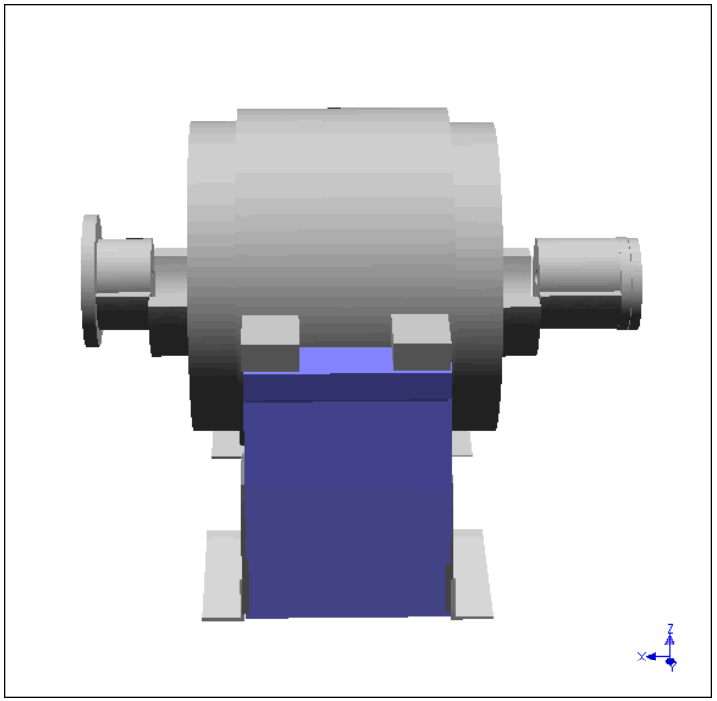
The 2005 Vibration Analysis included an Experimental Modal Analysis with the FWP32B in a non-operating condition. The analysis defined several natural frequencies in the system.

A Torsional Mode of the pump was detected within 1% of the normal operating speed @ 85 Hz (5,100 RPM). Excitation of this mode by residual unbalance and alignment forces created an elevated response in the horizontal direction.

The response could be detected at each bearing but was dominant at the pump outboard bearing. The Overlaid Measurement data set below shows a Magnitude Response and Phase Angle Response (Bode Plot).



Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips



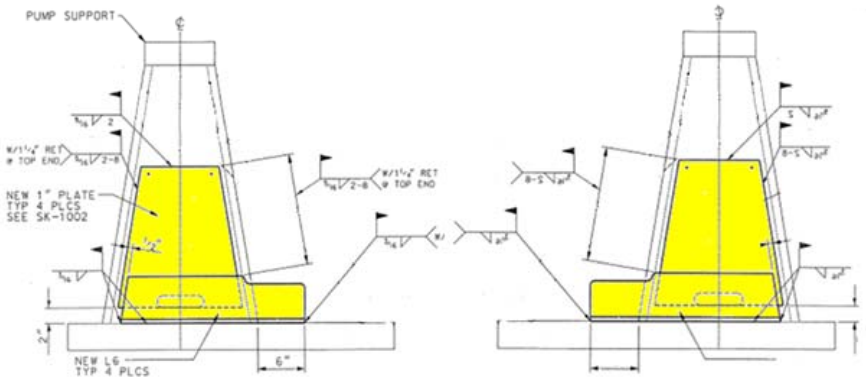
	2005 EMA Analysis		Modifications	Margin
1	37.7 Hz	→	44.0 Hz	-48.2 %
2	43.7 Hz	→	53.3 Hz	-37.3 %
3	69.9 Hz	→	70.7 Hz	-16.8 %
4	85.2 Hz	→	92.0 Hz	+ 8.0 %
5	98.3 Hz	→	106 Hz	+24.7 %

EXPERIMENTAL MODAL ANALYSIS:

The analysis at that time predicted that a gusset design similar to the one shown here would provide sufficient stiffness to push the torsional mode out of the operating speed range and reduce the horizontal vibration to acceptable levels.

The Actual Gusset Design (shown on right) was projected to provide the frequency margins shown in the table above. Typically, a margin of +/- 10% is desired.

Note that the (Vertical Pitching) mode at 69.9 Hz was not expected to increase due to the gusset modification, which was designed to restrict only the “torsional” response.



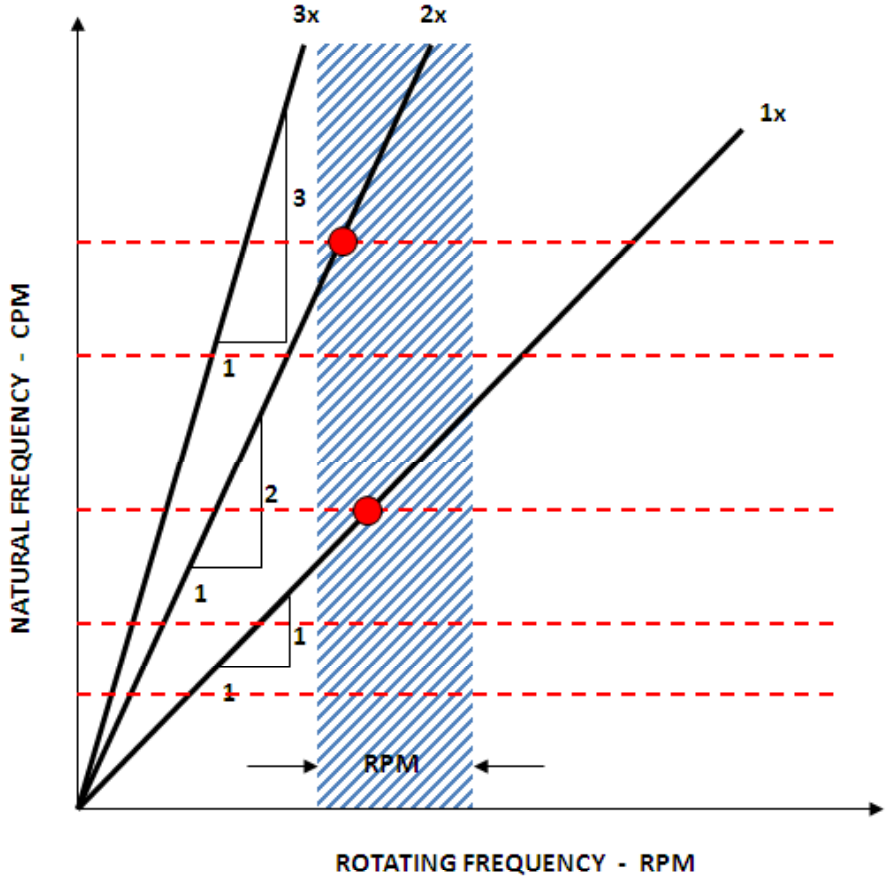
Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

THE CAMPBELL DIAGRAM:

A Campbell Diagram, also know as an Interference Diagram, allows the user to visually plot rotating orders of machinery versus natural frequencies in the system to determine if a coincidence situation exists, or more plainly, to determine potential resonance drivers in the system.

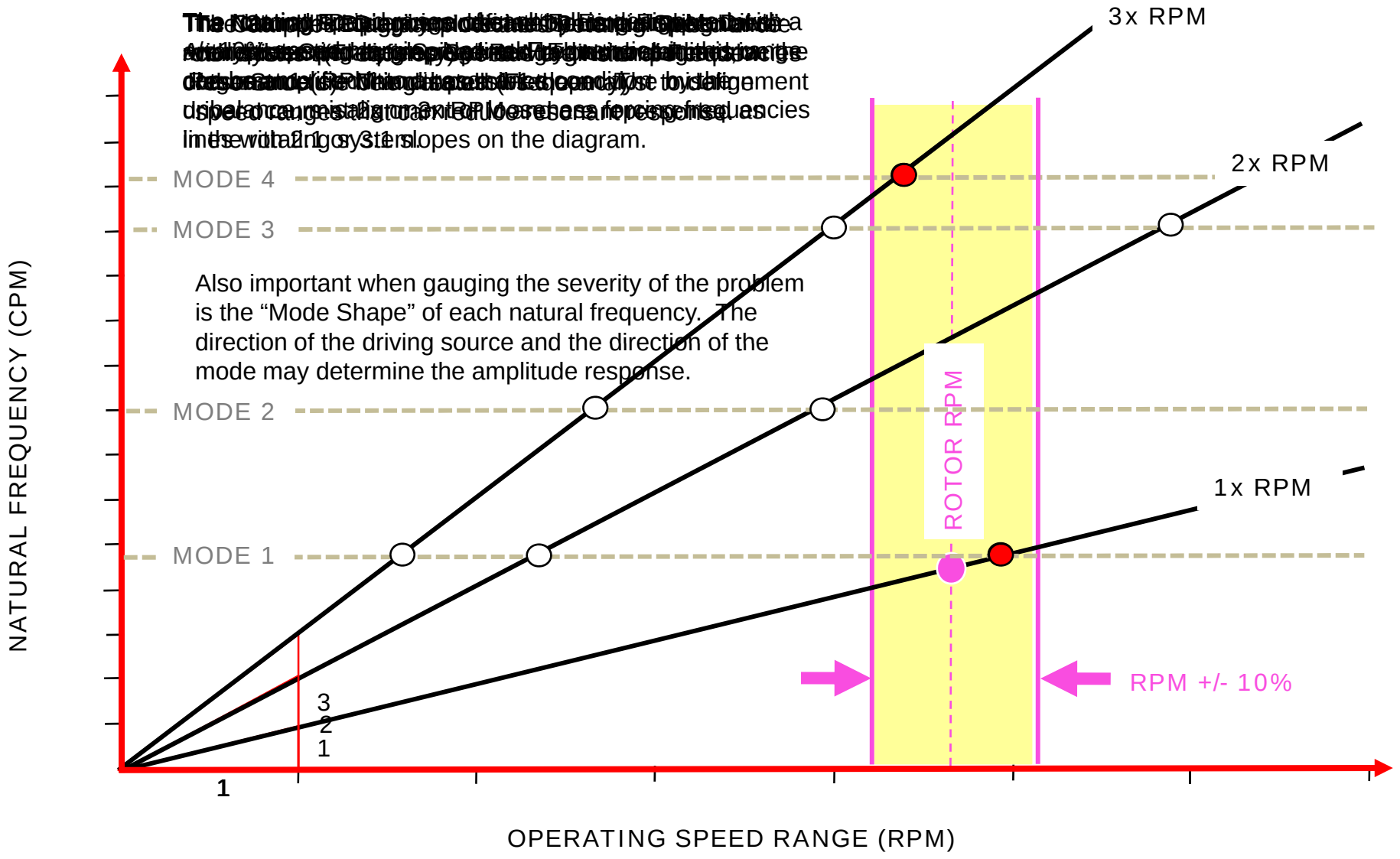
This diagram is a plot of Frequency (Natural Frequency) in CPM units versus Frequency (Rotational Speed) in RPM units. The natural frequencies of the Machine or Structures are defined from Experimental Modal testing and plotted as horizontal lines on the diagram. The operational speed frequency ranges are defined and plotted as a vertical range on the diagram. Rotating orders of running speed (1x, 2x, 3x, ….nx RPM) are plotted as sloping lines. The 1x RPM line has a 1:1 slope, the 2x RPM line has a 2:1 slope, and each higher harmonic follows the same characteristic.

Crossings of the rotating orders (1x, 2x, …RPM) and the plotted natural frequencies within the operating speed ranges indicate possible resonance concerns that may impact the vibratory amplitudes in the system. Note that mechanical systems are designed with rotating speed margin (difference) on natural frequencies to reduce amplification due to resonance.



Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

Use Arrow Keys or Space Bar to Advance Graphics



Also important when gauging the severity of the problem is the "Mode Shape" of each natural frequency. The direction of the driving source and the direction of the mode may determine the amplitude response.

2005 EMA Analysis: Campbell Diagram

1	37.7 Hz	Rigid Body (y)
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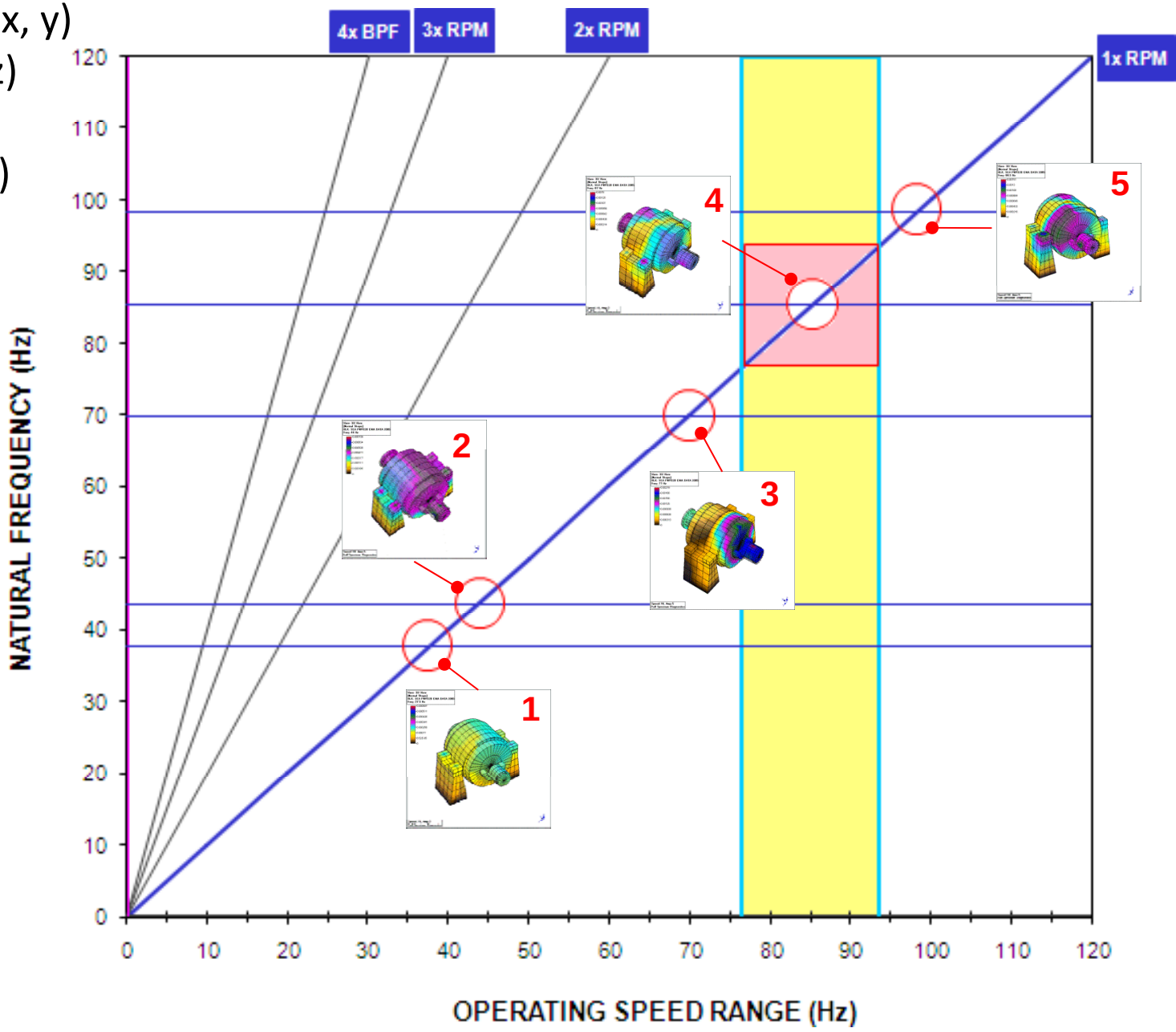
3	69.9 Hz	Vert Pitch (z)
4	**85.2 Hz**	**Torsion (z)**
5	98.3 Hz	Torsion (y, z)



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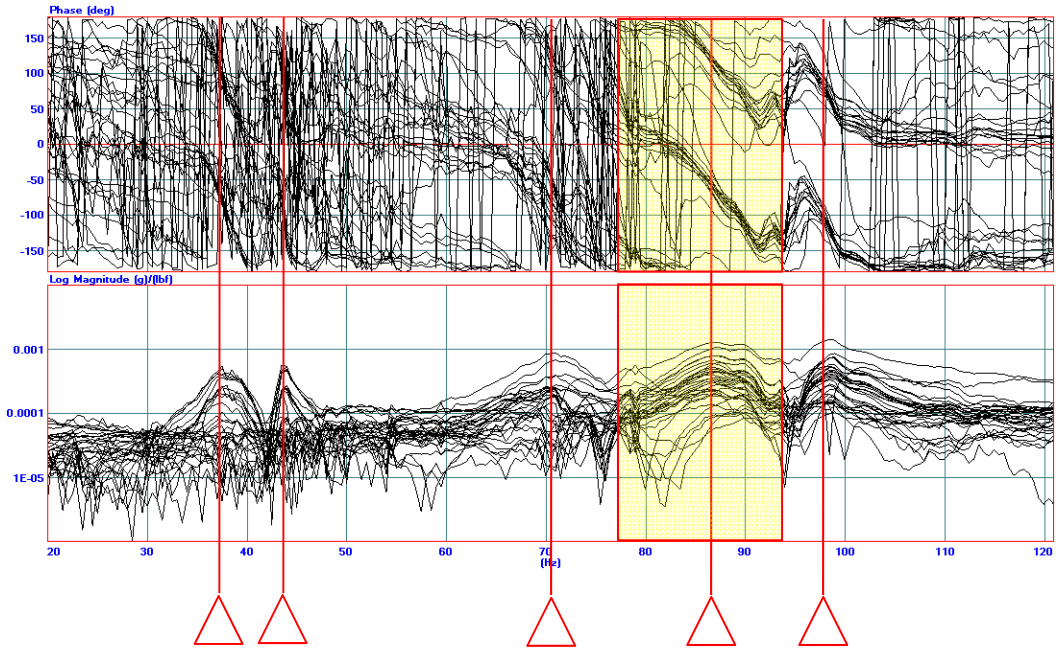

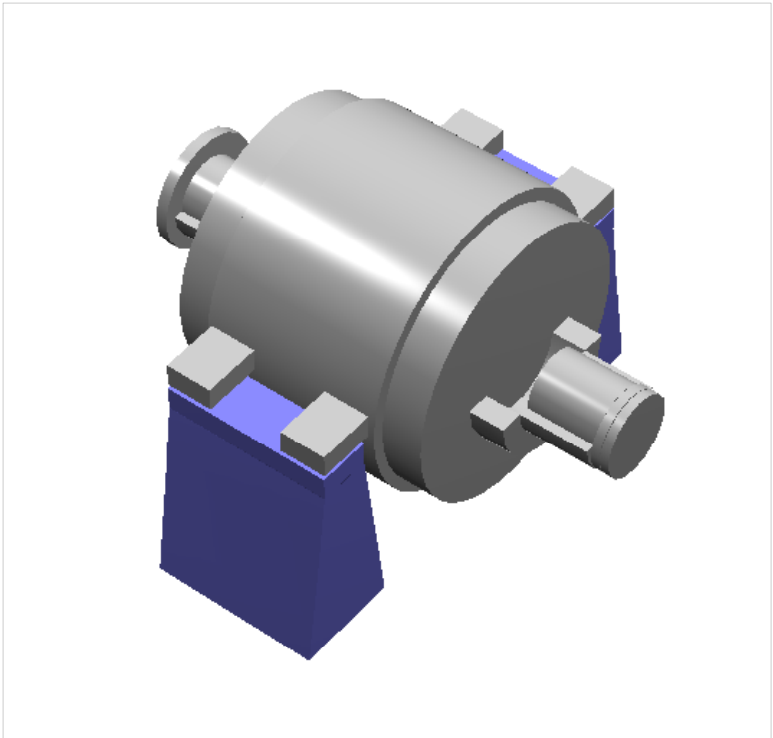

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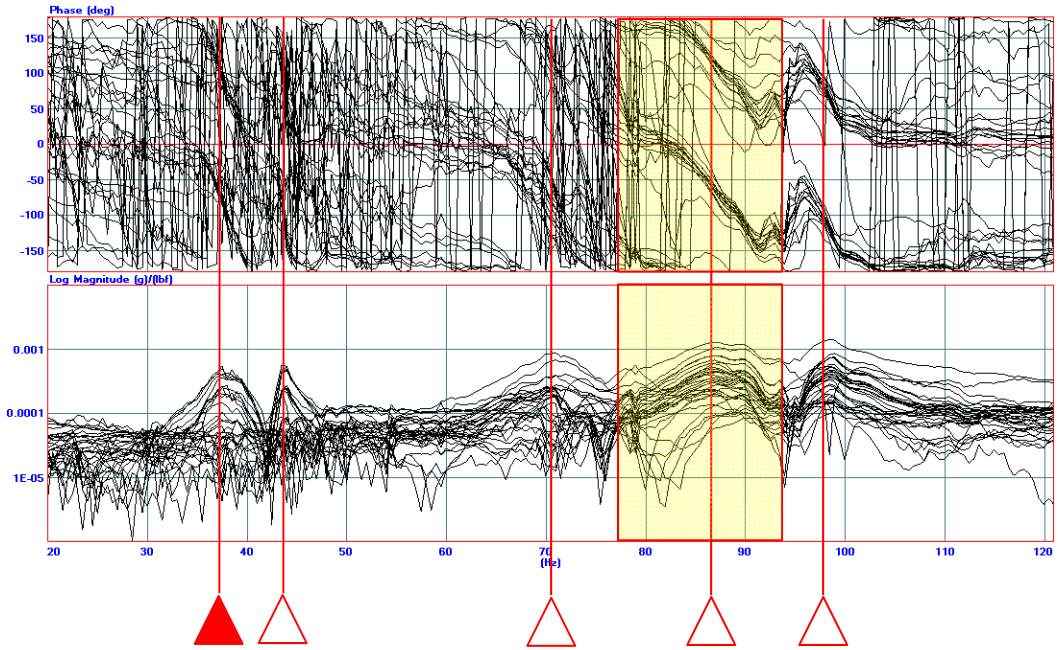

