Analysis of New Centrifugal Pump Installation Exhibiting Excessive Vibration

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Background

- **New Installation, Three 500 HP Pumps, Direct Coupled, Variable Frequency Drive; Waste Disposal System.**
- **Route Vibration data identified excessive vibration. Vibration varied with speed. Resonance was suspected.**

Background

- **Motor & Pump Mounted on Fabricated Skid.**
- **Skid Bolted & Epoxy Grouted To Concrete Base.**
- **Skid filled with grout.**
- **Project received to investigate root cause of excessive vibration and make recommendations for correction.**

Analysis Process

- **Review of Drawings, Vibration Data, Other Available Information.**
- **Visual Inspection of the Site and Equipment.**
- **Acquire Route type Vibration Data.**
- **Acquire Transient Vibration Data on multiple channels During Speed Changes.**
- **Develop Model of Pump in ME’scopeVES.**
- **Acquire Data for Operating Deflection Shape & Analysis Motion.**
- **Perform Experimental Impact Modal Test & Analyze Test Data.**
- **Develop Recommendations for Resolution of Problem.**
- **Corrections Implemented.**

Visual Inspection of Equipment

Fabricated Motor Pedestal: 1” Plate Welded to 16” wide flange beams.

The Vertical center plate was welded to the Wide Flange beams.

Visual Inspection of Equipment

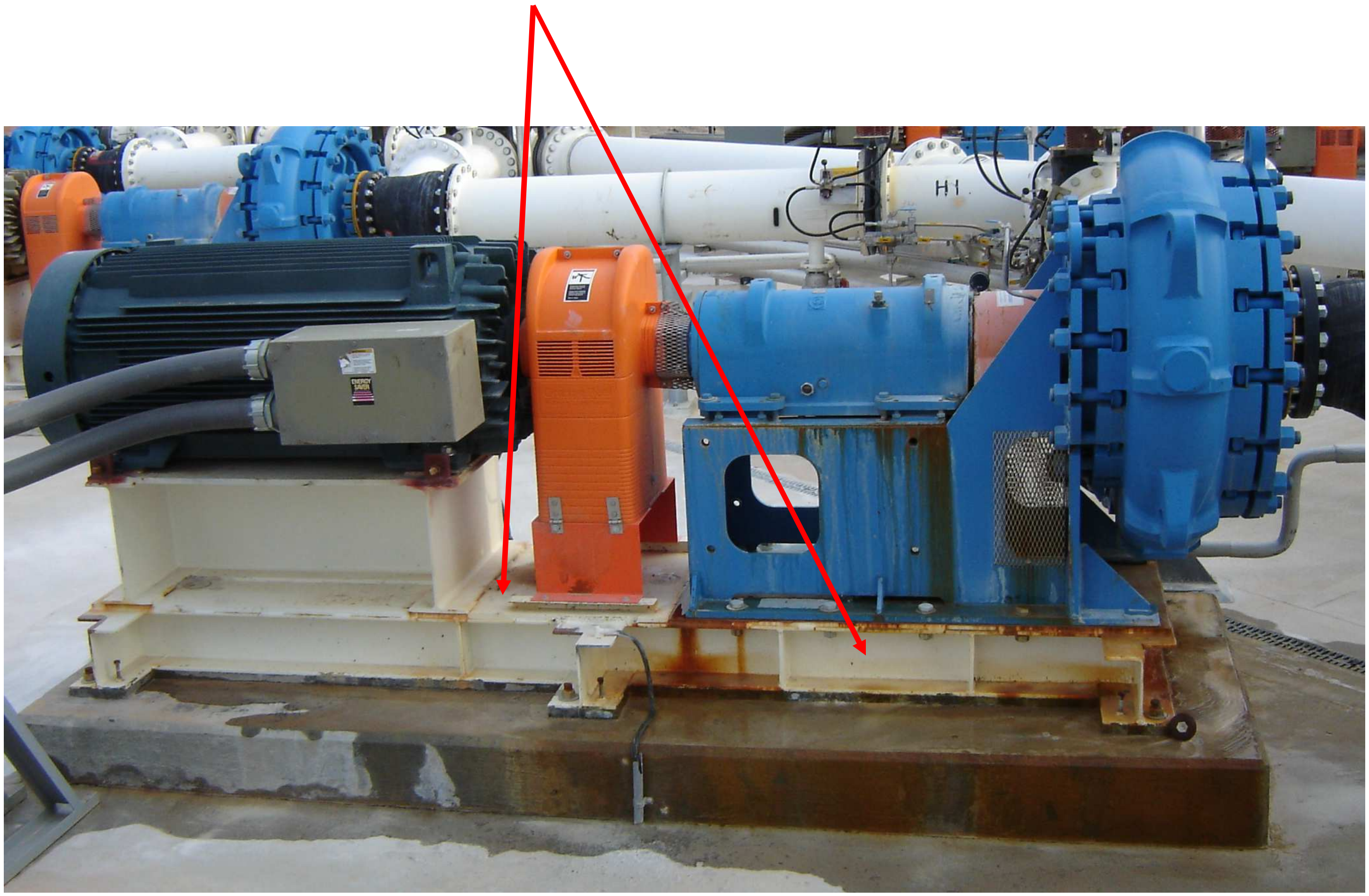
Pump Bearing Housing - One piece cast housing.

Visual Inspection of Equipment

Fabricated Pump Base is bolted to the skid

Visual Inspection of Equipment

The Skid Base is fabricated of 6” Channel, with wide flange beams and ½” top plate.



Visual Inspection of Equipment

Skid Epoxy Grouted to the Concrete Base.

Six anchor bolts fastened the skid to the concrete base.