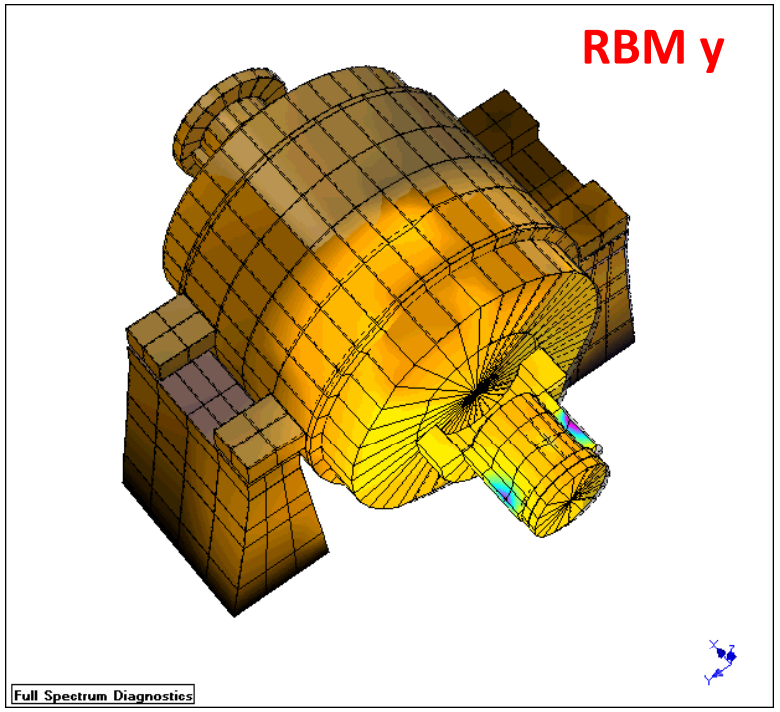

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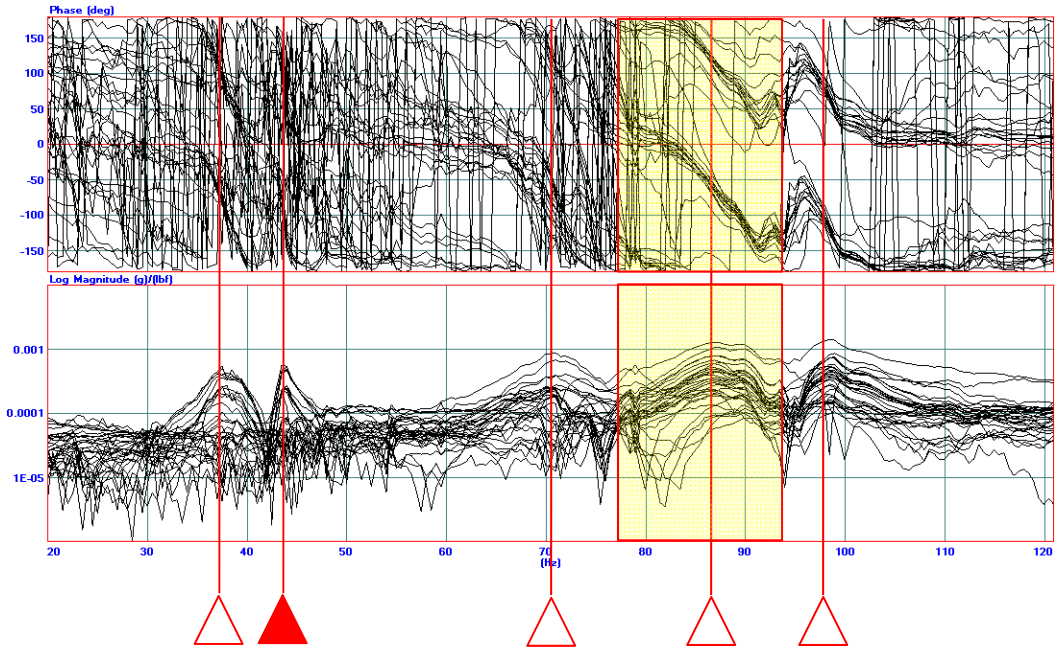

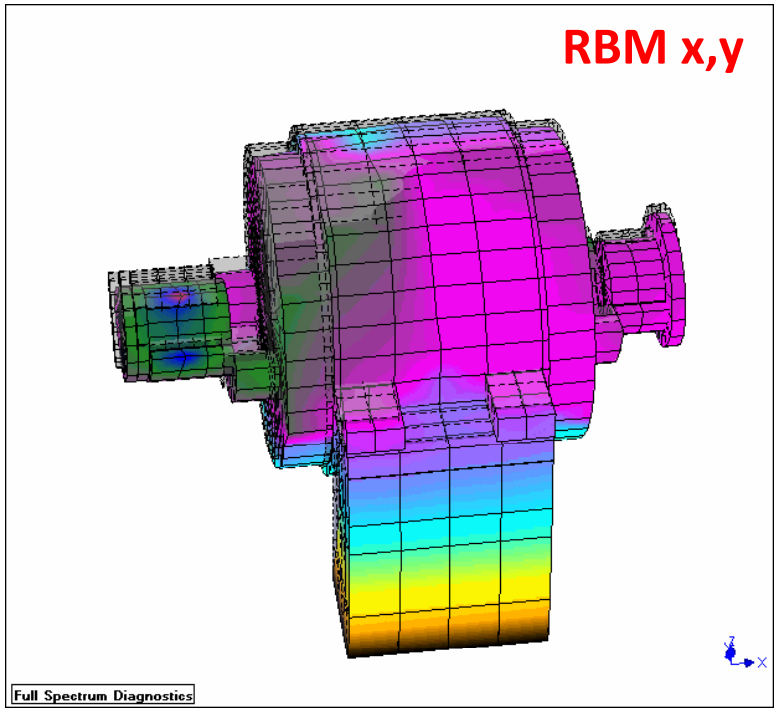

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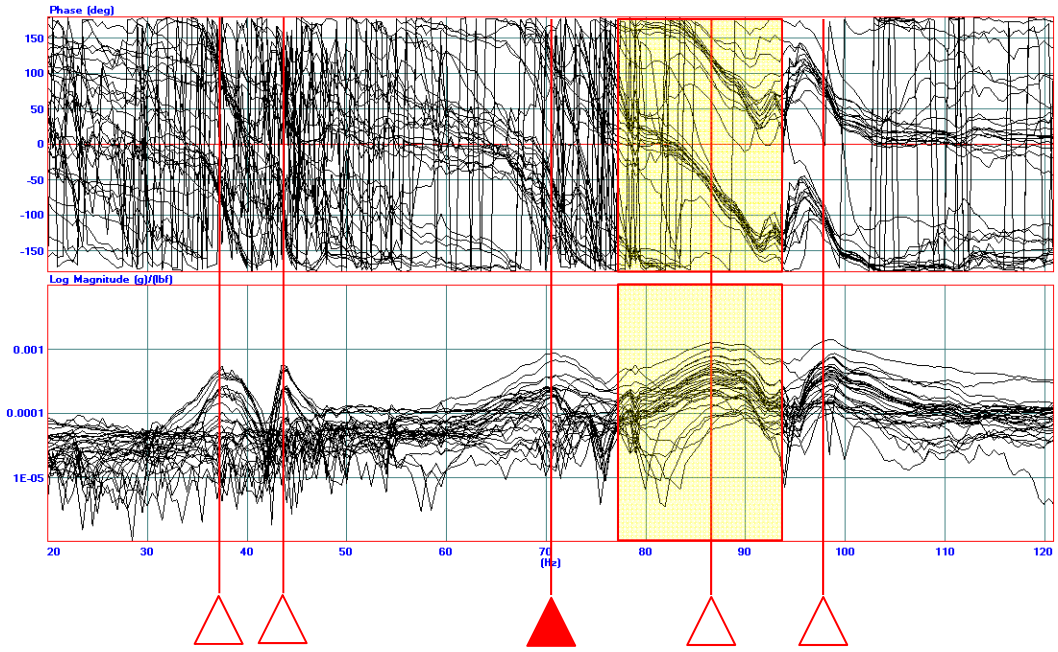

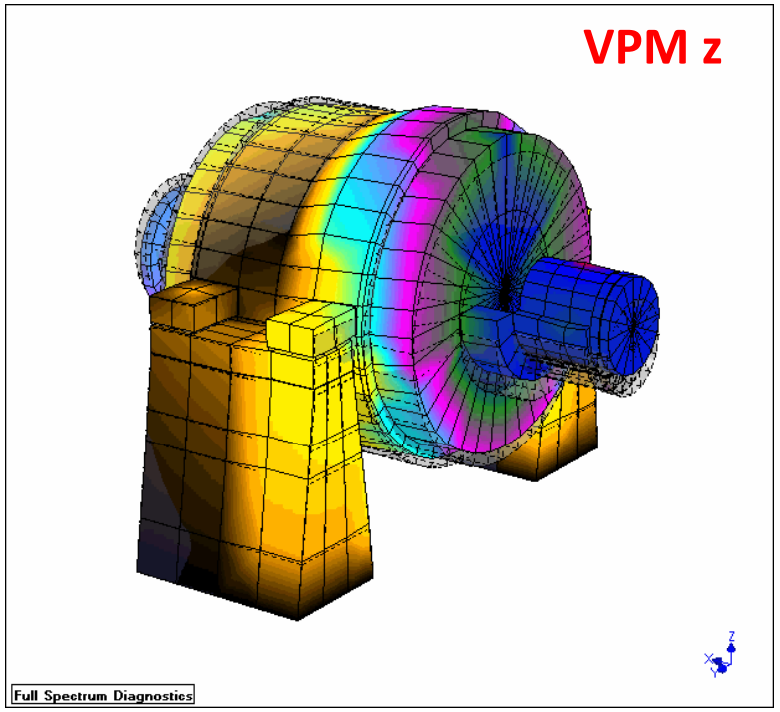

Machine Class: Feed Water Pump (Nuclear)
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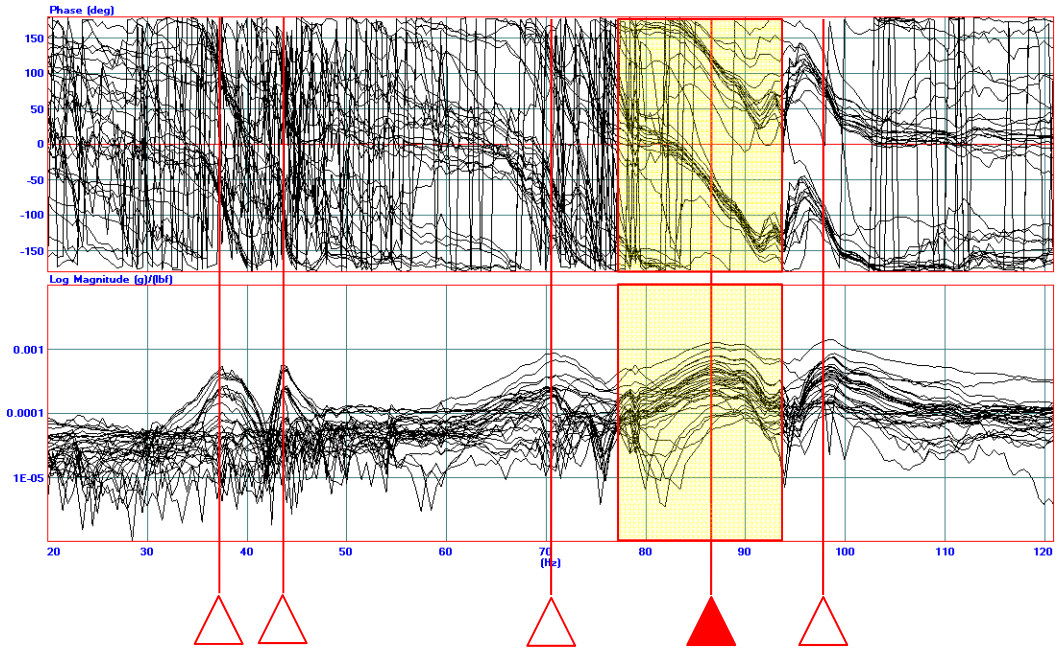
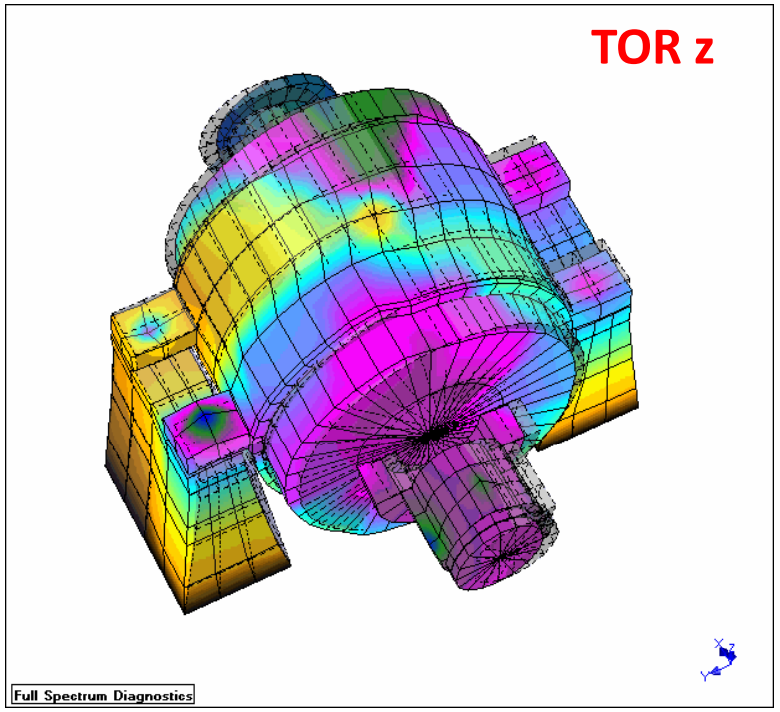
5	98.3 Hz	Torsion (y, z)

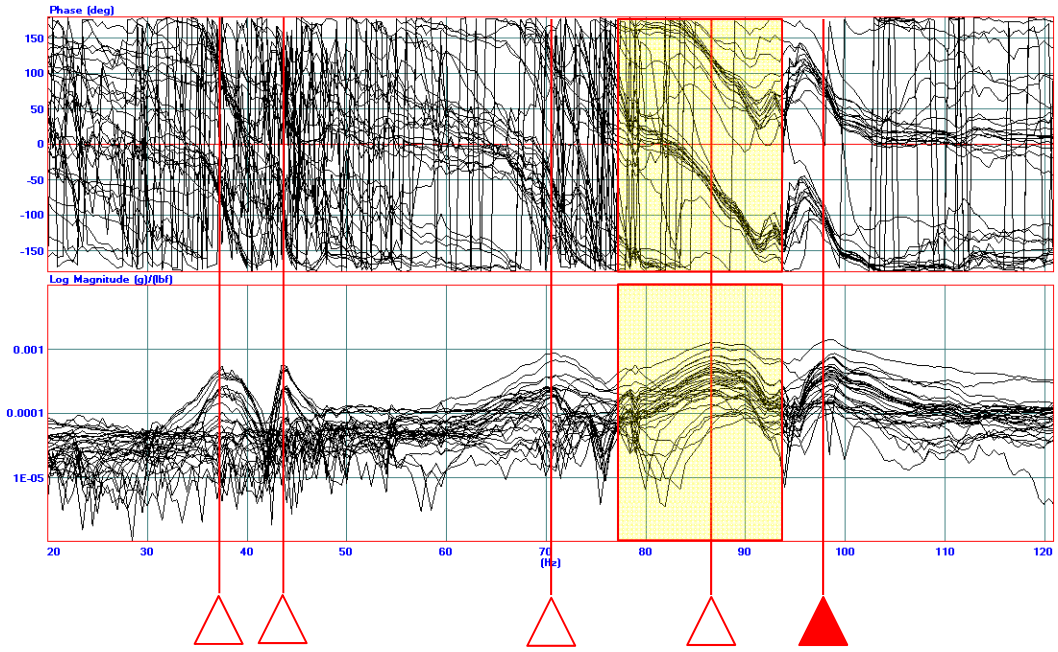


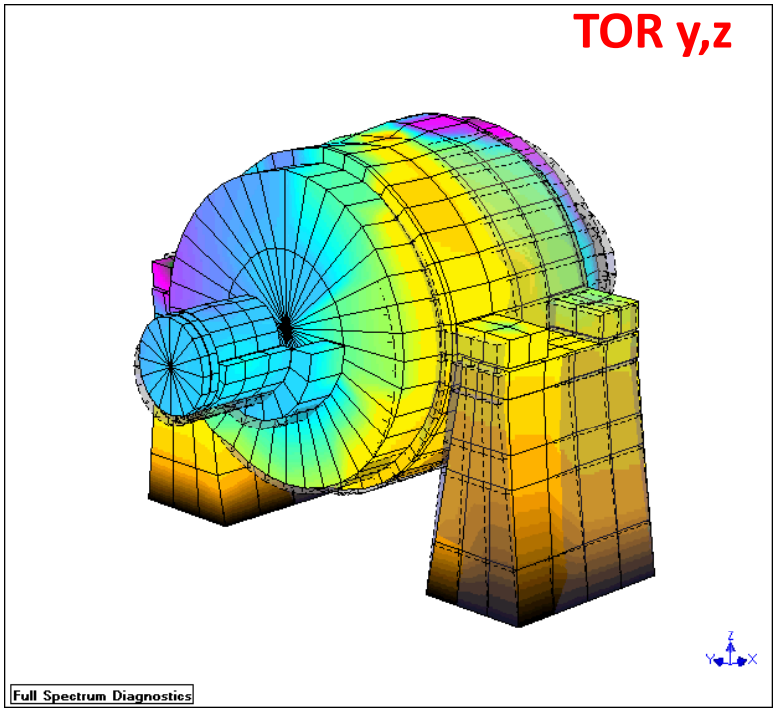


Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2005 EMA Analysis

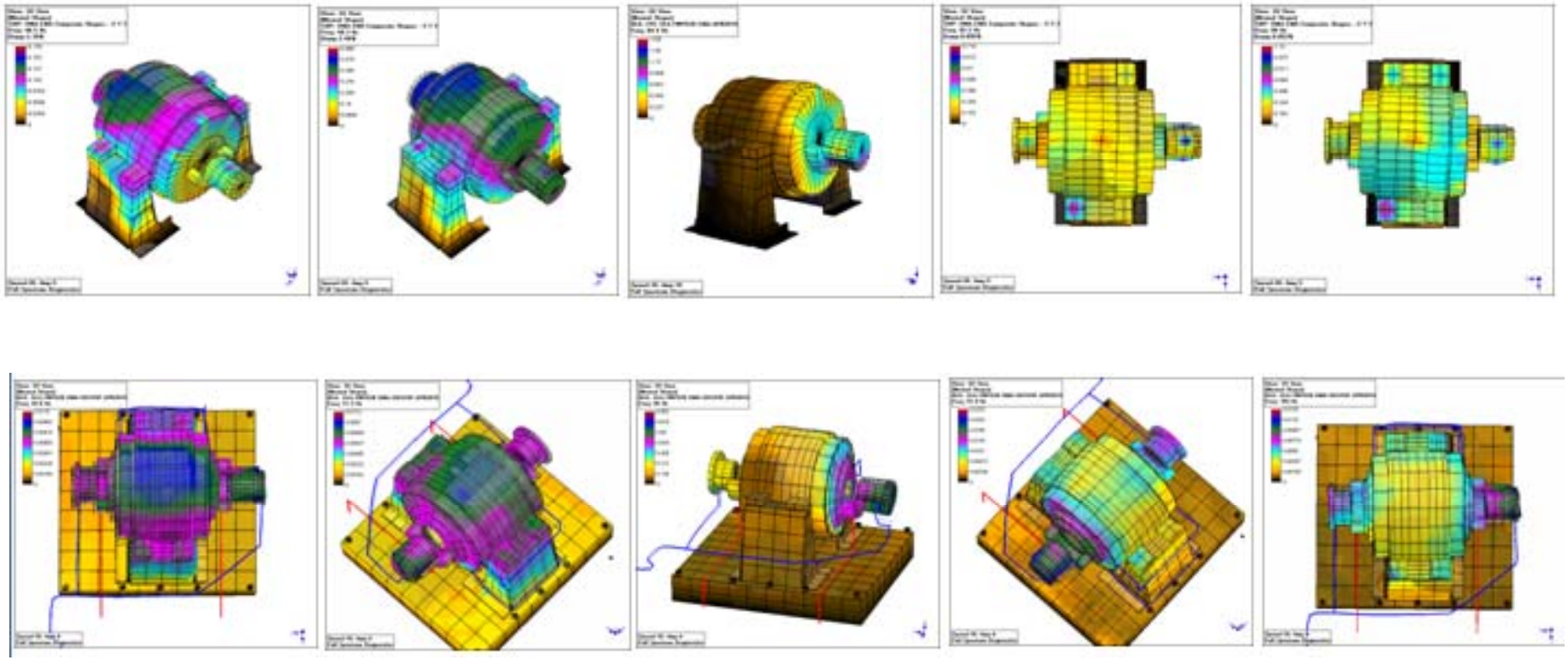
1	37.7 Hz	Rigid Body (y)
2	43.7 Hz	Rigid Body (x, y)
3	69.9 Hz	Vert Pitch (z)
4	85.2 Hz	Torsion (z)
5	**98.3 Hz**	**Torsion (y, z)**





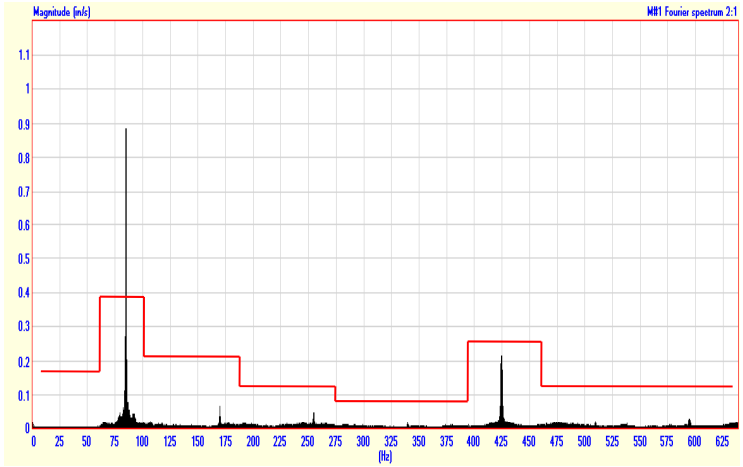
Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 OPERATING MODAL ANALYSIS



PERFORM Operating Modal Analysis (OMA) on FW-P-32B
Determine Current Natural Frequencies & Mode Shapes

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

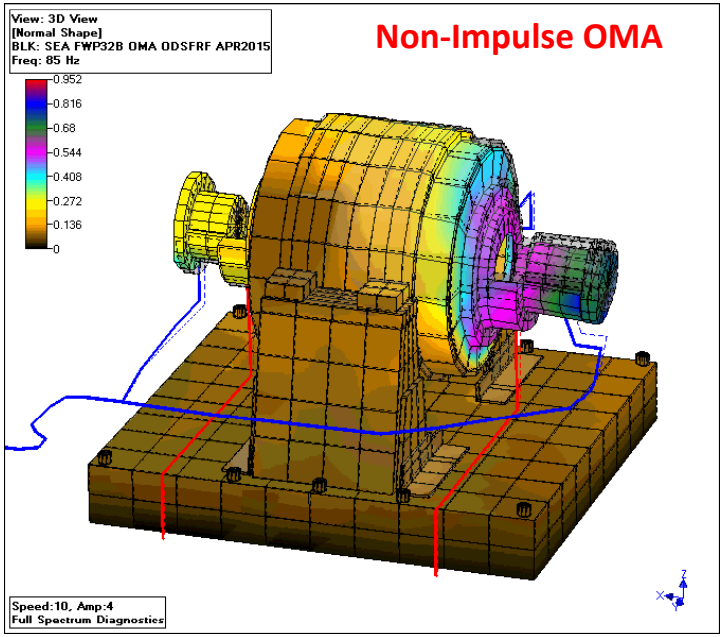


OPERATING MODAL ANALYSIS:

Operating Modal Analysis is an analysis method used to extract resonant frequencies, damping, and/or operating shapes (un-scaled mode shapes) of a structure. This method sometime called output-only modal analysis because only the response of the structure is measured. The structure might be excited using natural operating conditions or some other excitations might be applied to the structure; however, as long as the operating shapes are not scaled based on the applied force, it is called operational modal analysis.