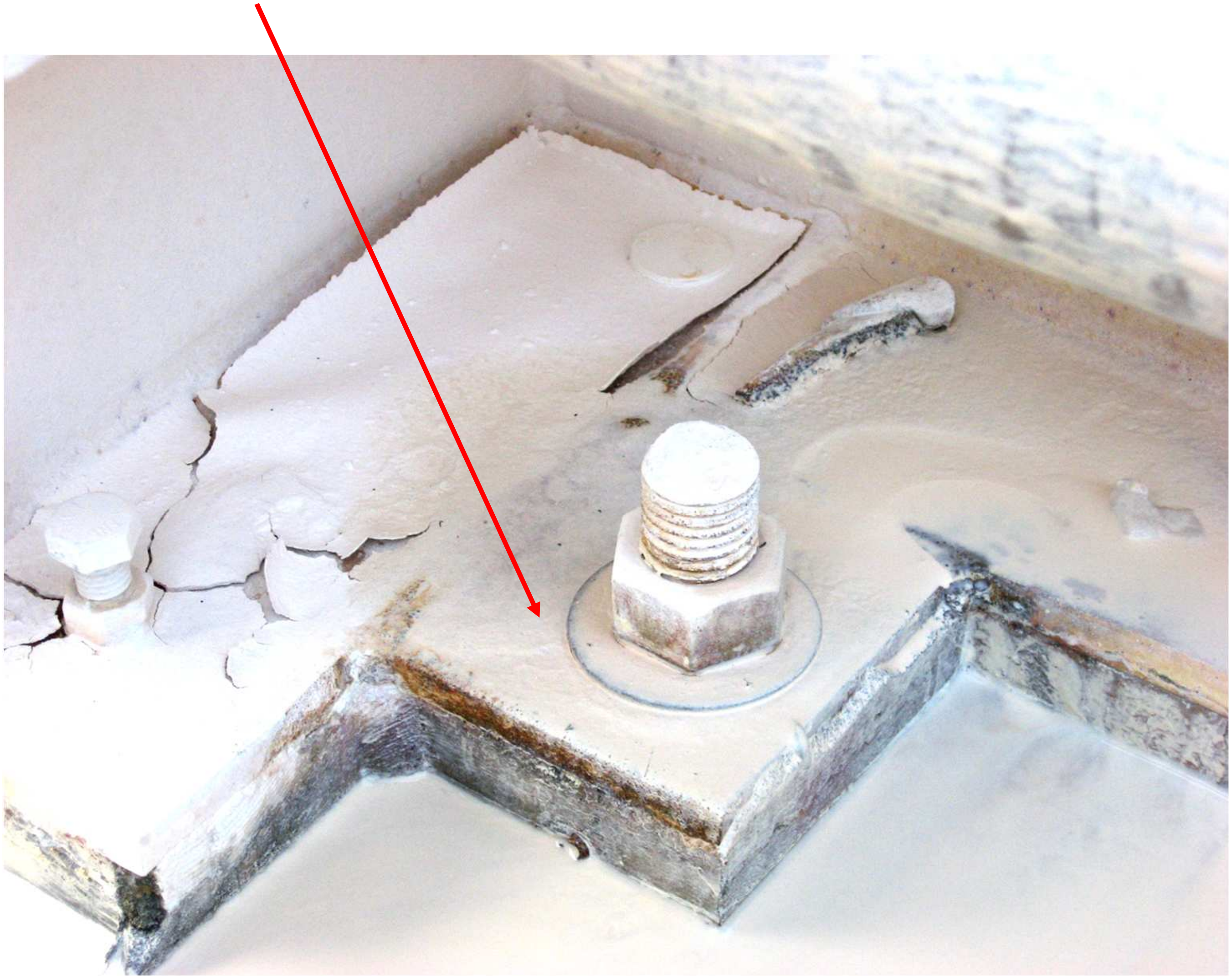
Leveling Jack Bolts beside each anchor bolt.

Visual Inspection of Equipment

Per the drawings, the Concrete Base was 1 foot deep.

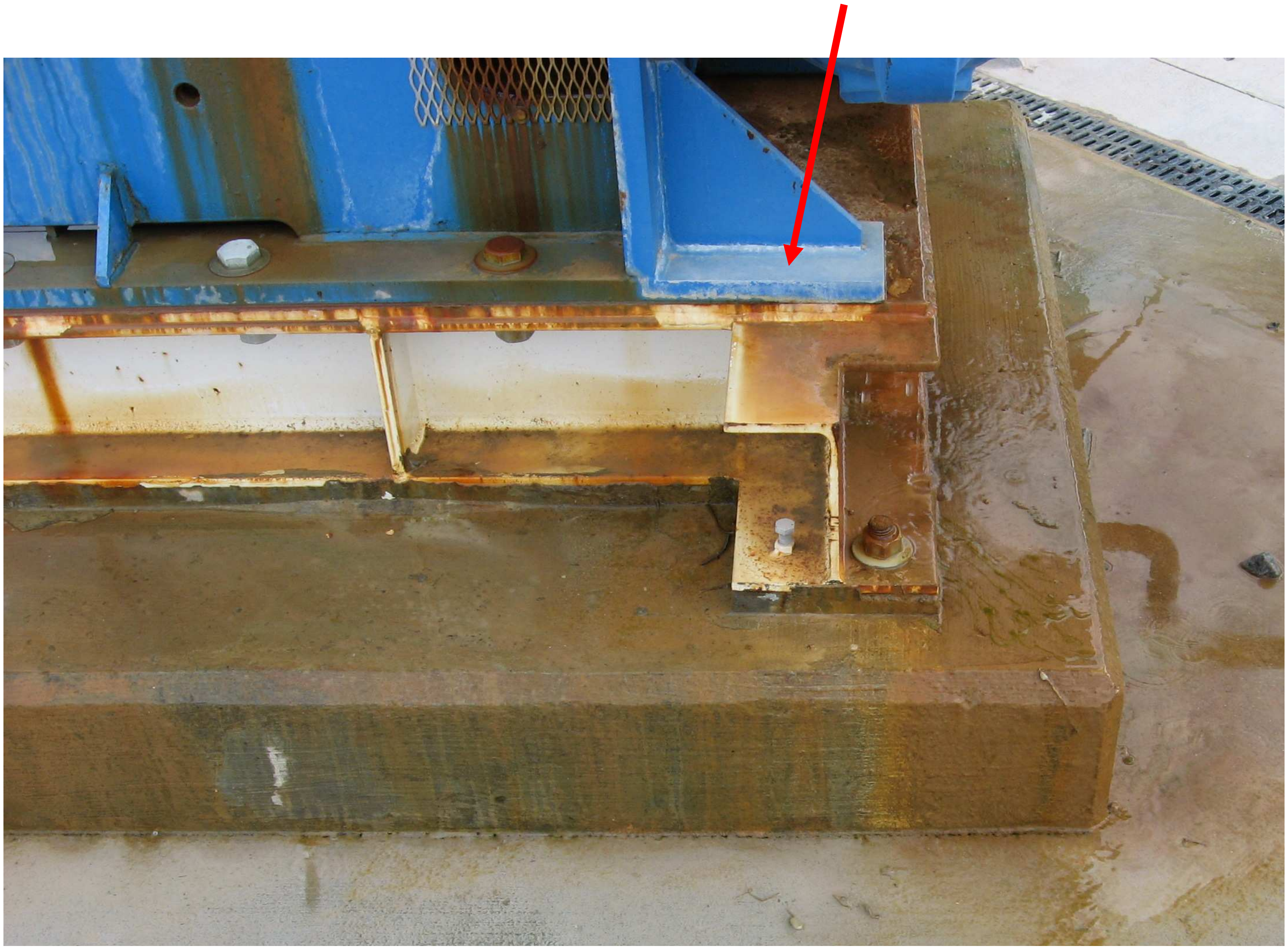
Visual Inspection of Equipment

Plate Welded to Skid at the Pump End For Anchor Bolt.