The operating characteristics of the Feed Water Pump include a sufficient level of "random" background response from turbulent steam flow and rotor energy. If this low-level background noise is processed with significant averaging, the Modal Frequencies and Mode Shapes can be extracted from the final data. This OMA is referred to here as a "**Non-Impulse Operating Modal Analysis.** "

Vertical Pitching Mode: 85 Hz

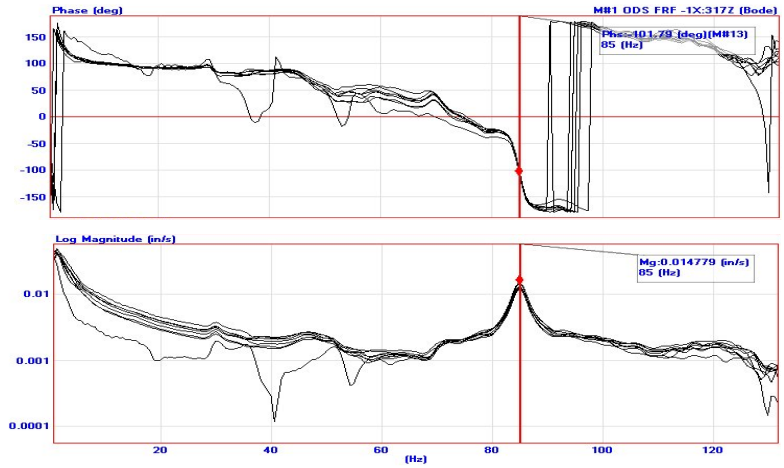


Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

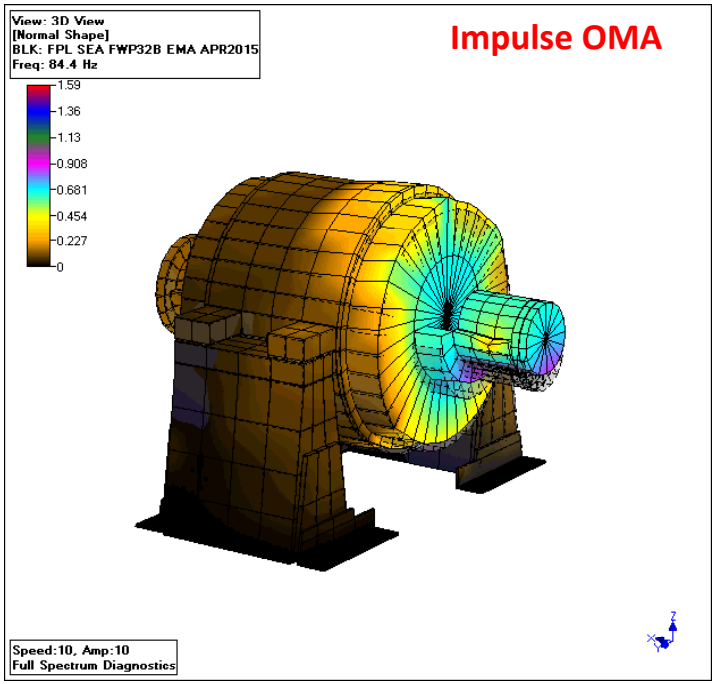
OPERATING MODAL ANALYSIS:

Operating Modal Analysis is an analysis method used to extract resonant frequencies, damping, and/or operating shapes (un-scaled mode shapes) of a structure. This method sometime called output-only modal analysis because only the response of the structure is measured. The structure might be excited using natural operating conditions or some other excitations might be applied to the structure; however, as long as the operating shapes are not scaled based on the applied force, it is called operational modal analysis.

The 2015 Vibration Analysis also included an Experimental Modal Analysis Impact Test with the FWP32B in an operating condition. This analysis is sometimes called an Operating Modal Analysis. Here it is referred to as an "**Impulse Operating Modal Analysis.** "

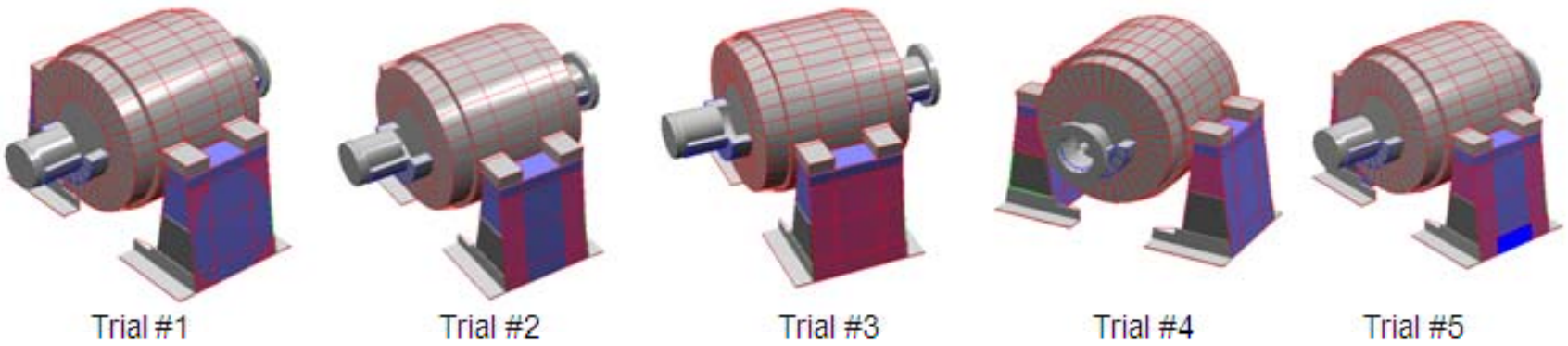


Vertical Pitching Mode: 85 Hz



Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 FINITE ELEMENT ANALYSIS



CONTRUCT Finite Element Analysis (FEA) Model of Pump
Use 2005 EMA and 2015 OMA Analyses for Correlation of Modes & Mode Shapes

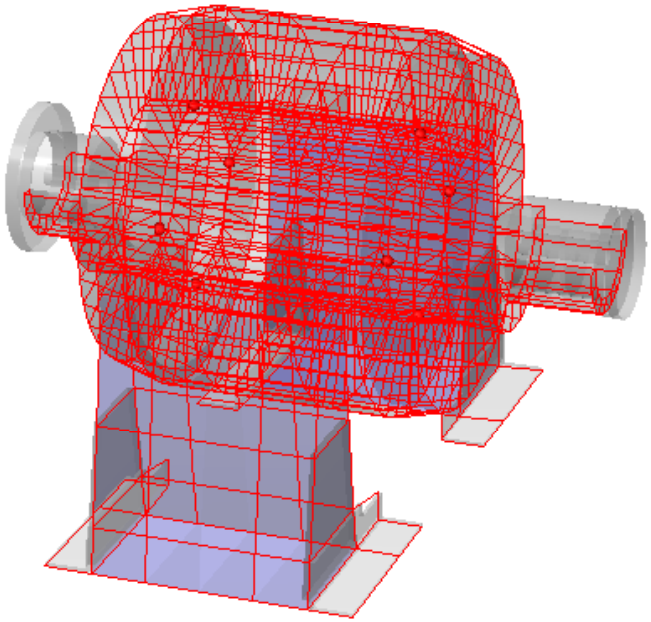
Use FEA Model to **DEFINE** Structural Modifications to Eliminate or Reduce 1x RPM Vibration Response: Stiffness / Mass / Damping / Phase Cancellation

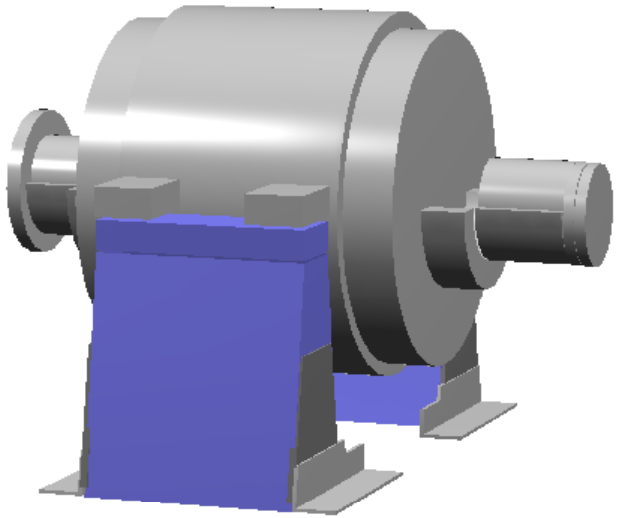
Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

FINITE ELEMENT ANALYSIS:

Finite Element Analysis, or FEA, is a numerical computer modeling method of analysis used for structural design and evaluation. This analysis involves the creation of a computer representation of a structure or machine. The representation consists of points, lines, and surfaces that define the elements, or three-dimensional volume(s) of the component under investigation.

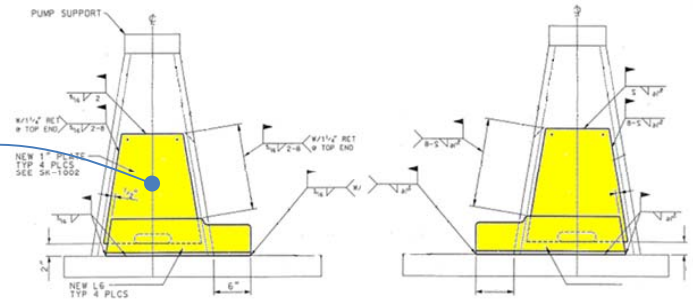
Additional engineering material(s) properties information in the form of Mass Density (lb/in3), Modulus of Elasticity (lb/in2), Shear Modulus (lb/in2), and Poisson's Ratio are assigned to the elements. As well as artificial stiffness, added mass and flexibilities to simulate their boundary (mounted) conditions. If designed correctly, the FEA model can accurately predict the "Modes of Vibration" (natural frequencies) in the analysis structure. FEA models typically require some experimental data for empirical correlation. A common method, as in this case is a natural frequency correlation from an Experimental Modal Analysis.





Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 3600 RPM
Overall Alarm: 0.400 ips

OPERATING MODAL ANALYSIS:



Pre-Shutdown Analysis & Testing

Mode	Mode Shape	2005 EMA[1] Analysis	FEA BL 2015[2] [w/ Gussets]	2015 OMA[3] [Impulse]	2015 OMA[4] [non-Impulse]	FEA BL 2015[5] [Correlation]
1	Lateral RBM*(y)	37.7 Hz	44.0 Hz	46.5 Hz	45.6 Hz	3.6%
2	Axial RBM*(x)	43.7 Hz	53.3 Hz	49.2 Hz	51.3 Hz	3.9%
3	Vertical RBM*(z)	**	**	**	**	**
4	**Vertical Pitch (z)**	**69.9 Hz**	**70.7 Hz**	**85.3 Hz**	**85.0 Hz**	**20.2%**
5	Torsion (z)	85.2 Hz	92.0 Hz	92.2 Hz	91.9 Hz	0.2%
6	Torsion (y,z)	98.3 Hz	106 Hz	99.0 Hz	103 Hz	2.8%

(1) 2005 EMA Test Conditions [Cold, Coupled, Dewatered, All Piping Attached]
(2) 2015 FEA Analysis based on 2005 Geometry and 2014 Pedestal Gussets Modification Installed
(3) 2015 OMA Analysis (Non-Impulse) de-convolution of the ME'scope ODSFRF® measurements
(4) 2015 OMA Analysis (Impulse) Operating EMA Analysis
(5) FEA Baseline analysis Correlation with OMA (Impulse) and OMA (Non-Impulse) Results
(*) RBM denotes Rigid Body Mode. Typically, in-phase translational motion (x, y, z) without significant bending
(**) The Vertical RBM (bounce) was not detected in the 2005 EMA data & below detection in the OMA data.

Excellent Correlation with 2005 EMA analysis and Modified Pedestal Gussets introduced into the FEA model.

Except FEA model did NOT Predict the Vertical Pitching Mode to move into the operating speed range.

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 FEA Analysis

1 44.0 Hz Lateral RBM
2 53.3 Hz Axial RBM
3 ***
4 70.7 Hz Vert Pitch Mode
5 92.0 Hz Torsional Mode
6 106 Hz Torsional Mode

Pre-Shutdown Analysis & Testing

Mode	Mode Shape	2005 EMA(1) Analysis	FEA BL 2015(2) [w/ Gussets]	2015 OMA(3) [Impulse]	2015 OMA(4) [non-Impulse]	FEA BL 2015(5) [Correlation]
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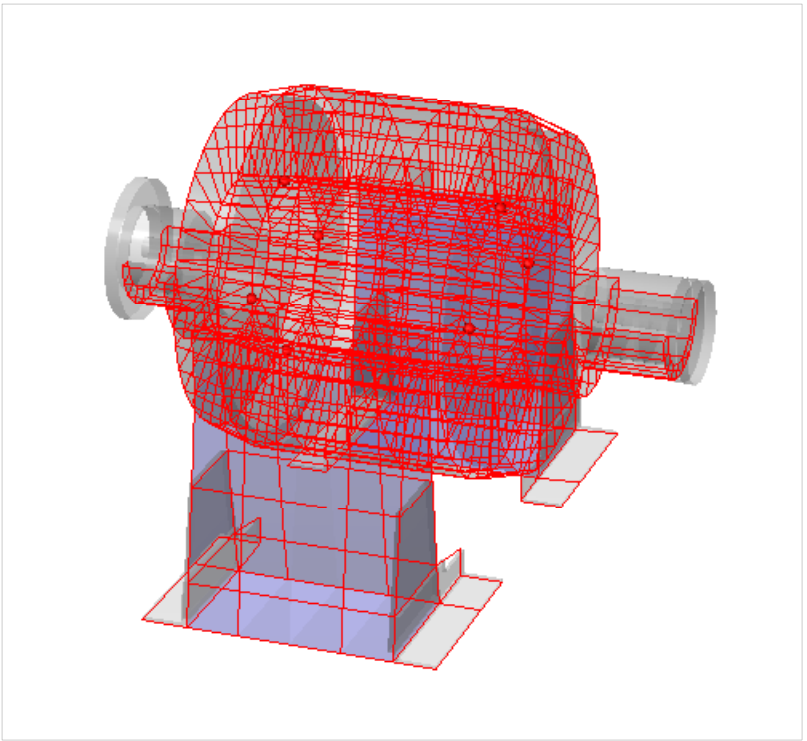

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 FEA Analysis

1 44.0 Hz Lateral RBM
2 53.3 Hz Axial RBM
3 ***
4 70.7 Hz Vert Pitch Mode
5 92.0 Hz Torsional Mode
6 106 Hz Torsional Mode

Pre-Shutdown Analysis & Testing

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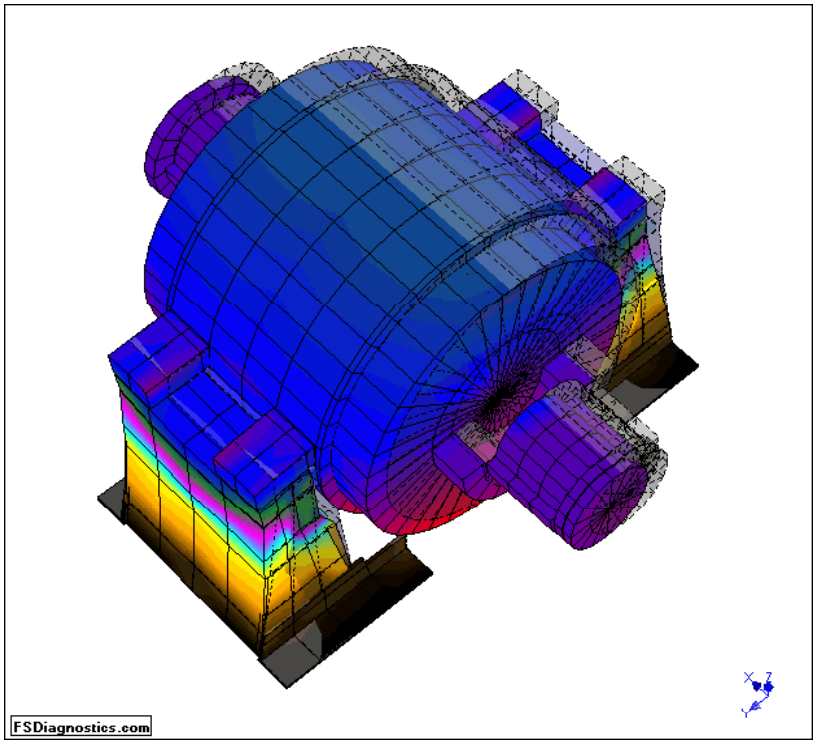

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 FEA Analysis

1 44.0 Hz Lateral RBM
2 53.3 Hz Axial RBM
3 ***
4 70.7 Hz Vert Pitch Mode
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Pre-Shutdown Analysis & Testing

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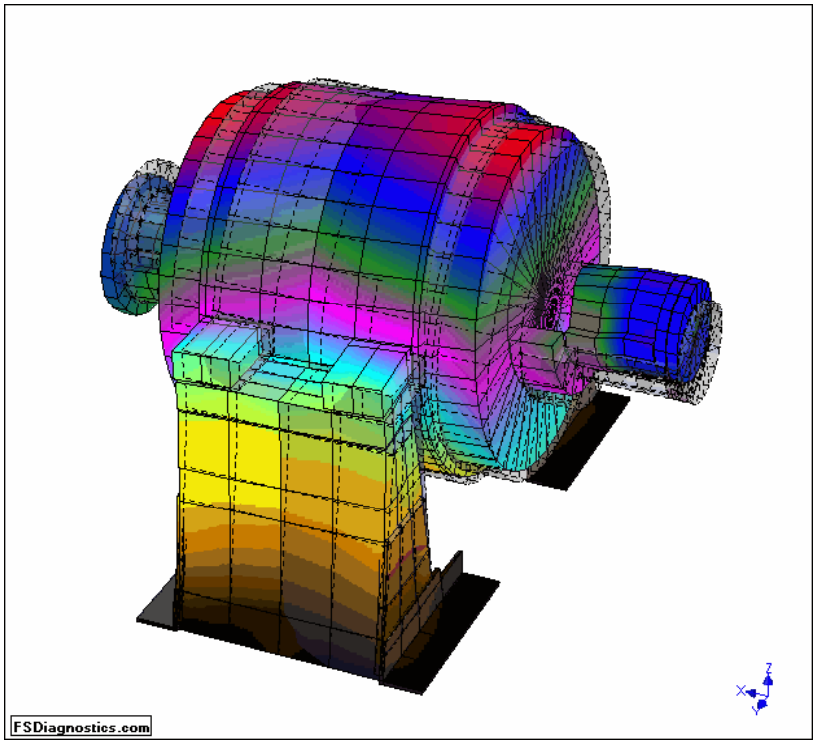

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 FEA Analysis

1 44.0 Hz Lateral RBM
2 53.3 Hz Axial RBM
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Pre-Shutdown Analysis & Testing

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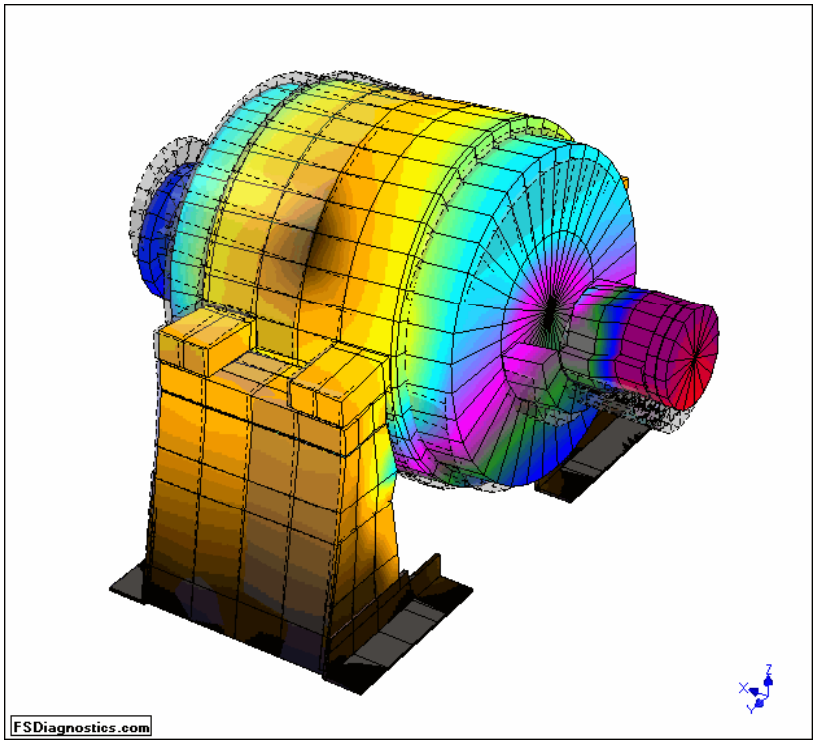

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 FEA Analysis

1 44.0 Hz Lateral RBM
2 53.3 Hz Axial RBM
3 ***
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Pre-Shutdown Analysis & Testing

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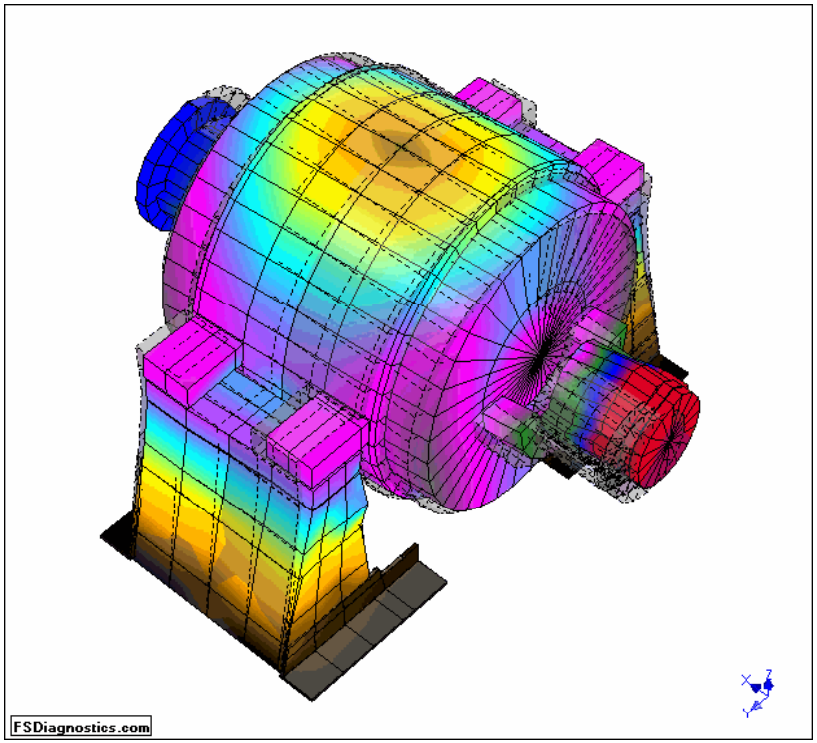

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 FEA Analysis

1 44.0 Hz Lateral RBM
2 53.3 Hz Axial RBM
3 ***
4 70.7 Hz Vert Pitch Mode
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6 106 Hz Torsional Mode

Pre-Shutdown Analysis & Testing

Mode	Mode Shape	2005 EMA(1) Analysis	FEA BL 2015(2) [w/ Gussets]	2015 OMA(3) [Impulse]	2015 OMA(4) [non-Impulse]	FEA BL 2015(5) [Correlation]
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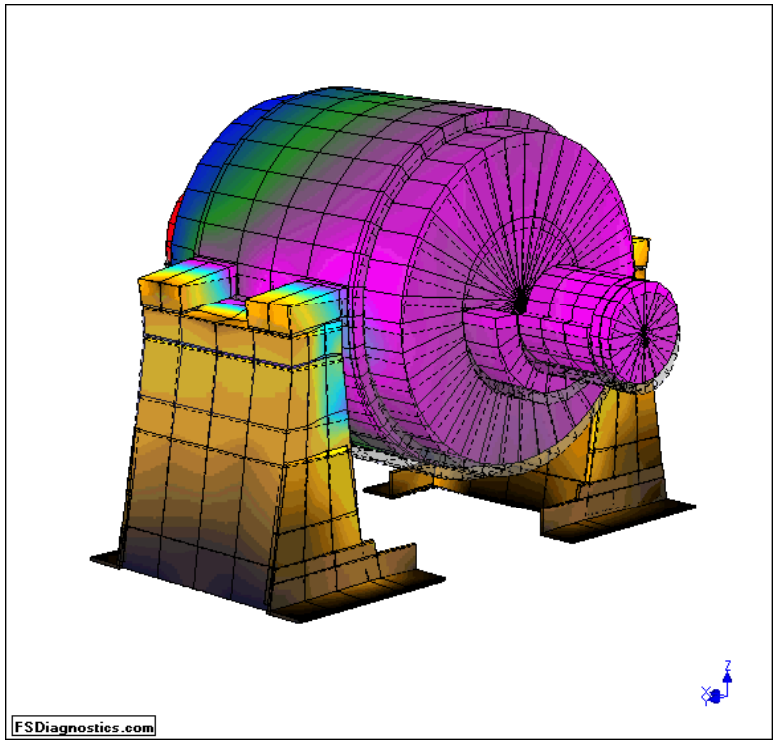
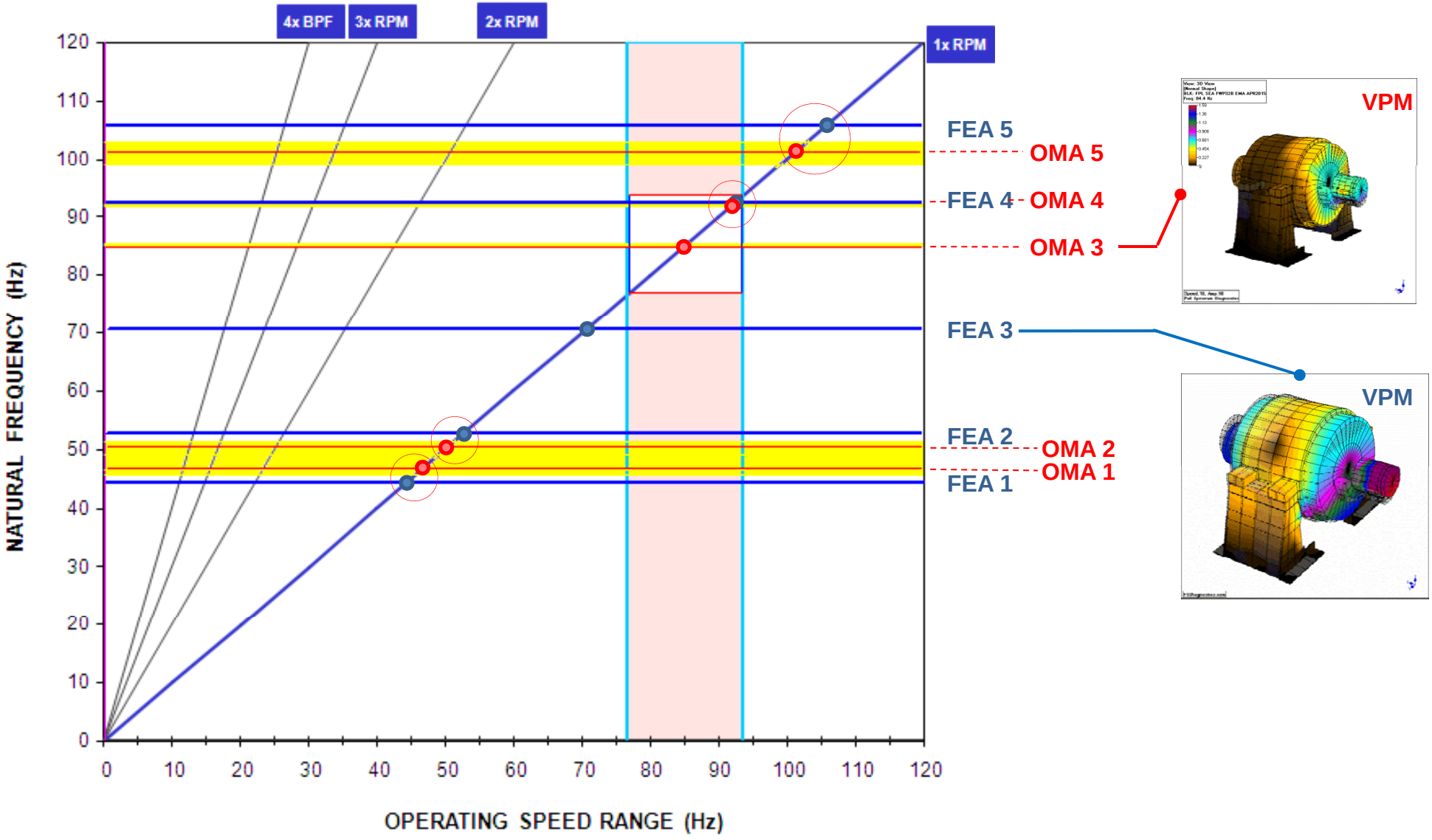
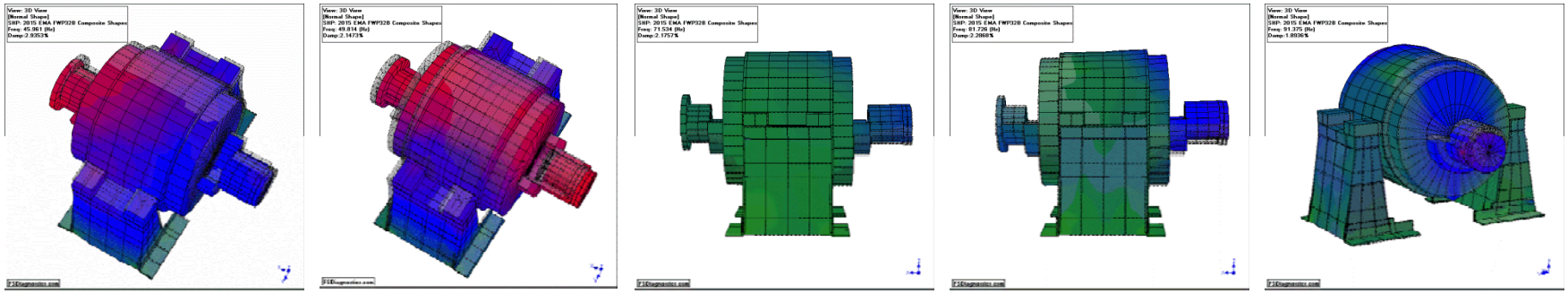


Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips



Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 EXPERIMENTAL MODAL ANALYSIS

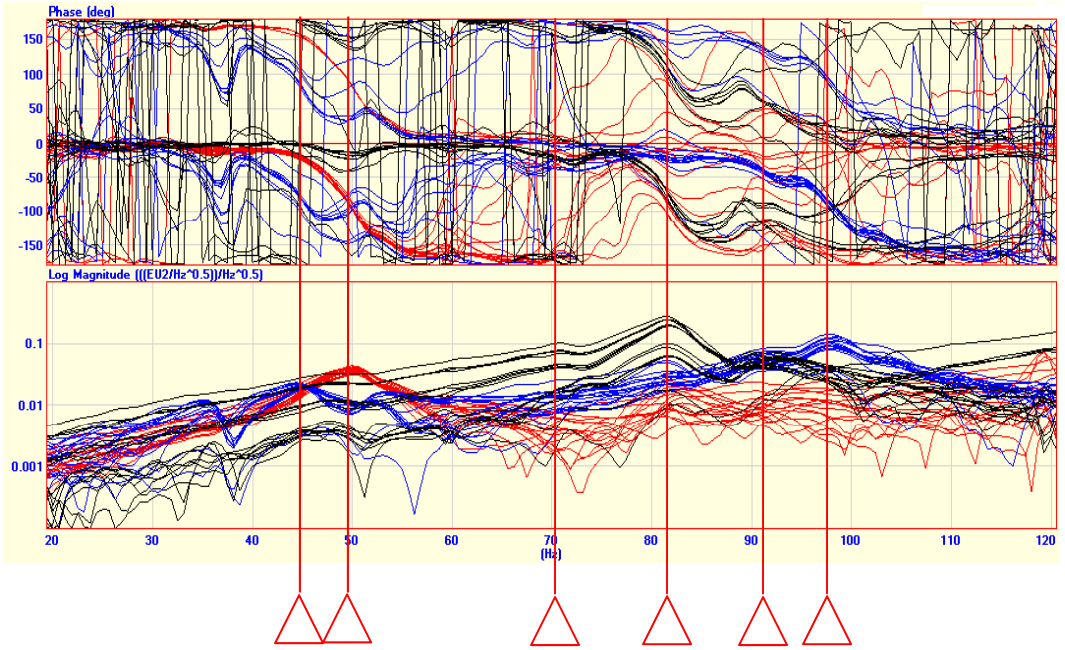


VERIFY Natural Frequencies and Mode Shapes during Maintenance Outage (OR17) Shutdown Experimental Modal Analysis

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 EMA Analysis
Pre-Modifications

1 47.4 Hz Lateral RBM
2 51.2 Hz Axial RBM
3 72.9 Hz Vertical RBM
4 83.7 Hz Vert Pitch Mode
5 97.0 Hz Torsional Mode
6 100 Hz Torsional Mode



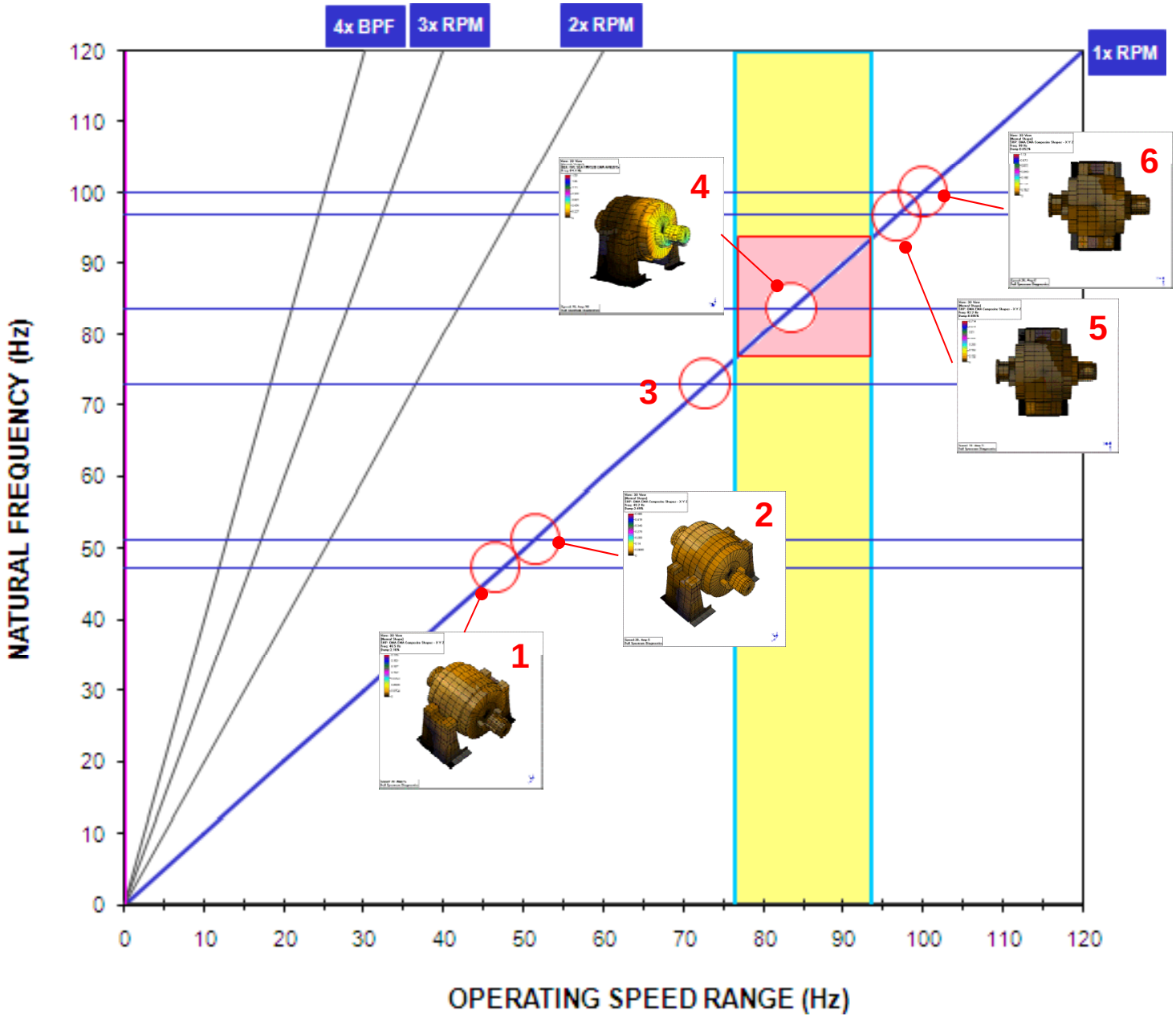
Post-Shutdown Analysis & Testing

Mode	Mode Shape	2015 EMA[1] [@ SD (hot)]	2015 EMA[2] [@ SD (cold)]	2015 EMA BL[3] [@SD Dewater]
1	Lateral RBM* (y)	46.0 Hz	46.7 Hz	47.4 Hz
2	Axial RBM* (x)	49.8 Hz	49.6 Hz	51.2 Hz
3	Vert ical RBM* (z)	71.5 Hz	71.4 Hz	72.9 Hz
4	**Vertical Pitch (z)**	**81.7 Hz**	**81.7 Hz**	**83.7 Hz**
5	Torsion (z)	91.4 Hz	90.6 Hz	97.0 Hz
6	Torsion (y, z)	97.0 Hz	97.5 Hz	100 Hz

(1) EMA Test Oct 1, 2015 Conditions [Hot, Coupled, Full of Water, All Piping Attached]
(2) EMA Test Oct 2, 2015 Conditions [Cold, Coupled, Full of Water, All Piping Attached]
(3) EMA Baseline Test Oct 7, 2015 Conditions [Cold, Un-Coupled, Dewatered

2015 EMA Analysis
Pre-modifications

1	47.4 Hz
2	51.2 Hz
3	72.9 Hz
4	83.7 Hz
5	97.0 Hz
6	106 Hz

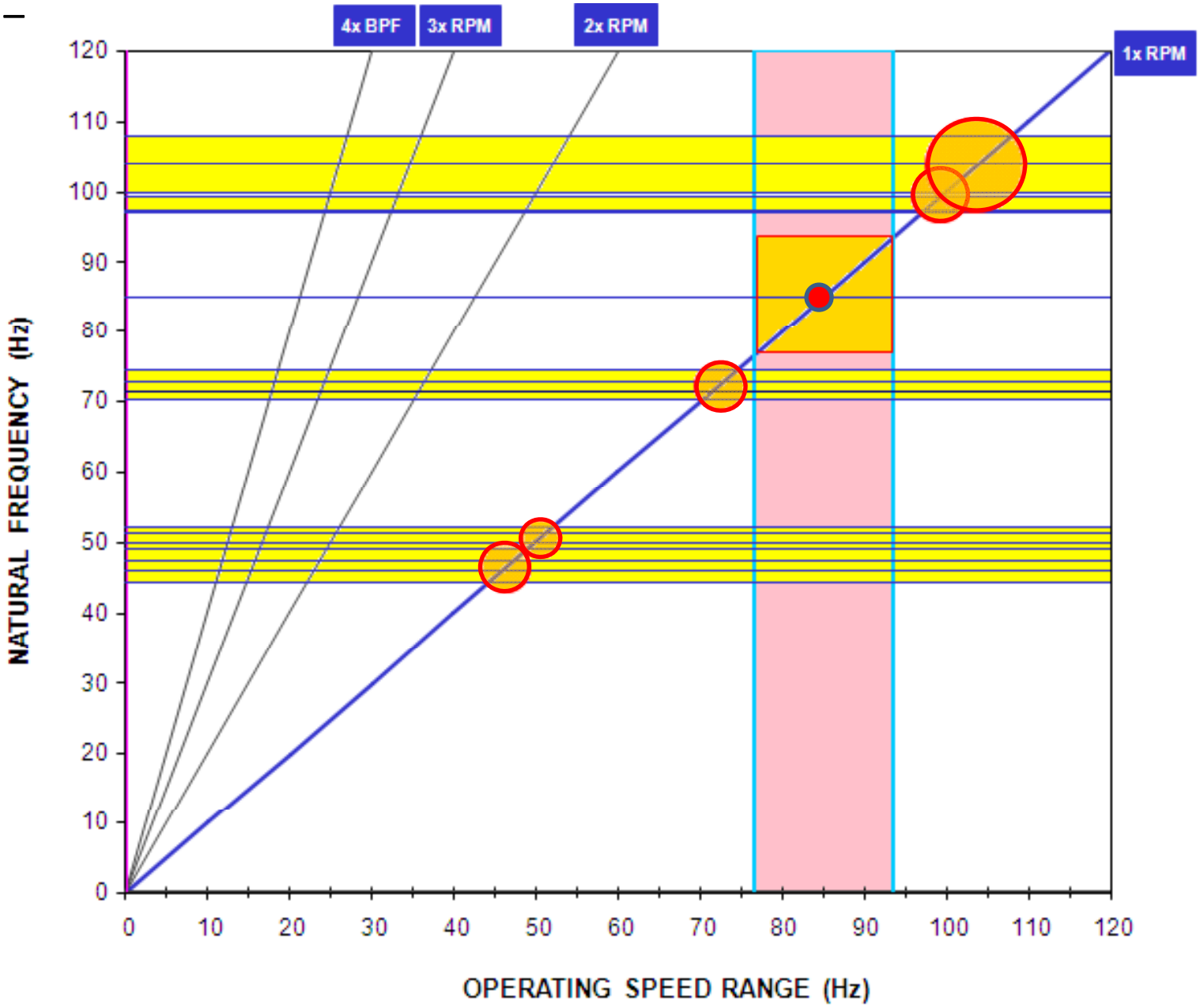


2015 EMA Analysis – Modal Frequency Variations

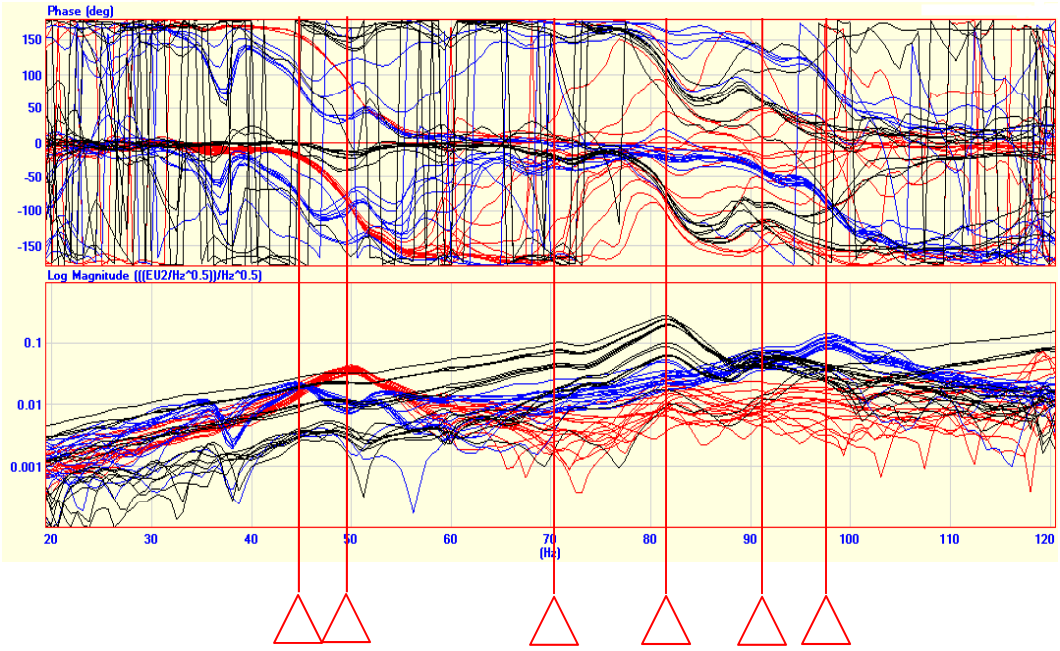
1	47.4 Hz
2	51.2 Hz
3	72.9 Hz
4	83.7 Hz
5	97.0 Hz
6	106 Hz