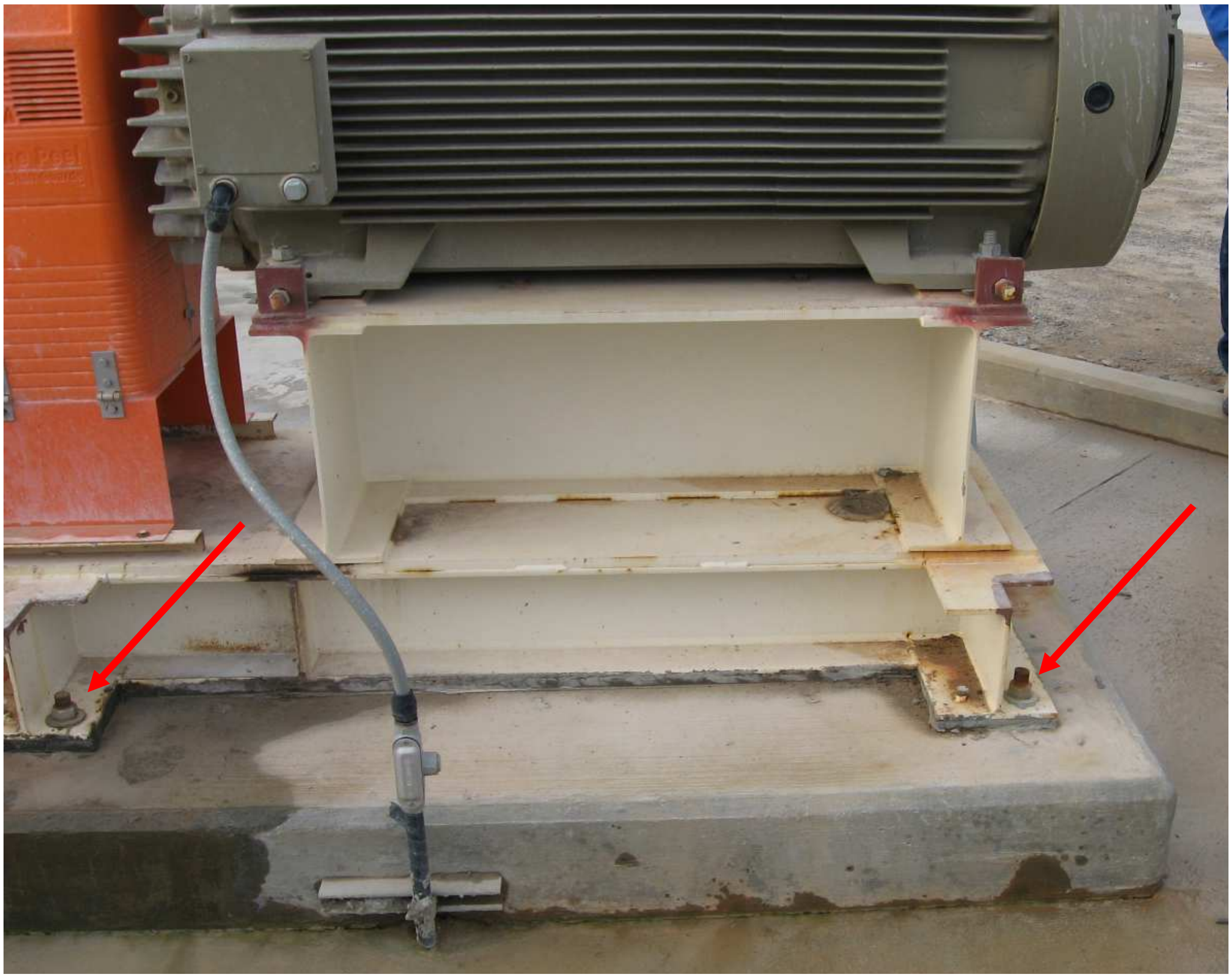
Visual Inspection of Equipment

No Hold Down Bolt At End of Pump Base For Attaching Base to The Skid.



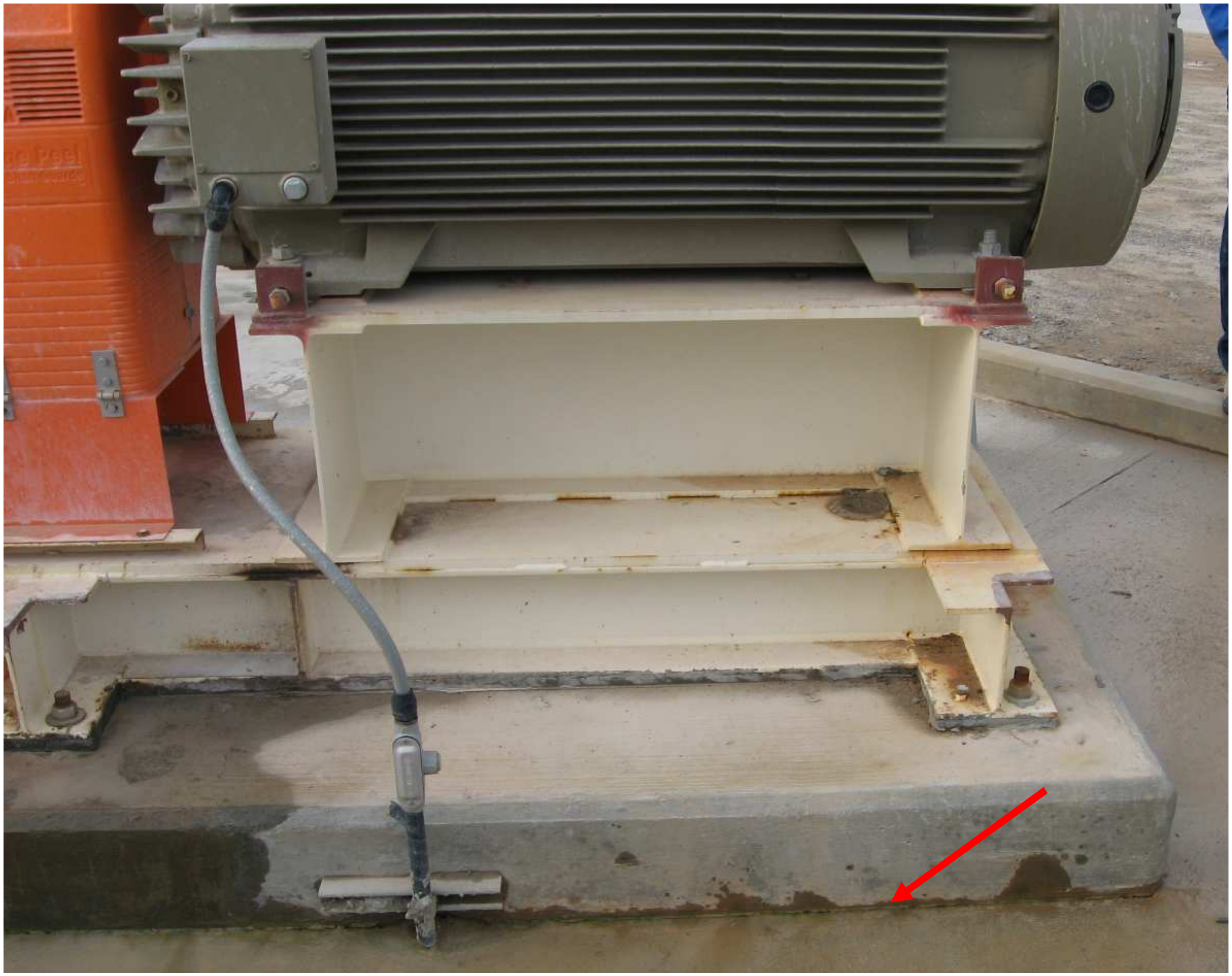
Visual Inspection of Equipment

Wide Flange Beam Skid Extensions Used For Anchor Bolt Hold Downs were very flexible.



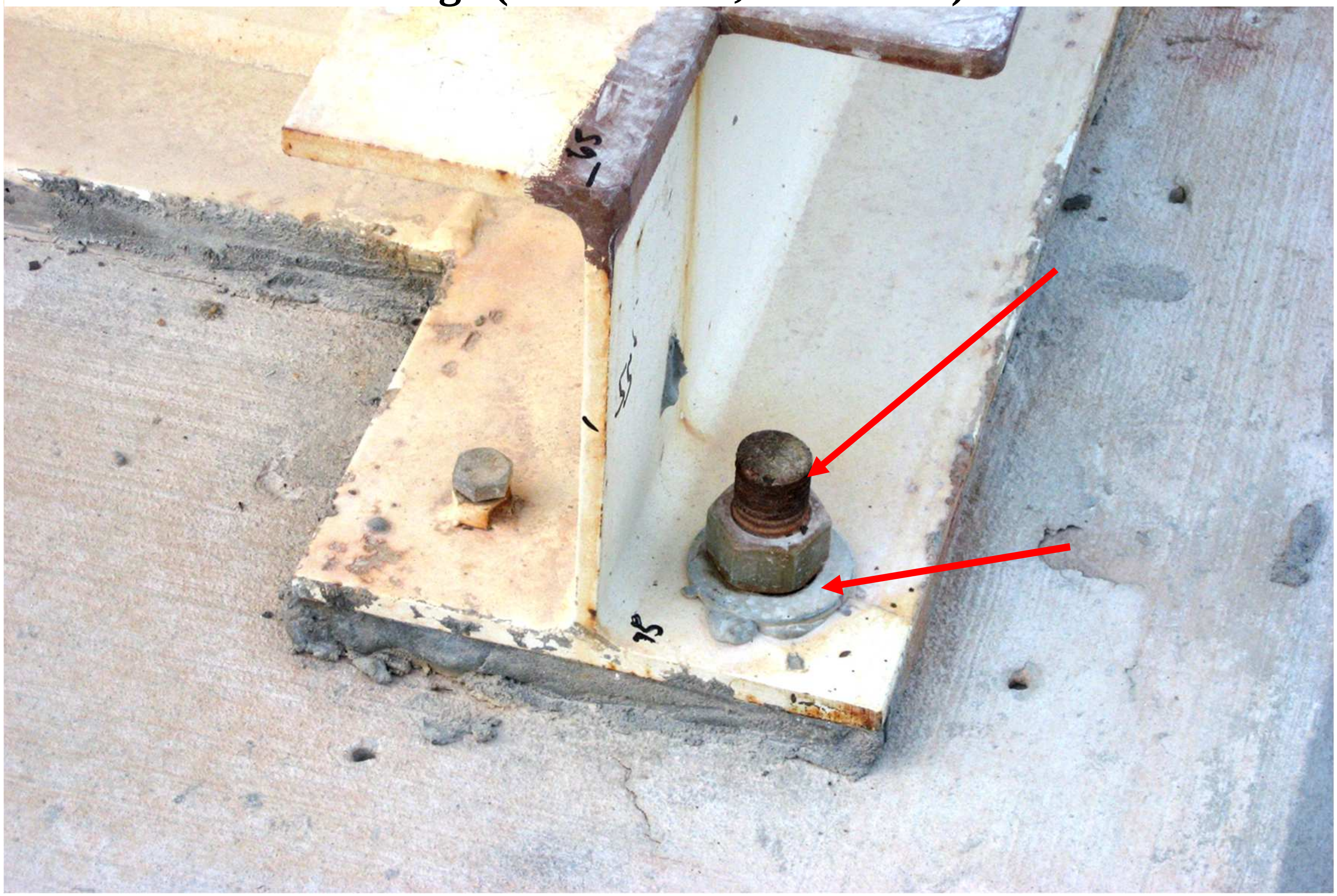
Visual Inspection of Equipment

Lack of Bonding of the Concrete Base to the Concrete Mat.