- Temperature
- Water Load
- Coupling
- Piping Removed
- Plating

All Modes out of resonant range except VPM

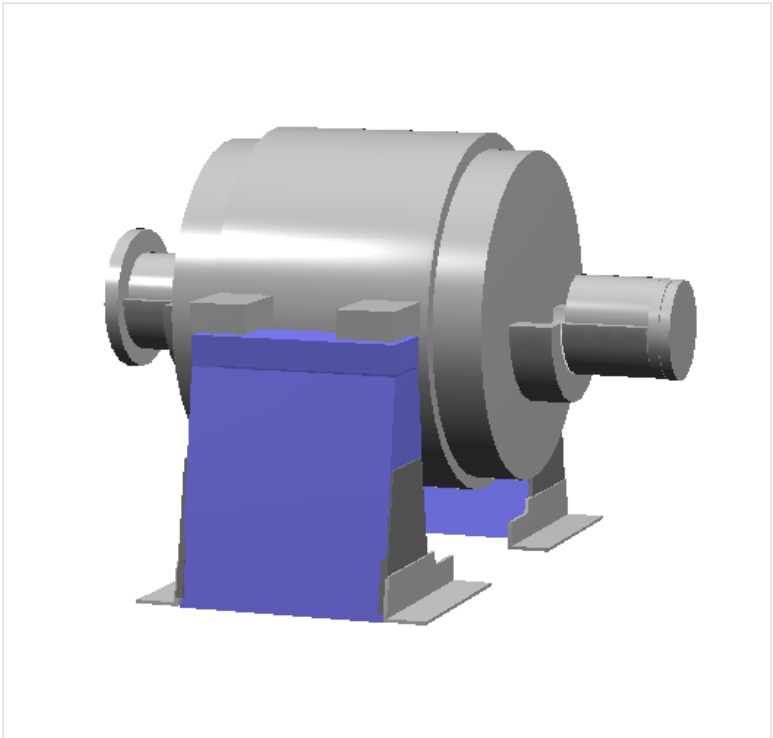


Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips



2015 EMA Analysis
Pre-Modifications

1 47.4 Hz Lateral RBM
2 51.2 Hz Axial RBM
3 72.9 Hz Vertical RBM
4 83.7 Hz Vert Pitch Mode
5 97.0 Hz Torsional Mode
6 100 Hz Torsional Mode

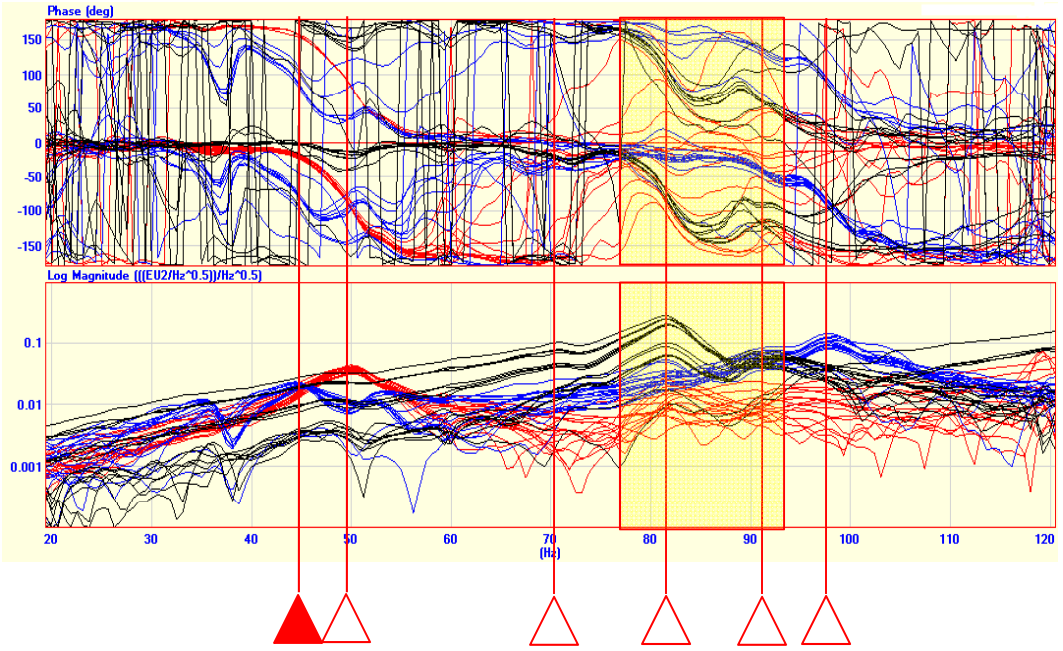


Post-Shutdown Analysis & Testing

Mode	Mode Shape	2015 EMA(1) [@ SD (hot)]	2015 EMA(2) [@ SD (cold)]	2015 EMA BL(3) [@SD Dewater]
1	Lateral RBM* (y)	46.0 Hz	46.7 Hz	**47.4 Hz**
2	Axial RBM* (x)	49.8 Hz	49.6 Hz	**51.2 Hz**
3	Vert ical RBM* (z)	71.5 Hz	71.4 Hz	**72.9 Hz**
4	**Vertical Pitch (z)**	**81.7 Hz**	**81.7 Hz**	**83.7 Hz**
5	Torsion (z)	91.4 Hz	90.6 Hz	**97.0 Hz**
6	Torsion (y, z)	97.0 Hz	97.5 Hz	**100 Hz**

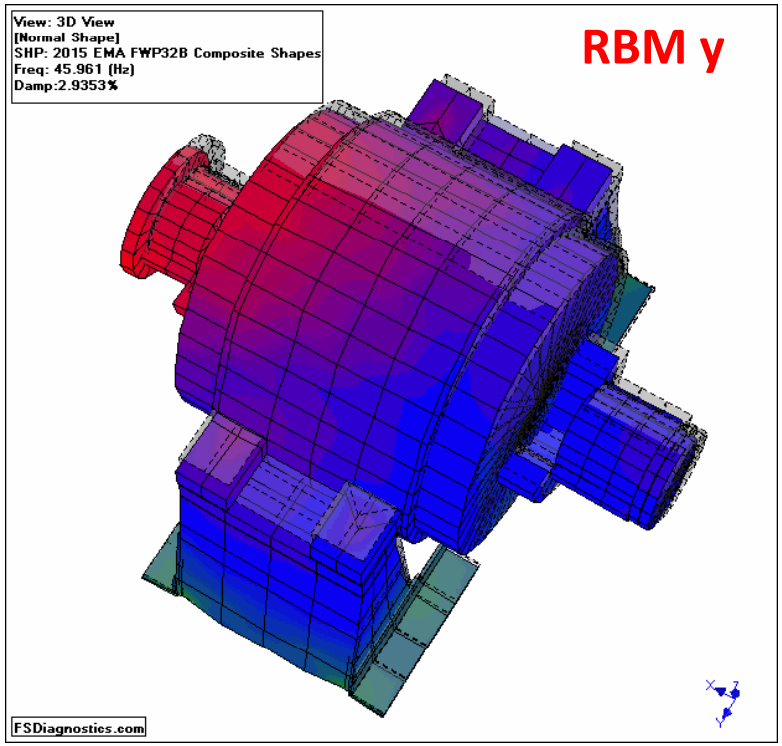
(1) EMA Test Oct 1, 2015 Conditions [Hot, Coupled, Full of Water, All Piping Attached]
(2) EMA Test Oct 2, 2015 Conditions [Cold, Coupled, Full of Water, All Piping Attached]
(3) EMA Baseline Test Oct 7, 2015 Conditions [Cold, Un-Coupled, Dewatered, Small Line Piping Removed]

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips



2015 EMA Analysis
Pre-Modifications

1 47.4 Hz Lateral RBM
2 51.2 Hz Axial RBM
3 72.9 Hz Vertical RBM
4 83.7 Hz Vert Pitch Mode
5 97.0 Hz Torsional Mode
6 100 Hz Torsional Mode



Post-Shutdown Analysis & Testing

Mode	Mode Shape	2015 EMA[1] [@ SD (hot)]	2015 EMA[2] [@ SD (cold)]	2015 EMA BL[3] [@SD Dewater]
1	Lateral RBM* (y)	46.0 Hz	46.7 Hz	47.4 Hz
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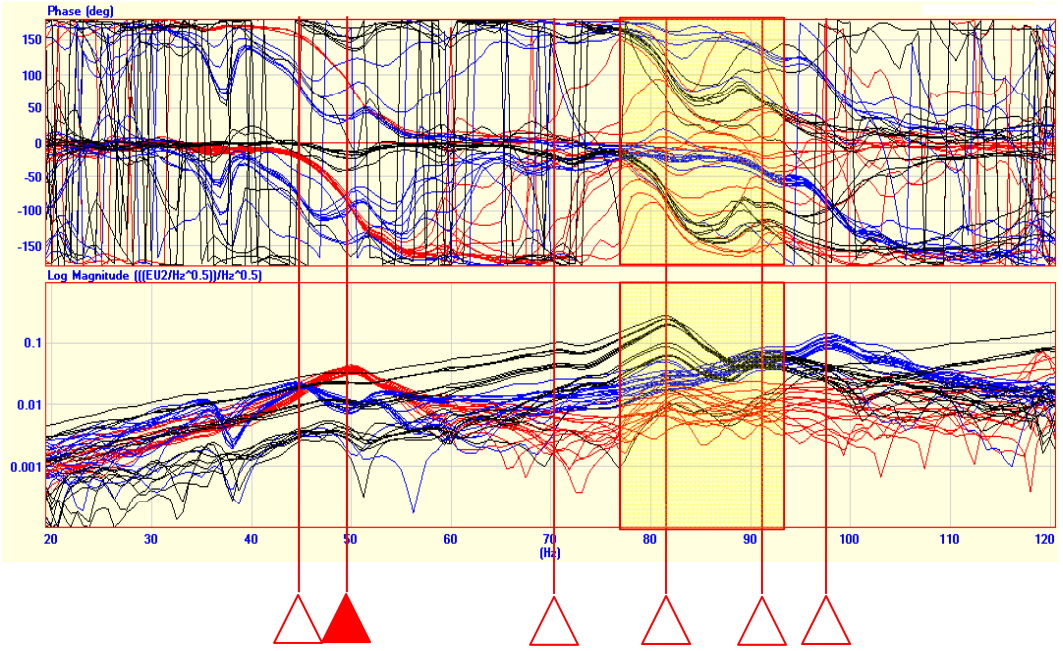
3	Vert ical RBM* (z)	71.5 Hz	71.4 Hz	72.9 Hz
4	**Vertical Pitch (z)**	**81.7 Hz**	**81.7 Hz**	**83.7 Hz**
5	Torsion (z)	91.4 Hz	90.6 Hz	97.0 Hz
6	Torsion (y, z)	97.0 Hz	97.5 Hz	100 Hz

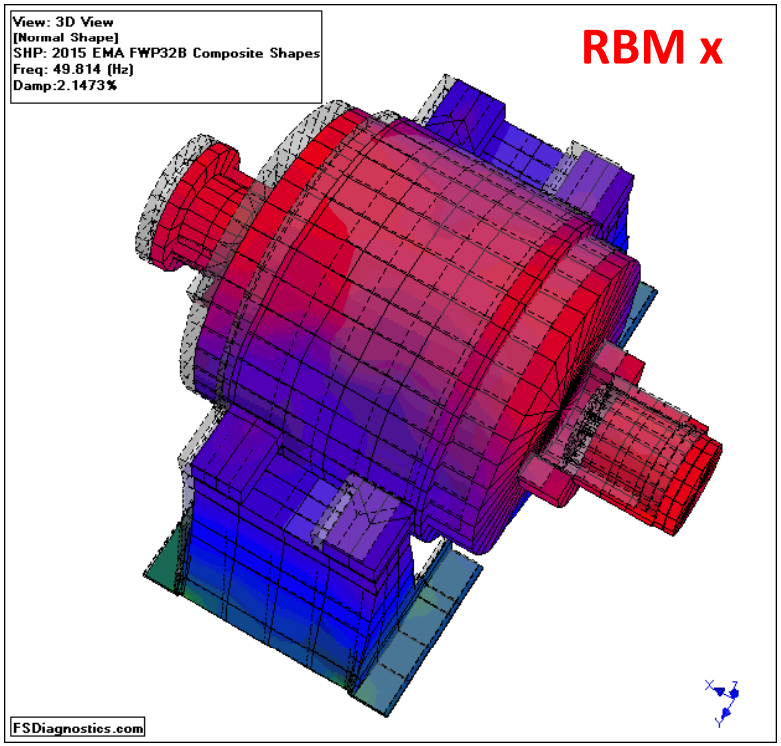
(1) EMA Test Oct 1, 2015 Conditions [Hot, Coupled, Full of Water, All Piping Attached]
(2) EMA Test Oct 2, 2015 Conditions [Cold, Coupled, Full of Water, All Piping Attached]
(3) EMA Baseline Test Oct 7, 2015 Conditions [Cold, Un-Coupled, Dewatered, Small Line Piping Removed]

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips



2015 EMA Analysis
Pre-Modifications

1 47.4 Hz Lateral RBM
2 51.2 Hz Axial RBM
3 72.9 Hz Vertical RBM
4 83.7 Hz Vert Pitch Mode
5 97.0 Hz Torsional Mode
6 100 Hz Torsional Mode



Post-Shutdown Analysis & Testing

Mode	Mode Shape	2015 EMA[1] [@ SD (hot)]	2015 EMA[2] [@ SD (cold)]	2015 EMA BL[3] [@SD Dewater]
1	Lateral RBM* (y)	46.0 Hz	46.7 Hz	47.4 Hz
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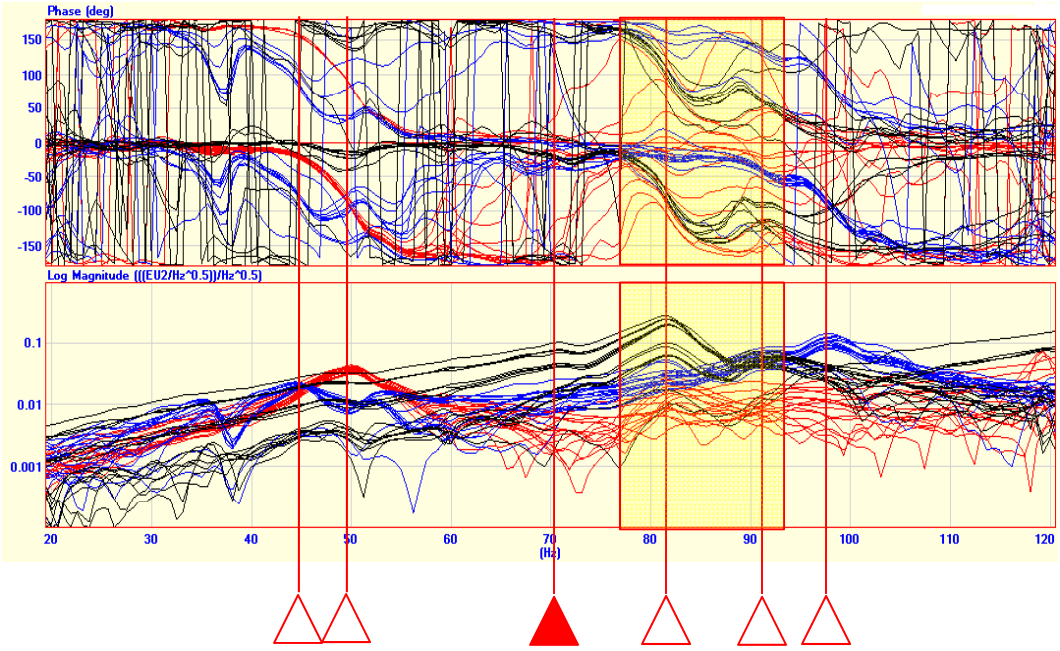
3	Vert ical RBM* (z)	71.5 Hz	71.4 Hz	72.9 Hz
4	**Vertical Pitch (z)**	**81.7 Hz**	**81.7 Hz**	**83.7 Hz**
5	Torsion (z)	91.4 Hz	90.6 Hz	97.0 Hz
6	Torsion (y, z)	97.0 Hz	97.5 Hz	100 Hz

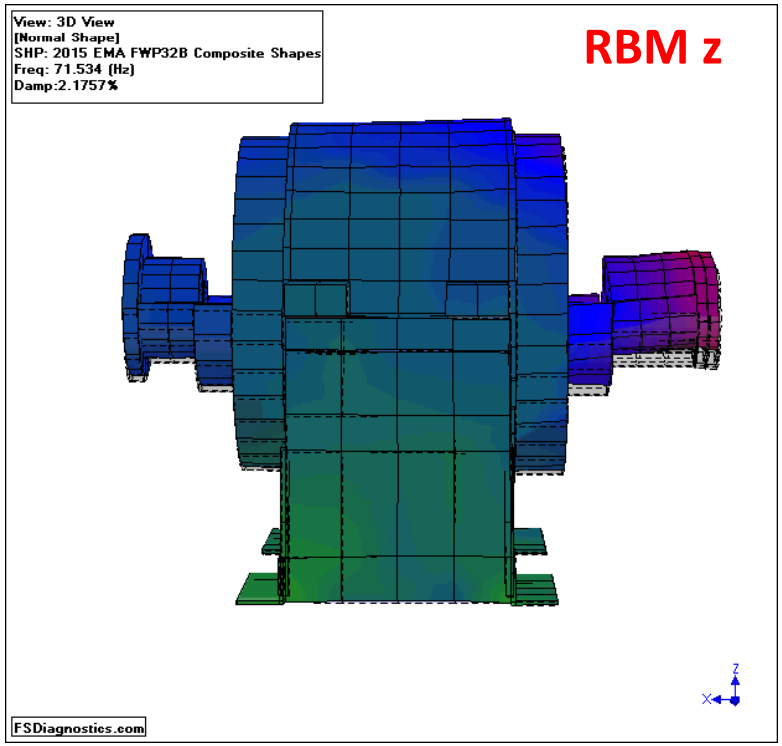
(1) EMA Test Oct 1, 2015 Conditions [Hot, Coupled, Full of Water, All Piping Attached]
(2) EMA Test Oct 2, 2015 Conditions [Cold, Coupled, Full of Water, All Piping Attached]
(3) EMA Baseline Test Oct 7, 2015 Conditions [Cold, Un-Coupled, Dewatered, Small Line Piping Removed]

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips



2015 EMA Analysis
Pre-Modifications

1 47.4 Hz Lateral RBM
2 51.2 Hz Axial RBM
3 72.9 Hz Vertical RBM
4 83.7 Hz Vert Pitch Mode
5 97.0 Hz Torsional Mode
6 100 Hz Torsional Mode

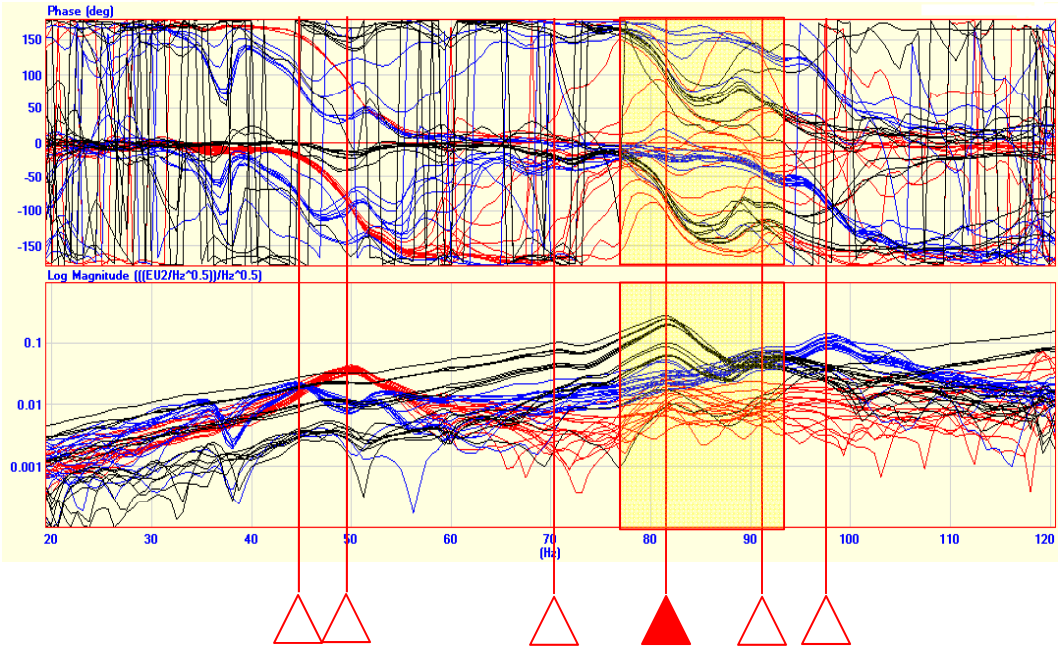


Post-Shutdown Analysis & Testing

Mode	Mode Shape	2015 EMA[1] [@ SD (hot)]	2015 EMA[2] [@ SD (cold)]	2015 EMA BL[3] [@SD Dewater]
1	Lateral RBM* (y)	46.0 Hz	46.7 Hz	**47.4 Hz**
2	Axial RBM* (x)	49.8 Hz	49.6 Hz	**51.2 Hz**
3	Vert ical RBM* (z)	71.5 Hz	71.4 Hz	**72.9 Hz**
4	**Vertical Pitch (z)**	**81.7 Hz**	**81.7 Hz**	**83.7 Hz**
5	Torsion (z)	91.4 Hz	90.6 Hz	**97.0 Hz**
6	Torsion (y, z)	97.0 Hz	97.5 Hz	**100 Hz**