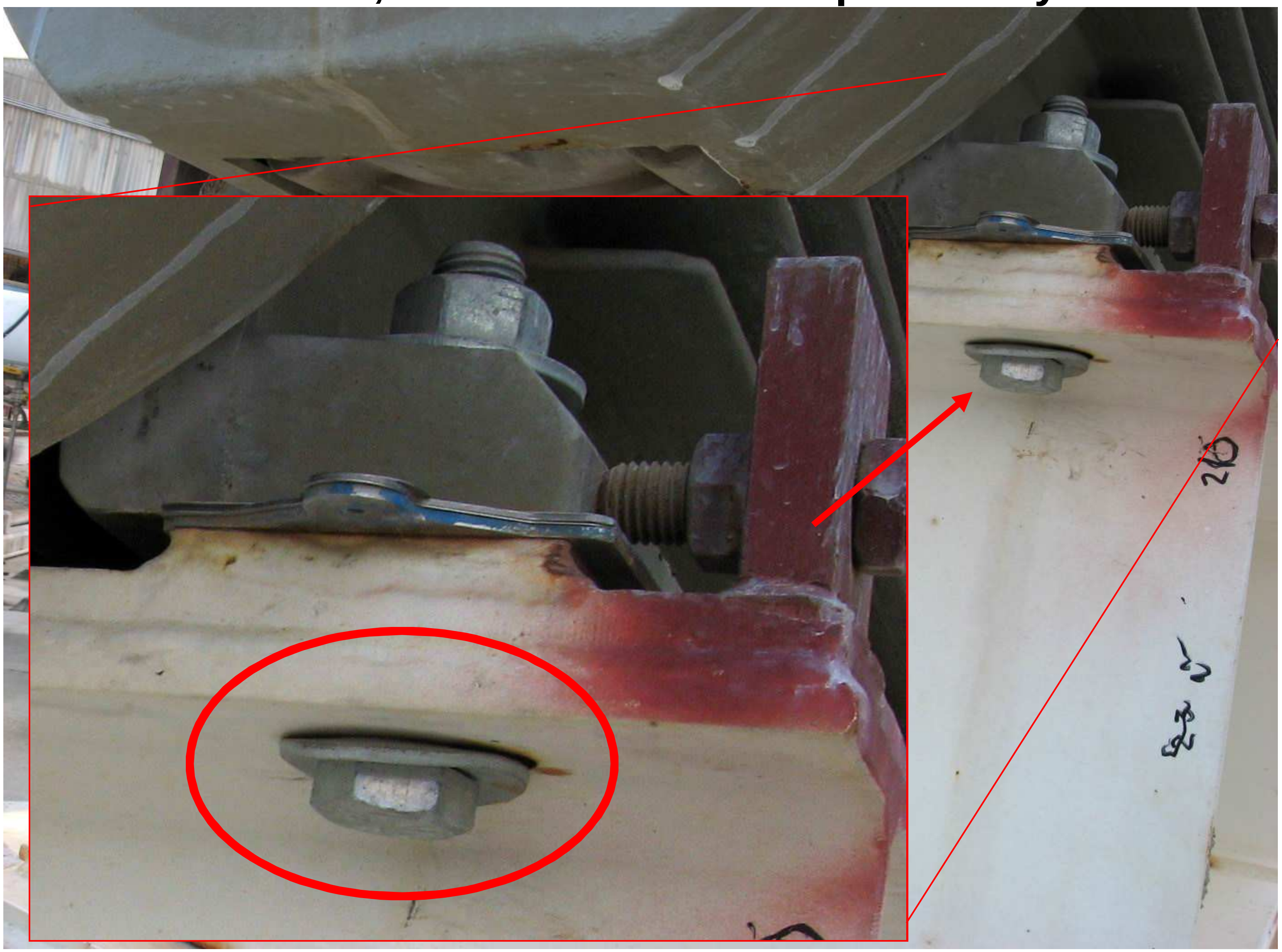
Visual Inspection of Equipment

Anchor Bolts of Carbon Steel instead of 304 Stainless.
Bolts exhibited corrosion.
Washers were too Large (1” Washers, 7/8” Bolts).



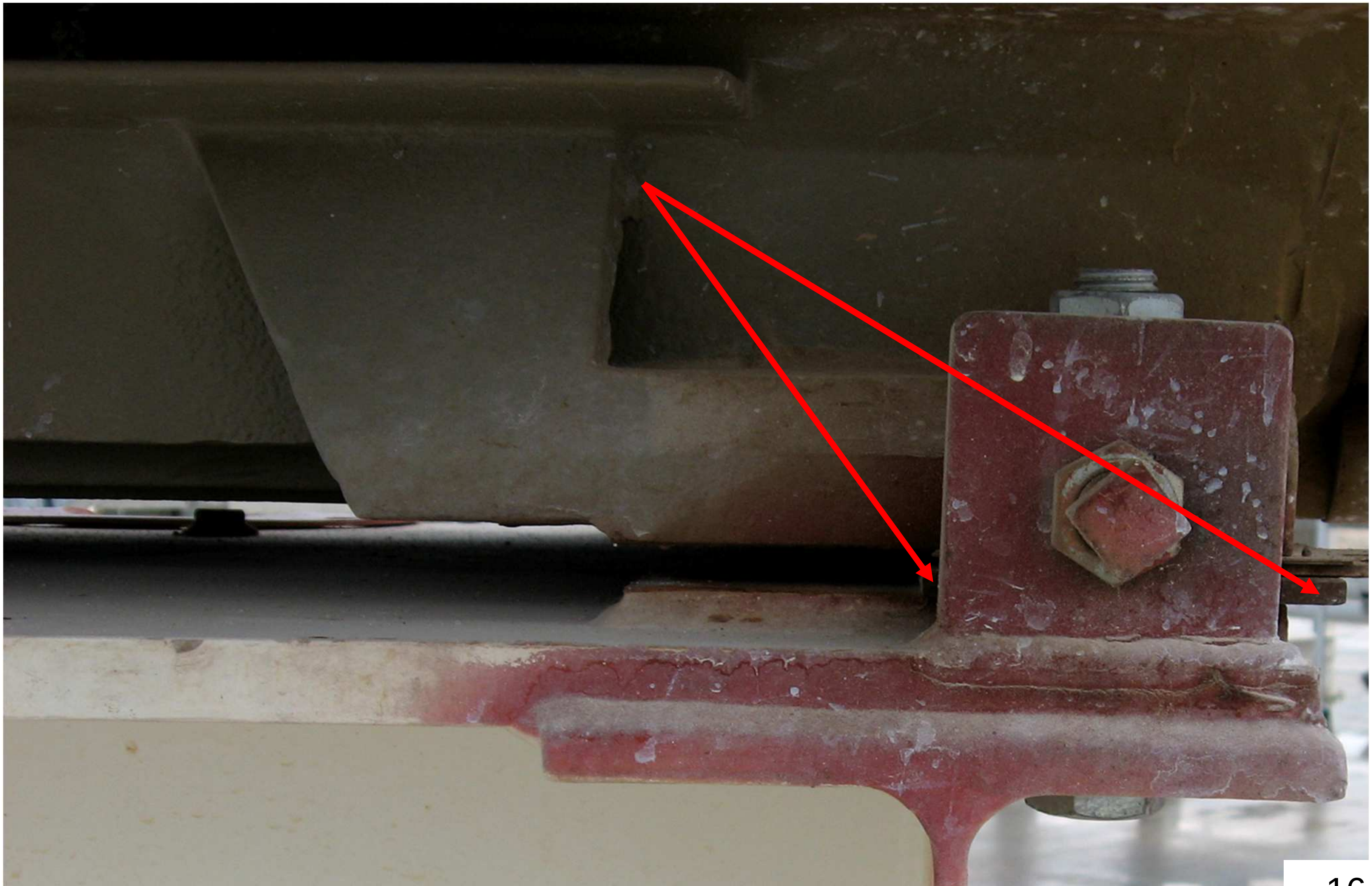
Visual Inspection of Equipment

Motor Hold Down Bolts; Oversized Washers Had Deformed Resulting in No Bolt Preload, Motor Foot Not Clamped Firmly to Plate.



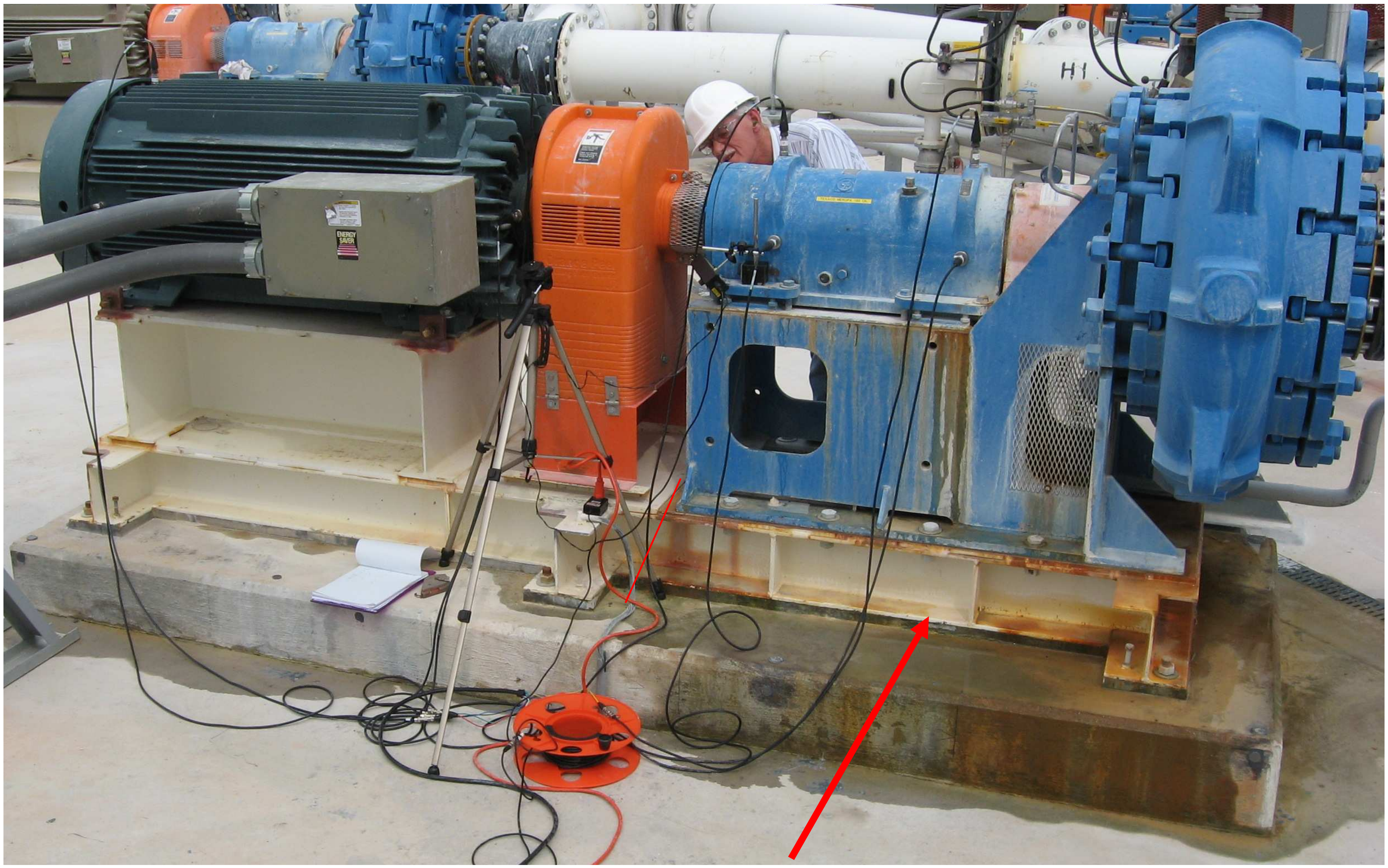
Visual Inspection of Equipment

Carbon Steel Shim used under Some Motor Feet had Corroded.



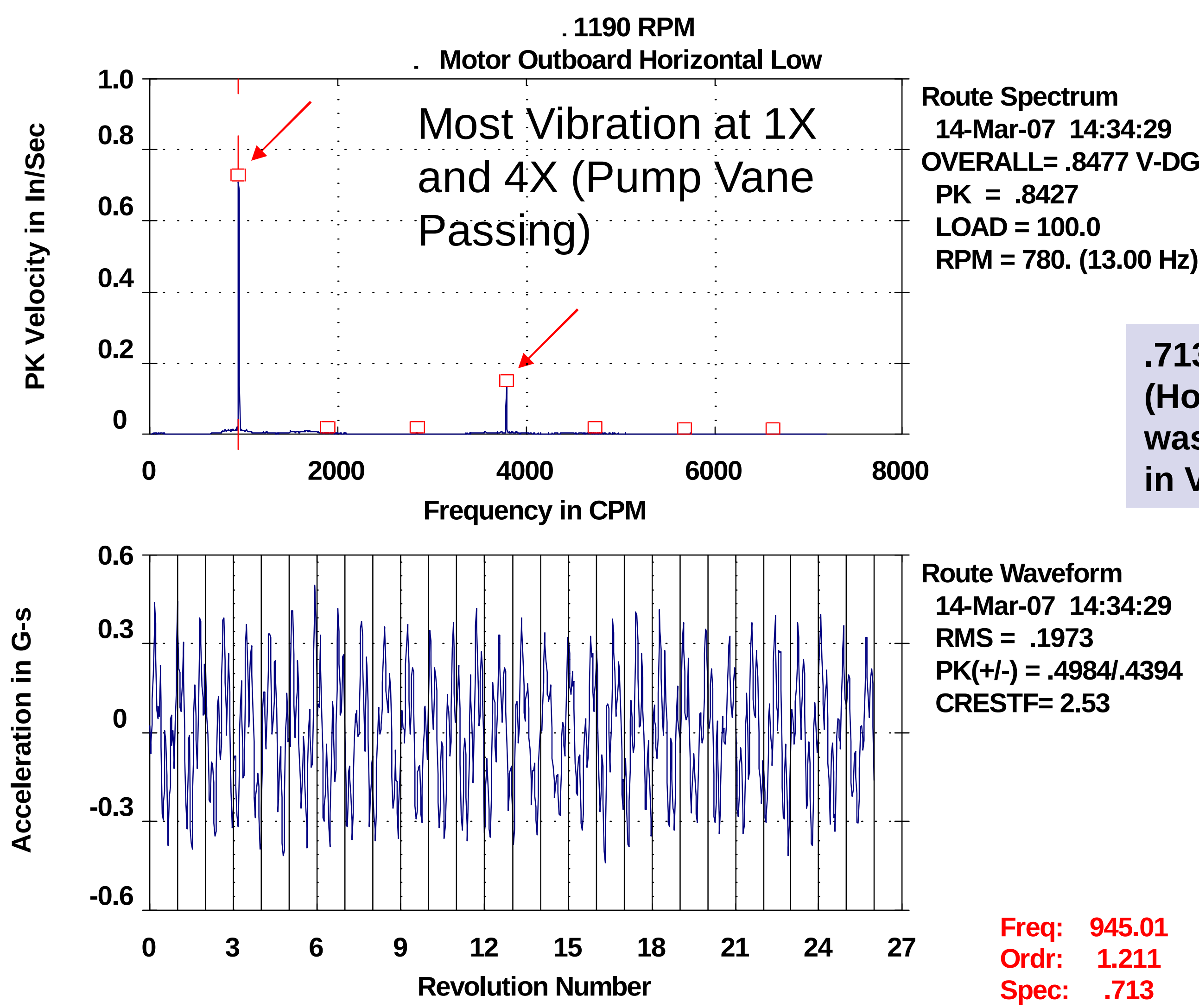
Visual Inspection of Equipment

Relative Movement at the Grout and Concrete Interface under the Skid, ("pumping water") - Indication of Lack of Bonding of Epoxy Grout.