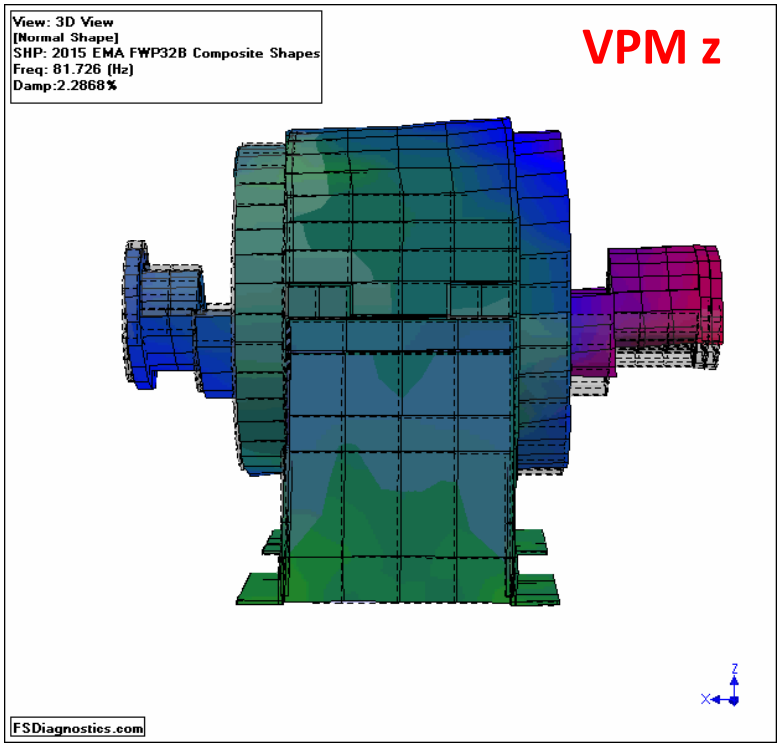
(1) EMA Test Oct 1, 2015 Conditions [Hot, Coupled, Full of Water, All Piping Attached]
(2) EMA Test Oct 2, 2015 Conditions [Cold, Coupled, Full of Water, All Piping Attached]
(3) EMA Baseline Test Oct 7, 2015 Conditions [Cold, Un-Coupled, Dewatered, Small Line Piping Removed]

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips



2015 EMA Analysis
Pre-Modifications

1 47.4 Hz Lateral RBM
2 51.2 Hz Axial RBM
3 72.9 Hz Vertical RBM
4 83.7 Hz Vert Pitch Mode
5 97.0 Hz Torsional Mode
6 100 Hz Torsional Mode



Post-Shutdown Analysis & Testing

Mode	Mode Shape	2015 EMA[1] [@ SD (hot)]	2015 EMA[2] [@ SD (cold)]	2015 EMA BL[3] [@SD Dewater]
1	Lateral RBM* (y)	46.0 Hz	46.7 Hz	47.4 Hz
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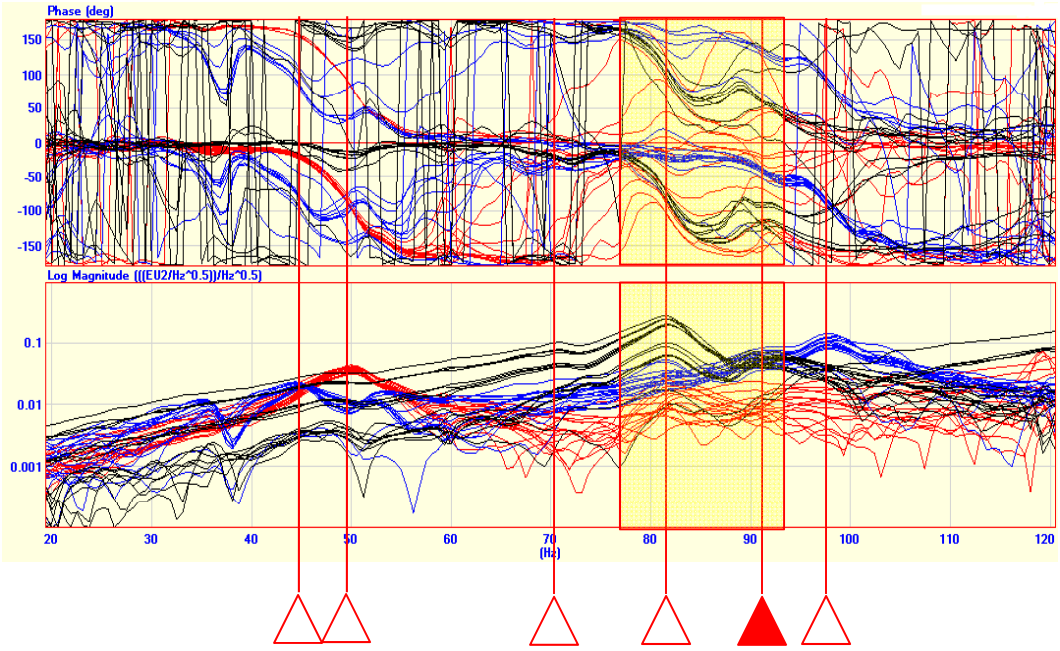
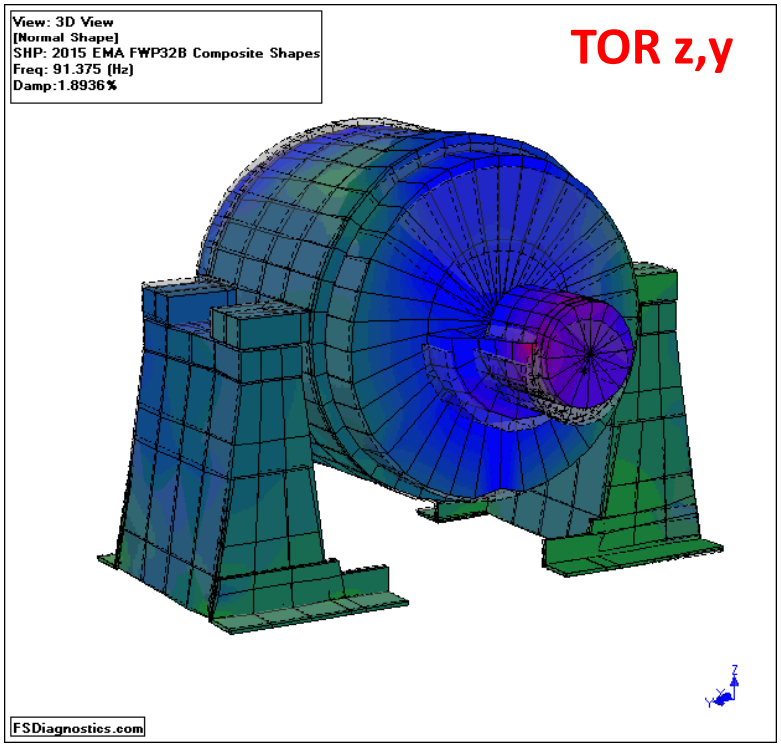
(1) EMA Test Oct 1, 2015 Conditions [Hot, Coupled, Full of Water, All Piping Attached]
(2) EMA Test Oct 2, 2015 Conditions [Cold, Coupled, Full of Water, All Piping Attached]
(3) EMA Baseline Test Oct 7, 2015 Conditions [Cold, Un-Coupled, Dewatered, Small Line Piping Removed]

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips



2015 EMA Analysis
Pre-Modifications

1 47.4 Hz Lateral RBM
2 51.2 Hz Axial RBM
3 72.9 Hz Vertical RBM
4 83.7 Hz Vert Pitch Mode
5 97.0 Hz Torsional Mode
6 100 Hz Torsional Mode



Post-Shutdown Analysis & Testing

Mode	Mode Shape	2015 EMA[1] [@ SD (hot)]	2015 EMA[2] [@ SD (cold)]	2015 EMA BL[3] [@SD Dewater]
1	Lateral RBM* (y)	46.0 Hz	46.7 Hz	47.4 Hz
2	Axial RBM* (x)	49.8 Hz	49.6 Hz	51.2 Hz
3	Vert ical RBM* (z)	71.5 Hz	71.4 Hz	72.9 Hz
4	**Vertical Pitch (z)**	**81.7 Hz**	**81.7 Hz**	**83.7 Hz**
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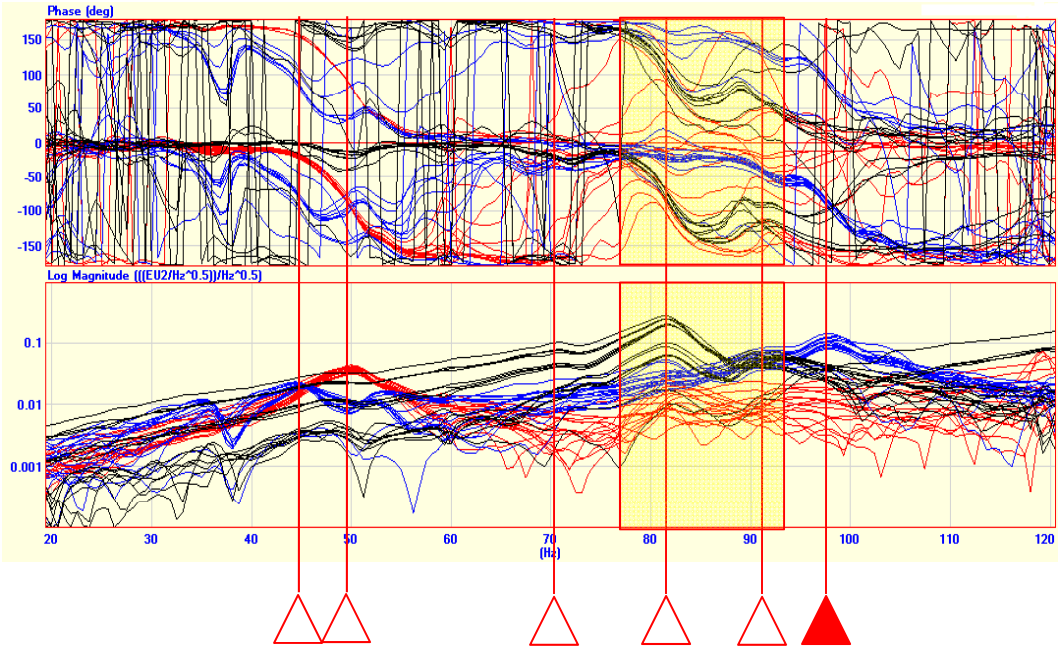
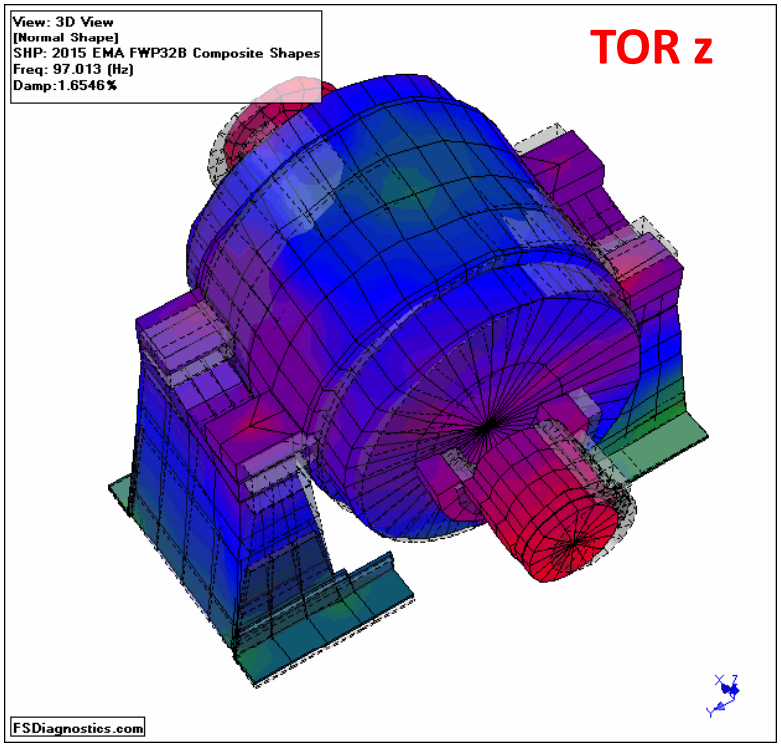
(1) EMA Test Oct 1, 2015 Conditions [Hot, Coupled, Full of Water, All Piping Attached]
(2) EMA Test Oct 2, 2015 Conditions [Cold, Coupled, Full of Water, All Piping Attached]
(3) EMA Baseline Test Oct 7, 2015 Conditions [Cold, Un-Coupled, Dewatered, Small Line Piping Removed]

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips



2015 EMA Analysis
Pre-Modifications

1 47.4 Hz Lateral RBM
2 51.2 Hz Axial RBM
3 72.9 Hz Vertical RBM
4 83.7 Hz Vert Pitch Mode
5 97.0 Hz Torsional Mode
6 100 Hz Torsional Mode

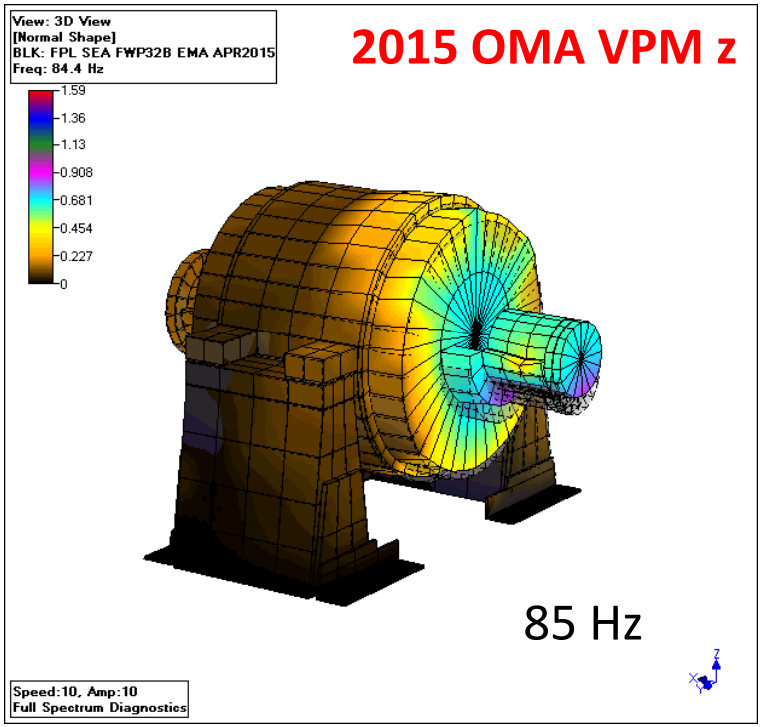


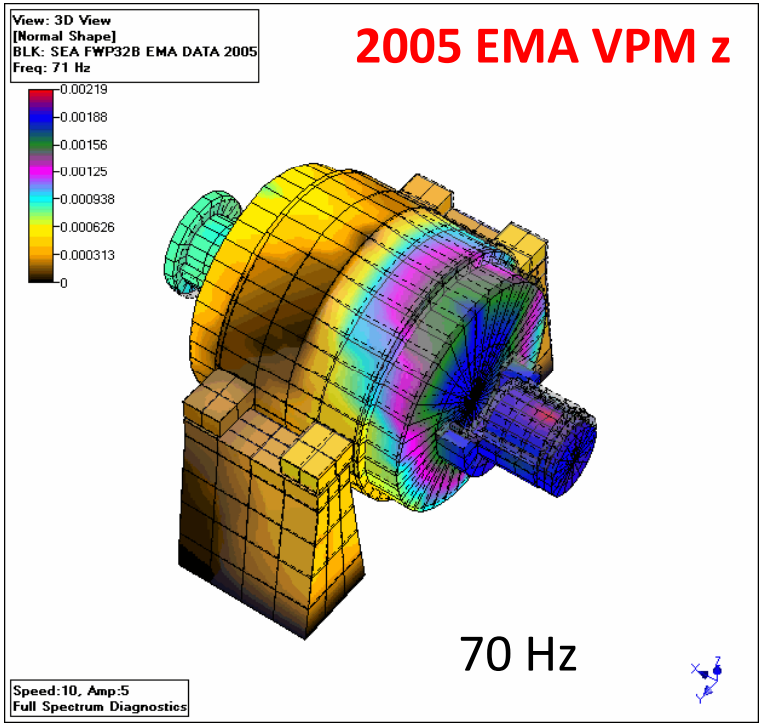
Post-Shutdown Analysis & Testing

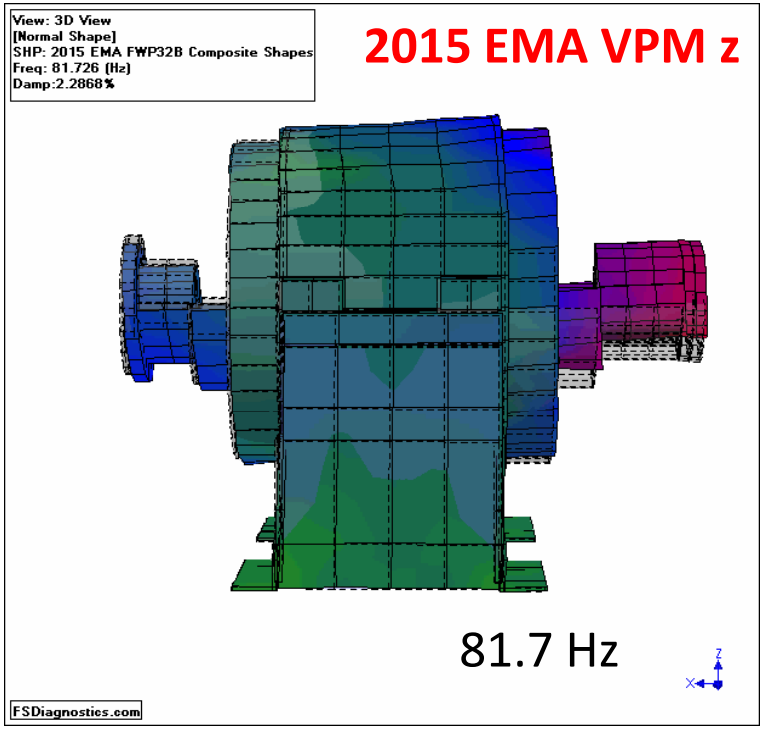
Mode	Mode Shape	2015 EMA[1] [@ SD (hot)]	2015 EMA[2] [@ SD (cold)]	2015 EMA BL[3] [@SD Dewater]
1	Lateral RBM* (y)	46.0 Hz	46.7 Hz	47.4 Hz
2	Axial RBM* (x)	49.8 Hz	49.6 Hz	51.2 Hz
3	Vert ical RBM* (z)	71.5 Hz	71.4 Hz	72.9 Hz
4	**Vertical Pitch (z)**	**81.7 Hz**	**81.7 Hz**	**83.7 Hz**
5	Torsion (z)	91.4 Hz	90.6 Hz	97.0 Hz
6	Torsion (y, z)	97.0 Hz	97.5 Hz	100 Hz

(1) EMA Test Oct 1, 2015 Conditions [Hot, Coupled, Full of Water, All Piping Attached]
(2) EMA Test Oct 2, 2015 Conditions [Cold, Coupled, Full of Water, All Piping Attached]
(3) EMA Baseline Test Oct 7, 2015 Conditions [Cold, Un-Coupled, Dewatered, Small Line Piping Removed]

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

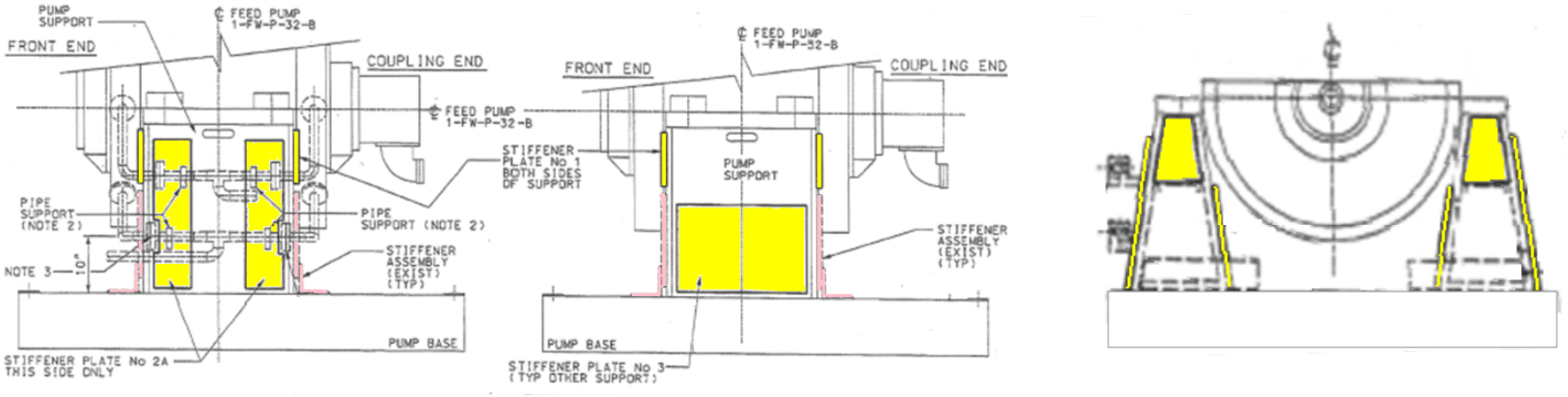






Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 STRUCTURAL MODIFICATIONS

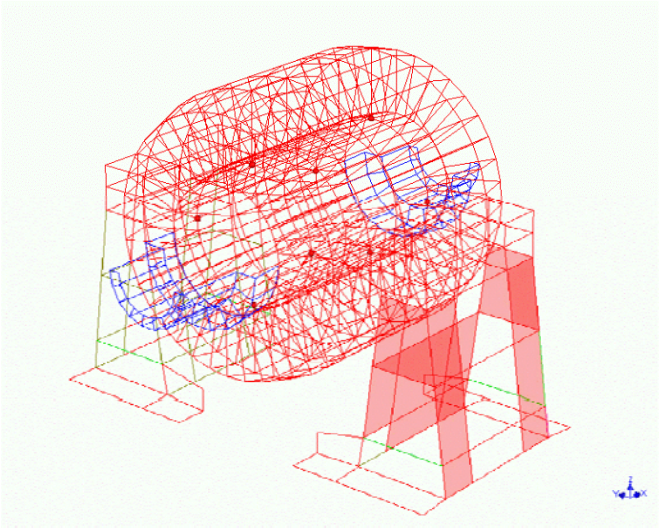


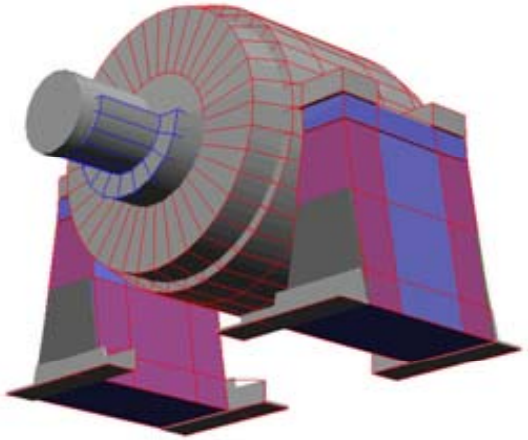
VERIFY Natural Frequencies and Mode Shapes during Maintenance Outage (OR17)