Vibration Data

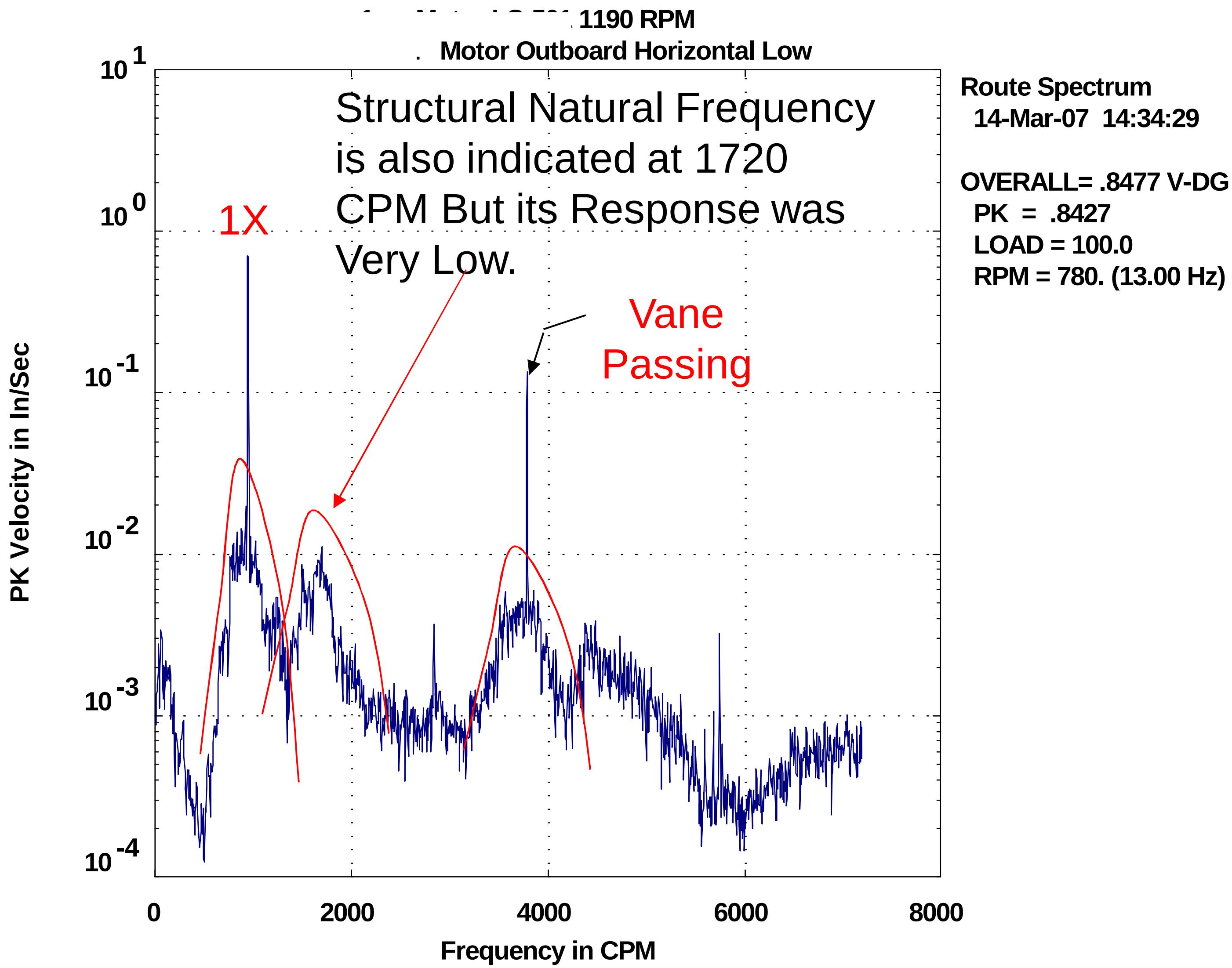
Vibration Data Measured at the #1 Motor & Pump Bearing Housings. Amplitudes Very High in Horizontal Direction. Motor OB Highest.



.713 in/sec at 1 X RPM (Horizontal Direction) – was over 12X higher than in Vertical Direction)

Vibration Data

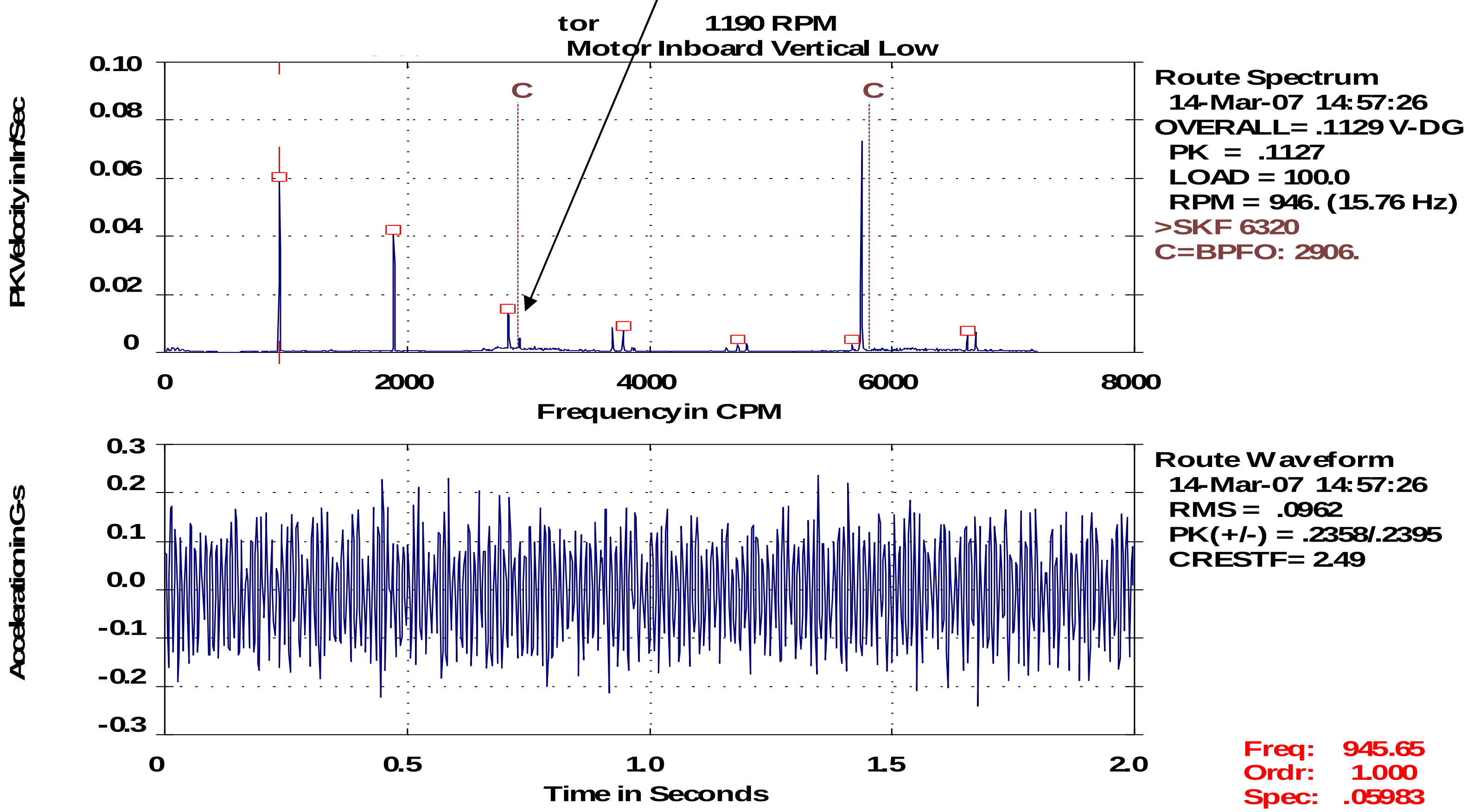
Plotting Spectrum Data in Log Magnitude Indicated Resonance at 1X and Vane Passing Frequency.