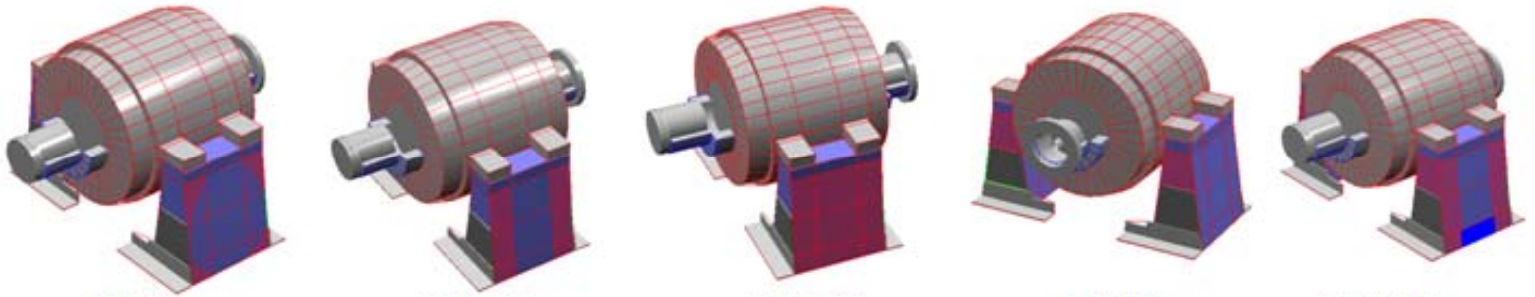
- Shutdown Experimental Modal Analysis
- Post-Modification EMA

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 STRUCTURAL MODIFICATIONS



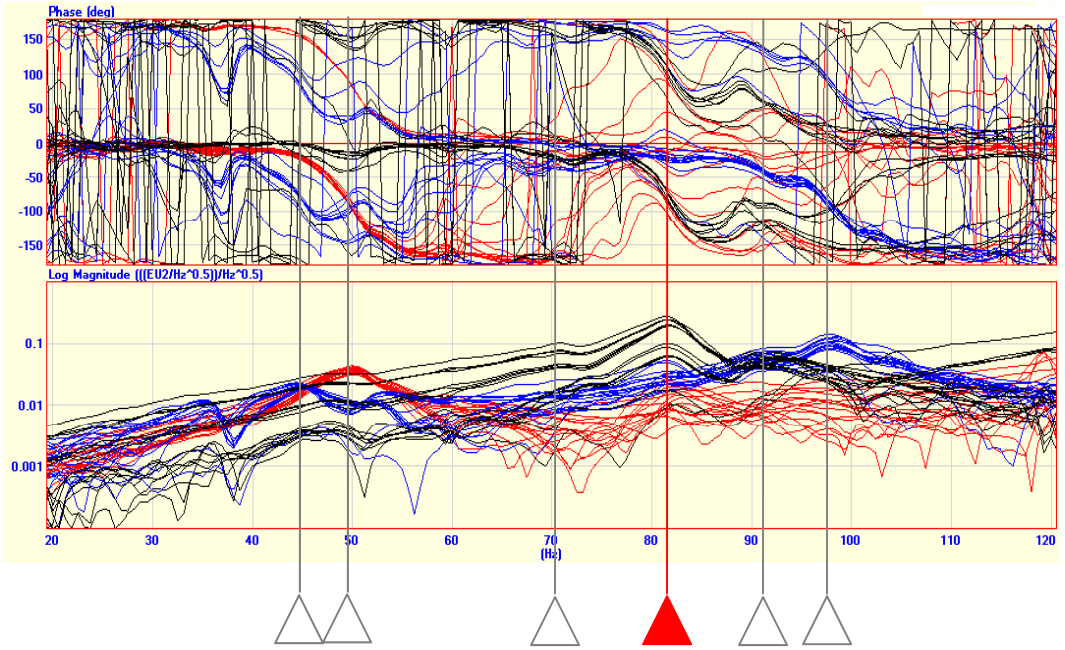




Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 EMA Analysis
Post Plating Modifications

1 49.1 Hz
2 52.1 Hz
3 74.5 Hz
4 86.9 Hz [Plating Δ 3.2 Hz]
5 97.4 Hz
6 104 Hz



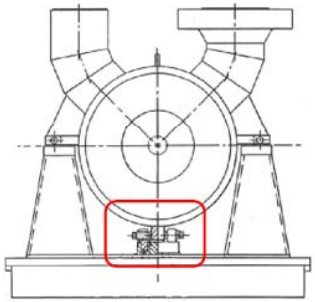
EMA Correlated FEA / SDM Plating (stiffening) Analysis

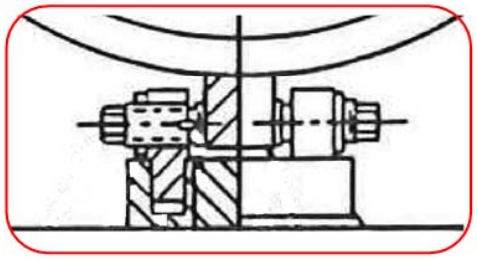
Mode	Mode Shape	SDM Plating[3] [EMA BL Projected]	2015 EMA[4] [Final Plating]
1	Lateral RBM* (y)	58.9 Hz	49.1 Hz
2	Axial RBM* (x)	74.8 Hz	52.1 Hz
3	Vertical RBM* (z)	75.3 Hz	74.5 Hz
4	**Vertical Pitch (z)**	**96.8 Hz**	**86.9 Hz**
5	Torsion (z)	92.3 Hz	97.4 Hz
6	Torsion (y, z)	113 Hz	104 Hz

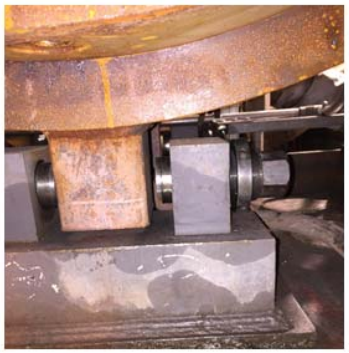
(3) SDM Plating Projection based on Baseline EMA analysis
(4) EMA Test Final Plating Complete Oct 16, 2015

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 ALIGNMENT GUIDE BARREL LUGS







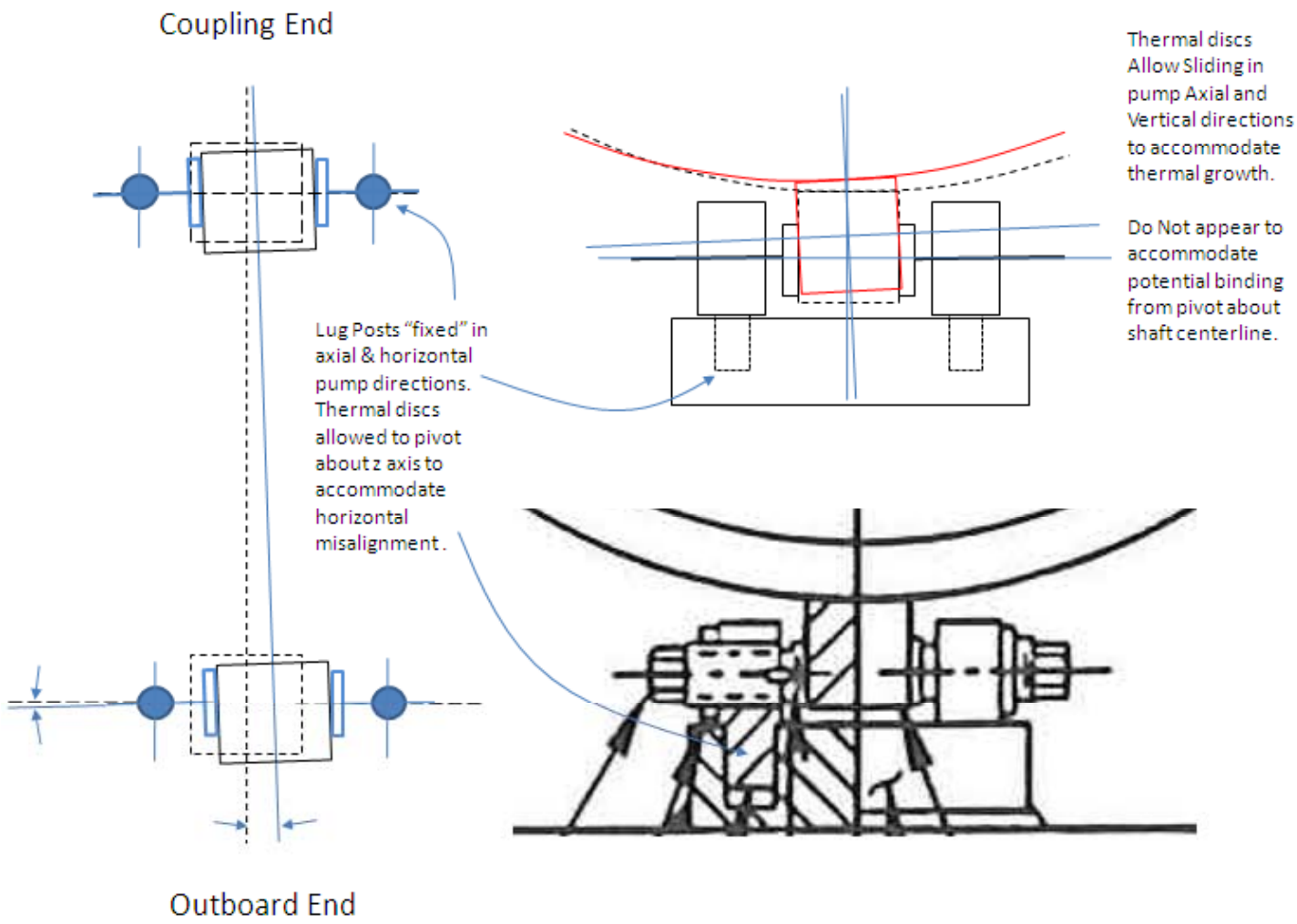
DIGGING DEEPER Searching for the Discrepancies in the Analysis vs. Data

Potential External Forces on Pump

Piping / Foundation / Alignment Guide Lugs

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

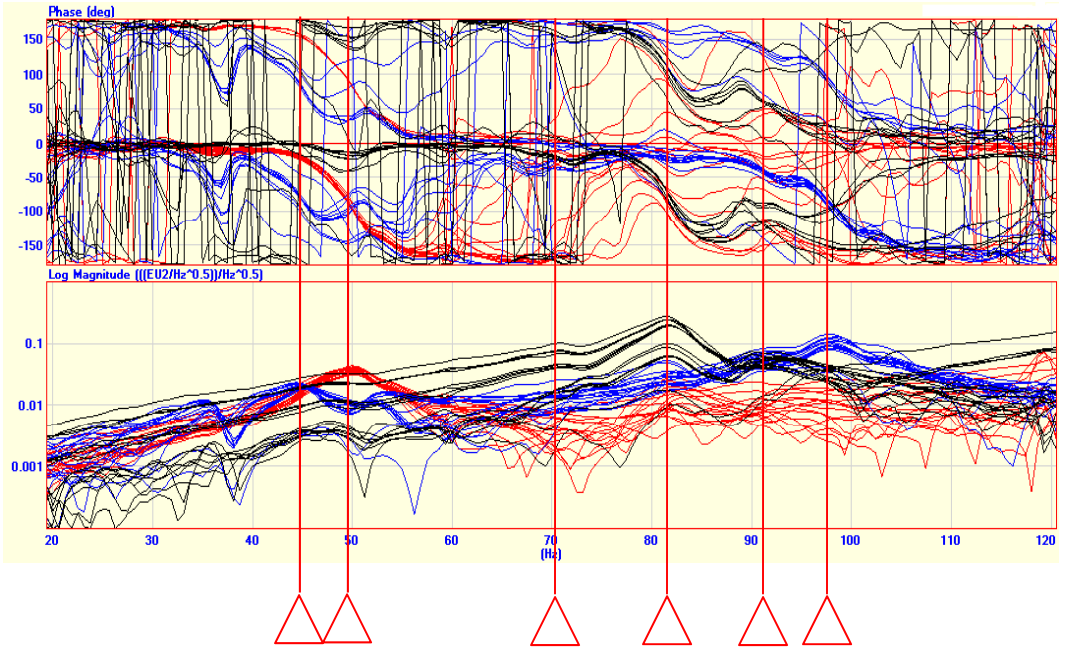
Attained Approval to "Un-Lock" the Alignment Guide Barrel Lugs



Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

2015 EMA Analysis
Post-Modifications
Lugs Released

1 44.1 Hz
2 50.6 Hz
3 70.6 Hz
4 76.8 Hz [Δf: -11.6%]
5 102 Hz
6 109 Hz



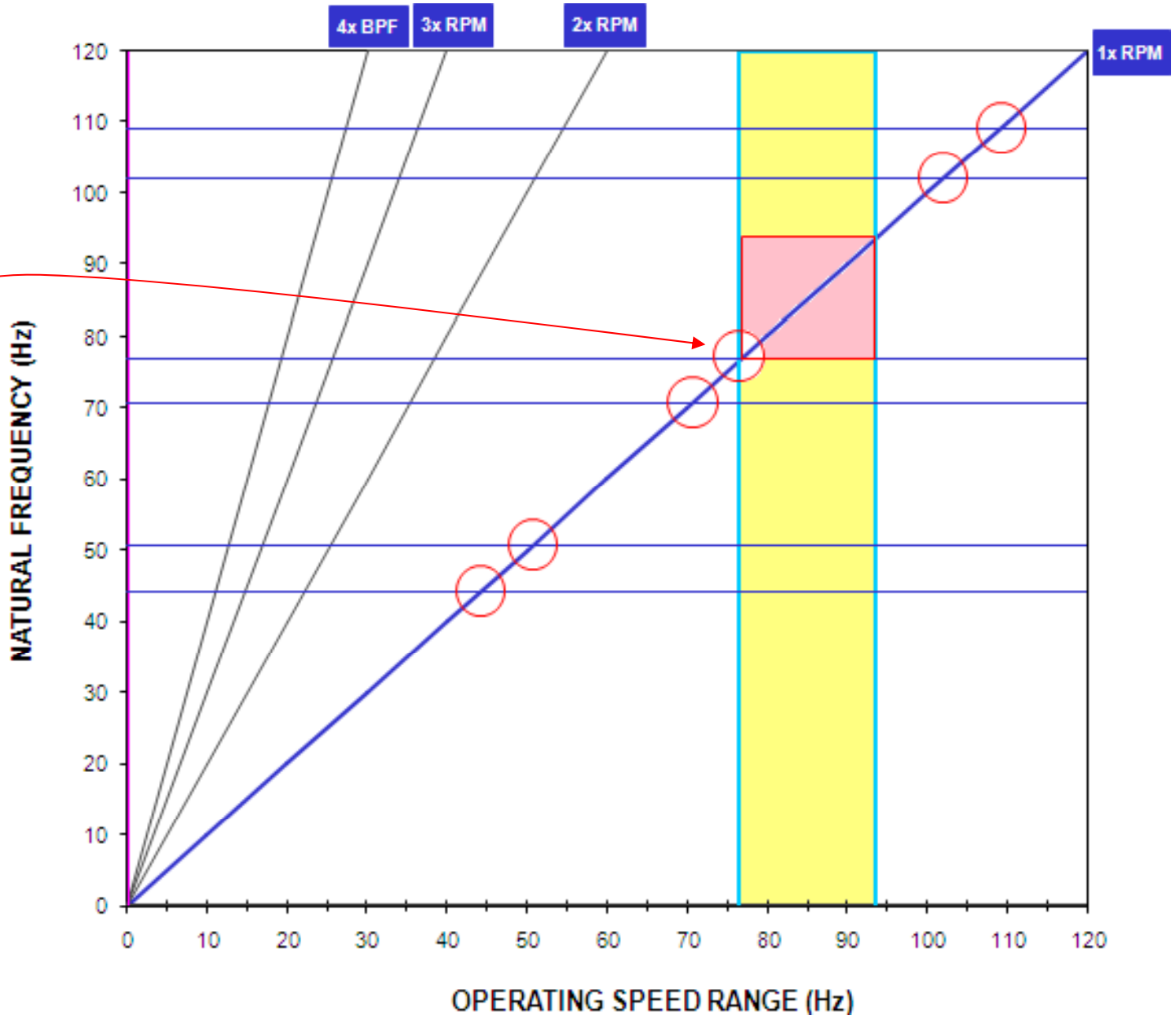
EMA Correlated FEA / SDM Plating (stiffening) Analysis

Mode	Mode Shape	SDM Plating[3] [EMA BL Projected]	2015 EMA[4] [Final Plating]	2015 EMA[5] [Lugs Released]
1	Lateral RBM* (y)	58.9 Hz	49.1 Hz	44.1 Hz
2	Axial RBM* (x)	74.8 Hz	52.1 Hz	50.6 Hz
3	Vertical RBM* (z)	75.3 Hz	74.5 Hz	70.6 Hz
4	**Vertical Pitch (z)**	**96.8 Hz**	**86.9 Hz**	**76.8 Hz**
5	Torsion (z)	92.3 Hz	97.4 Hz	102 Hz
6	Torsion (y, z)	113 Hz	104 Hz	109 Hz

(3) SDM Plating Projection based on Baseline EMA analysis [Cold, Uncoupled, Dewatered
(4) EMA Test Final Plating Complete Oct 16, 2015
(5) EMA Test Final Plating Complete, Alignment Guide Lugs Released Oct 18, 2015.

2015 EMA
Analysis – Plated
Lugs Relaxed

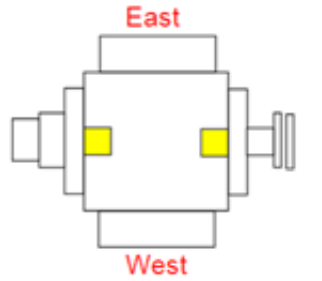
1	44.1 Hz
2	50.6 Hz
3	70.6 Hz
4	**76.8 Hz**
5	102 Hz
6	109 Hz

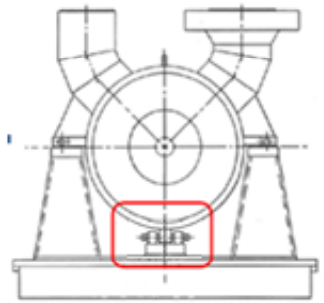


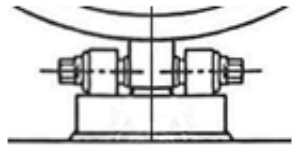
Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

Pump Alignment Centering Lug Sensitivity Testing

Test Case	Load[1] Configuration	Natural Frequency	Shift Frequency	Alignment[2] Effect	Matrix Load Diagram
0	Unloaded	77.7 Hz		0.0000	
1	SE Lug	84.1 Hz	+6.40 Hz	0.0007 W	
2	SE/NE Lugs	89.2 Hz	+11.5 Hz	0.0010 W	
3	NW/SE Lugs	89.5 Hz	+11.8 Hz	0.0007 W	
4	NW Lug	81.6 Hz	+3.90 Hz	0.0000	
5	NW/SW Lug	89.4 Hz	+11.7 Hz	0.0004 E	
6	SW Lug	82.0 Hz	+4.30 Hz	0.0004 E	
7	NE/SW Lugs	89.1 Hz	+11.4 Hz	0.0000	
8	NE Lug	81.4 Hz	+3.70 Hz	0.0003 W	
9	Unloaded	77.9 Hz	+0.20 Hz	0.0000	
10	All Hand Tight	80.0 Hz	+2.30 Hz	0.0000	





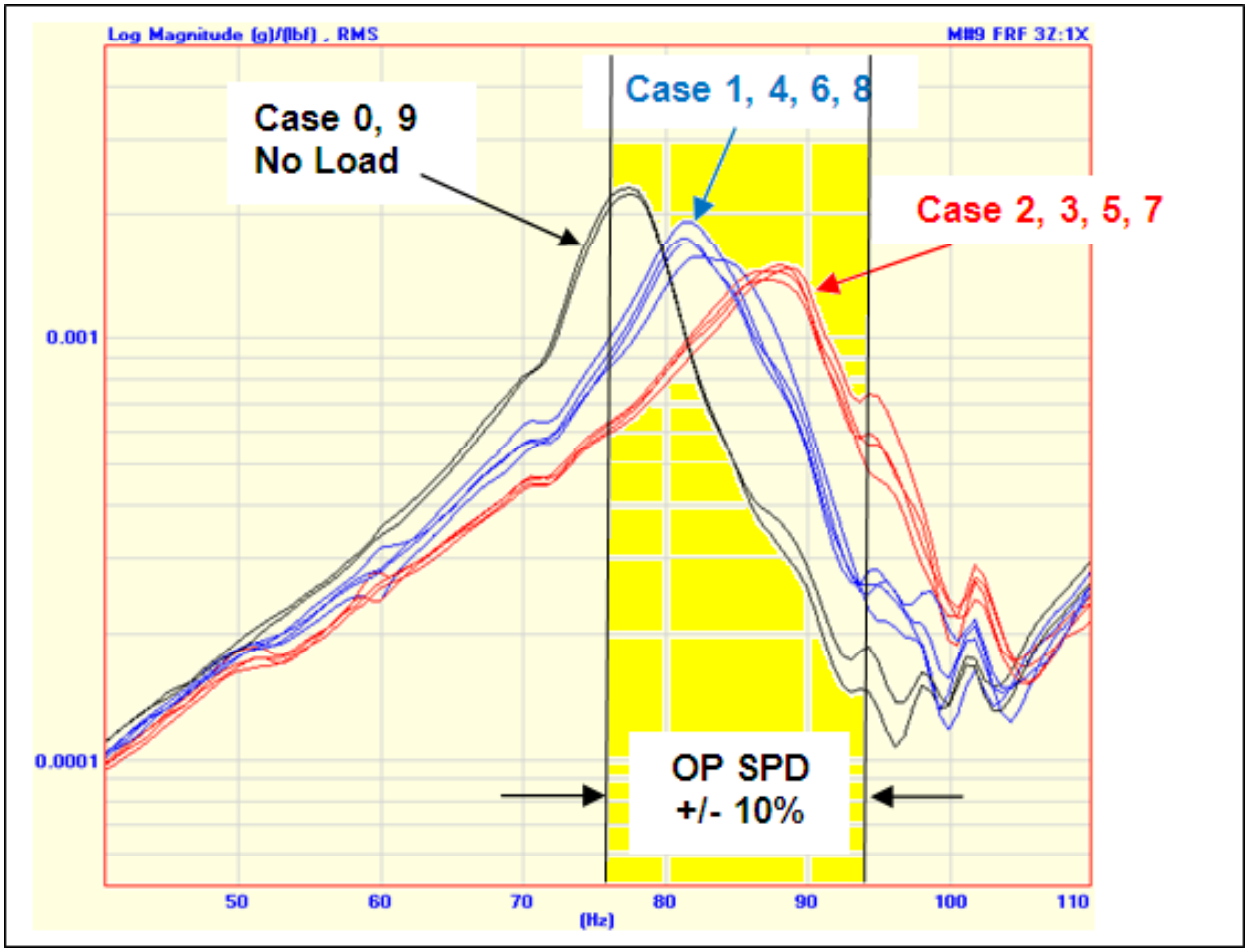


(1) All Loadings were Hand Tight + 1 Flat Engagement
(2) Alignment was monitored Real Time. Dimensions are inches

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

Sensitivity Testing proved that the Lug Loading induced a significant change in the response of the Vertical Pitching Mode (VPM_Z).

Testing indicated that the VPM_Z natural frequency was potentially “tunable”.



Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

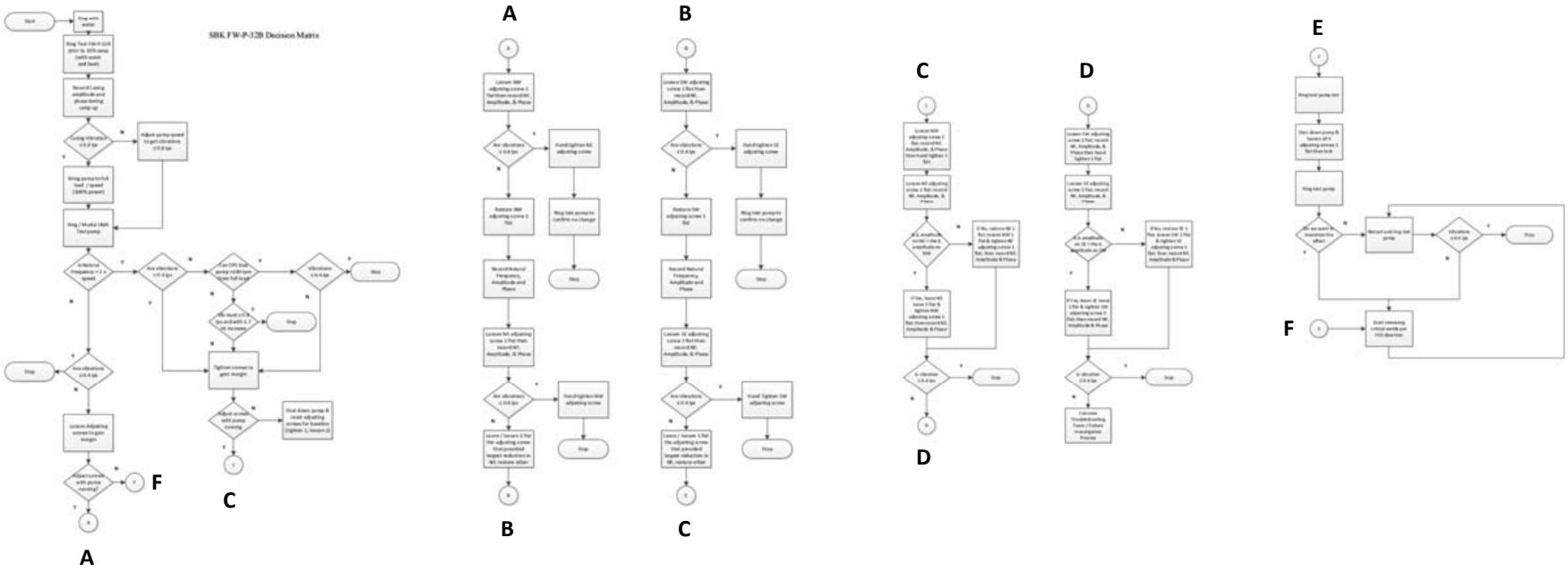
2015 UNIT START-UP

PERFORM Start-up Operating Modal Analysis (OMA) on FW-P-32B

Monitor Natural Frequencies, Mode Shapes

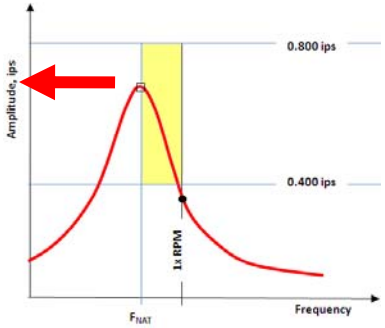
Verify Modification Results

Added Potential "Tuning" Decision Matrix



Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

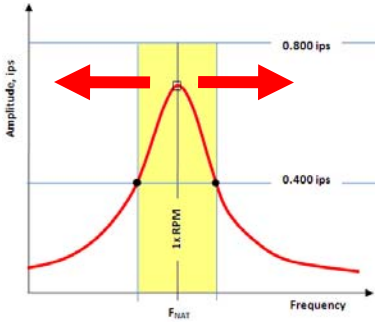
Decision Matrix Summary



Natural Frequency Below 1x RPM

Response Exceeds Limits

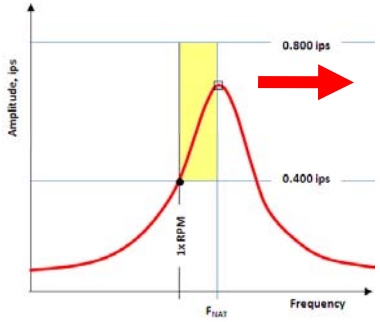
Unload Lugs to Reduce Stiffness / Attain Margin



Natural Frequency @ 1x RPM

Response Exceeds Limits

Load or Unload Lugs as required to Attain Margin



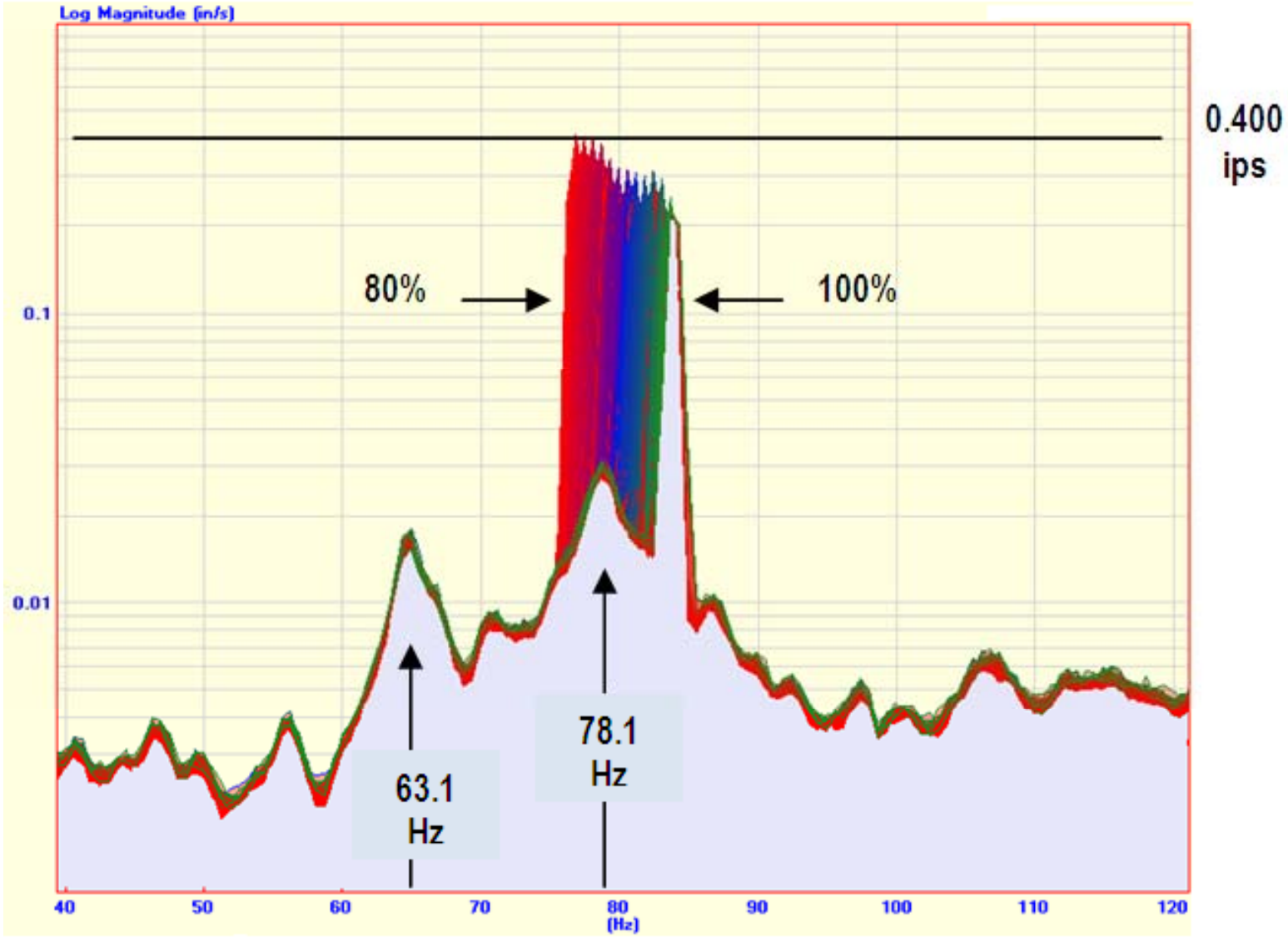
Natural Frequency Above 1x RPM

Response Exceeds Limits

Load Lugs to Increase Stiffness / Attain Margin

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

100% Power – Acceptable Response
60% Reduction in Vertical Vibration @ Outboard Bearing

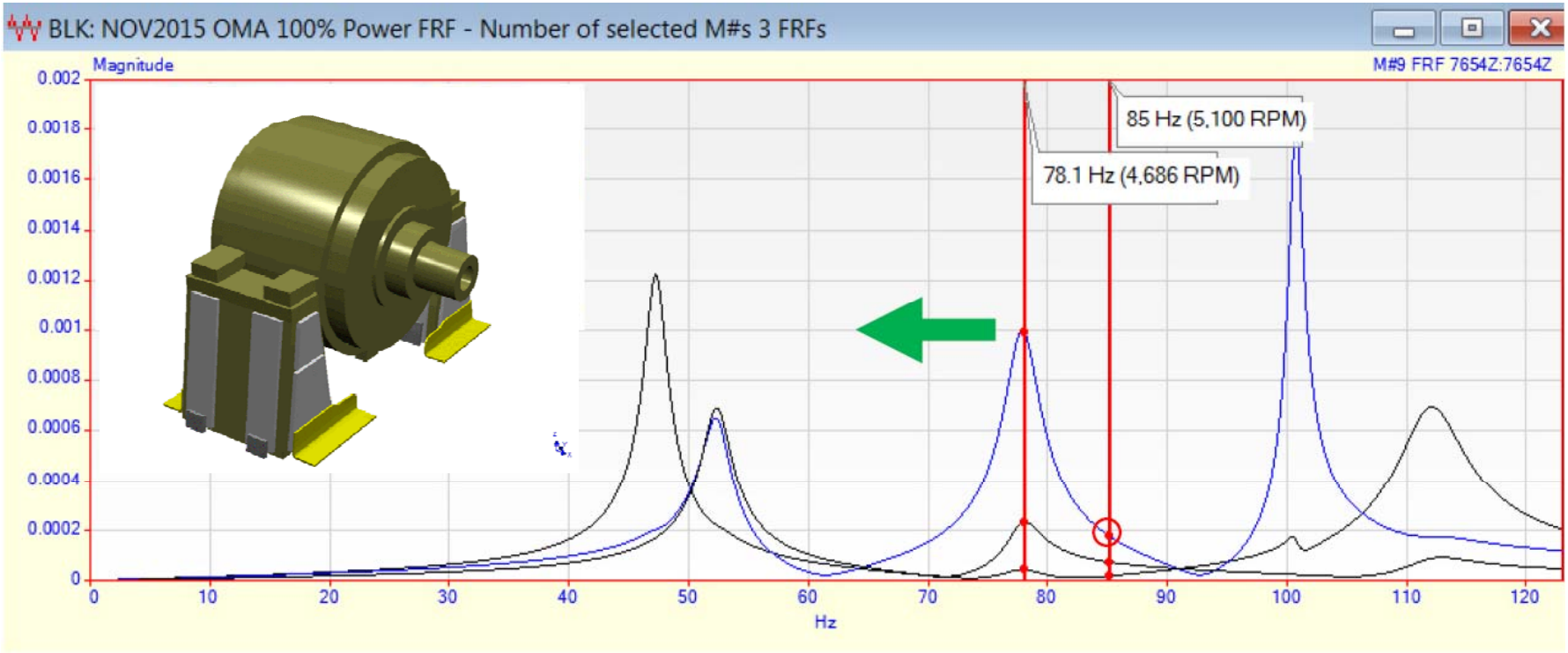


Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

DATE	CONDITION	NAT FREQ	AMPL FACTOR	
15APR15	100% OMA (Impulse)	5,118	**0.700 ips**	
15APR15	100% OMA (Non-Impulse)	5,100	**0.700 ips**	
01OCT15	S/D Hot EMA	81.7 Hz	Q = 21.4	
02OCT15	S/D Cold EMA	81.7 Hz	Q = 21.4	
07OCT15	S/D Cold, Uncap, Dwater	83.7 Hz	Q = 20.1	Damping Increase Due to Plating
16OCT15	S/D Plating Complete	86.9 Hz	Q = 17.7	
18OCT15	S/D AG Lugs Relaxed	76.8 Hz	Q = 24.0	
07NOV15	S/D Lug Sens (0,9)	77.5 Hz	Q = 17.1	Damping Lugs Disengaged
07NOV15	S/D Lug Sens (2,3,5,7)	82.4 Hz	Q = 10.9	
07NOV15	S/D Lug Sens (1,4,6,8)	87.9 Hz	Q = 11.5	
08NOV15	S/D Final Alignment	80.0 Hz	Q = 13.9	Damping Lugs “Hand Tight”
15NOV15	S/D Filler w/Water	78.0 Hz	***	

DATE	CONDITION	1x RPM	AMP (ips)
16NOV15	Start 80.0% Power	4,536	0.278 ips
17NOV15	Start 89.7% Power	4,730	0.380 ips
17NOV15	Start 91.7% Power	4,779	0.310 ips
17NOV15	Start 92.2% Power	4,827	0.270 ips
17NOV15	Start 93.7% Power	4,867	0.280 ips
17NOV15	Start 93.7% Power	4,870	0.290 ips
17NOV15	Start 93.7% Power	4,866	0.280 ips
17NOV15	Start 93.9% Power	4,870	0.280 ips
17NOV15	Start 100% Power	5,037	**0.225 ips**

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

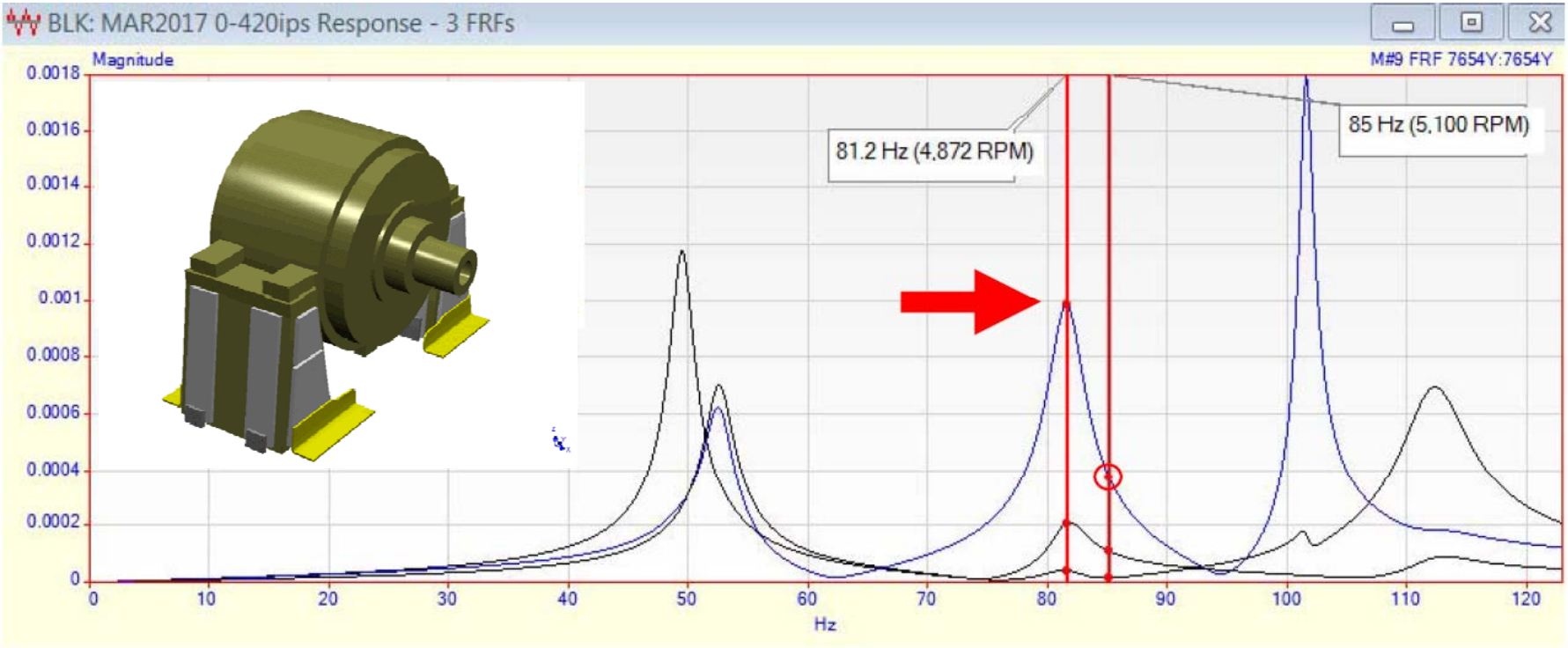


November 2015 Startup 100% Power (8.1% Resonance Margin)

Natural Frequency: 78.1 Hz (4,686 CPM)
Operating Speed: 85.0 Hz (5,100 RPM)

1x RPM Amplitude at 85 Hz: 0.225 ips
Resonance Margin: 8.1%

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips

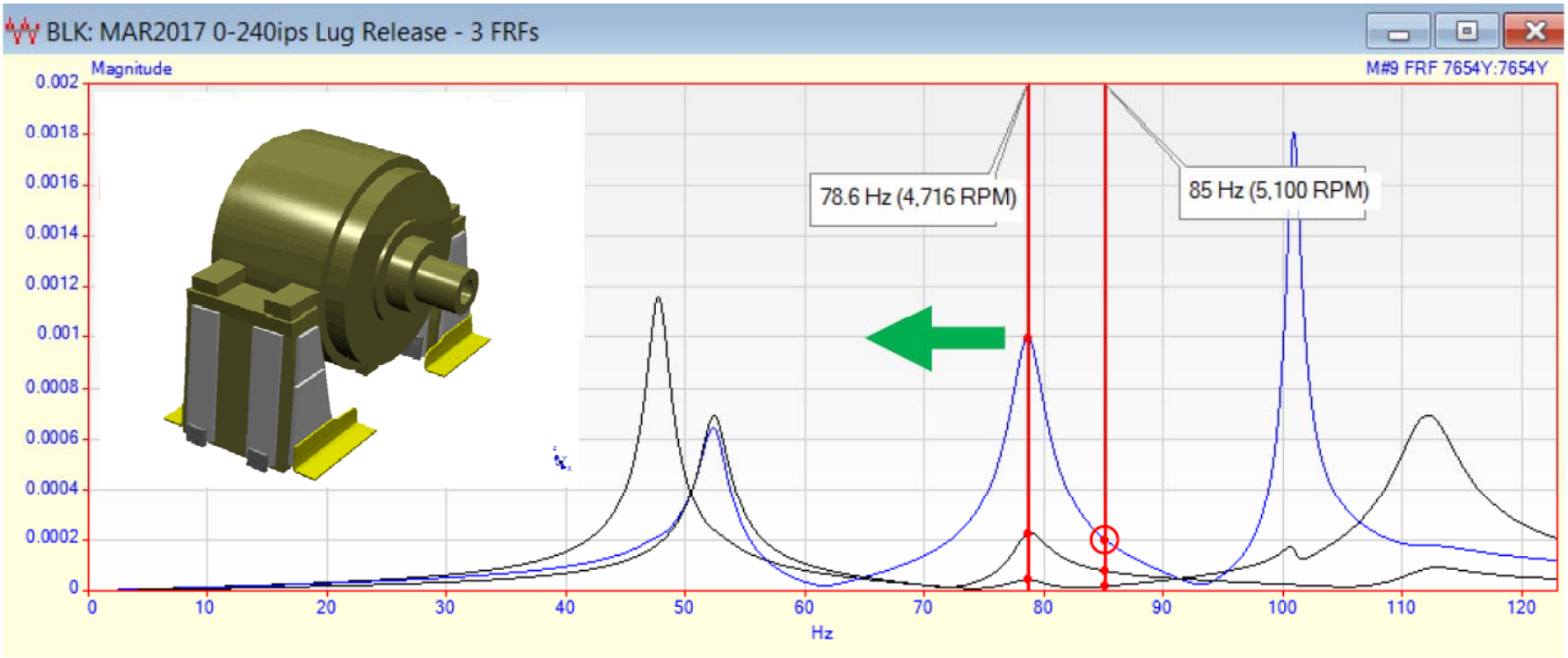


March 2017 Operating @ 100% Power (0.420 ips) (4.5% Resonance Margin)

Natural Frequency: 81.2 Hz (4,872 CPM)
Operating Speed: 85.0 Hz (5,100 RPM)

1x RPM Amplitude at 85 Hz: 0.420 ips
Resonance Margin: 4.5%

Machine Class: Feed Water Pump (Nuclear)
Rotating Speed: 5100 RPM
Overall Alarm: 0.400 ips



March 2017 100% Pwr Lugs Released (0.240 ips) (7.5% Resonance Margin)

Natural Frequency: 78.6 Hz (4,716 CPM)
Operating Speed: 85.0 Hz (5,100 RPM)

1x RPM Amplitude at 85 Hz: 0.240 ips
Resonance Margin: 7.5%

Vibrant Technology's ME'scope

- Operating Deflection Shape (ODS) Analysis
- Experimental Modal Analysis (EMA)
- Operating Modal Analysis (OMA)
- Structural Dynamic Modification (SDM)
- Finite Element Analysis (FEA)
- FRF Synthesis