Vibration Data

Motor Inboard Bearing Defect Frequency for the Outer Race Appeared in the Spectrum Data.

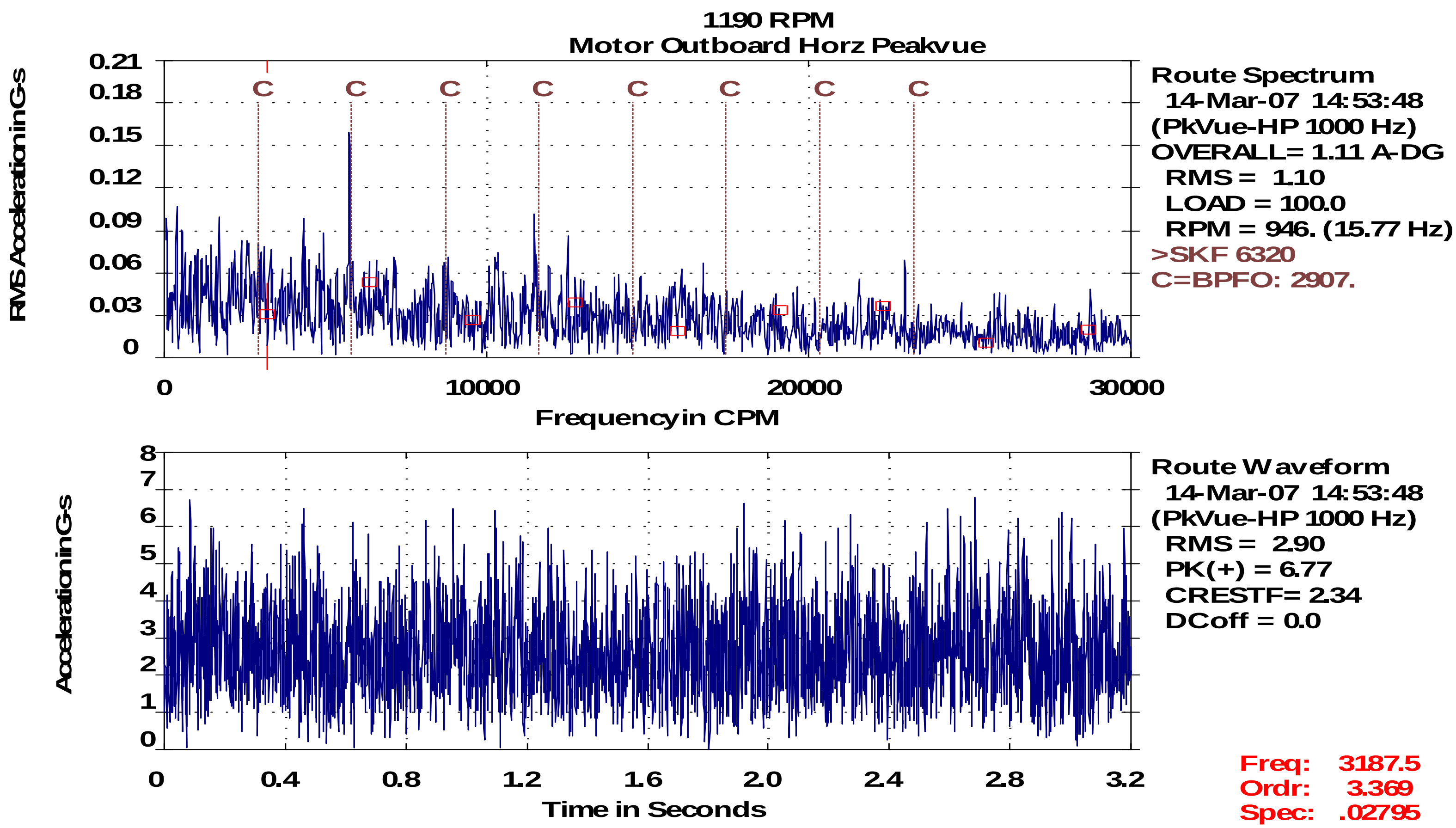
SKF 6320 Bearing Outer Race Ball Passing Frequency



The Outer Race Ball Passing Defect Frequency of the SKF 6320 Bearing was also Evident in Data Measured at the Motor Inboard Bearing Housing.

Vibration Data

CSI PeakVue Data was Above Alarm Level in the Time Domain. Twice Line Frequency of the VDF was The Primary Frequency.



PeakVue Data at the Motor OB Brg Housing Measured about 6 g's (Alarm Level). Twice Line Frequency of the VFD was the Highest Amplitude Frequency.

Vibration Data

TABLE 2: VIBRATION LIMITS*

Industry Housing Vibration Limits

	NEMA 1998	NEMA - Pre-1993			API 541 3rd Ed.	API 541 2nd Ed.			IEEE 841
	2,4,6 pole	2 pole	4 pole	6 pole	2, 4, 6 pole	2 pole	4 pole	6 pole	2, 4, 6 pole
Unfiltered (overall)	0.12 in/s (3 mm/s)	1.0 mil (0.03 mm)	2.0 mils (0.05 mm)	2.5 mils (0.06 mm)	0.1 in./s (2.5 mm/s)	0.8 mils (0.02 mm)	1.5 mils (0.04 mm)	1.5 mils (0.04 mm)	0.08 in/s (2.0 mm/s)
Filtered 1X	0.12 in/s 3 mm/s				0.1 in/s (2.5 mm/s)	0.5 mils (0.01 mm)	1.0 mil (0.03 mm)	1.0 mil (0.03 mm)	
Filtered 2X					0.1 in/s (2.5 mm/s)				0.05 in/s (1.3 mm/s)
Filtered 2ƒ									

Indust

	2 pole	4 pole	6 pole	2, 4, 6 pole	2 pole	4 pole	6 pole
Unfiltered (overall)	1.0 mil (0.03 mm)	2.0 mils (0.05 mm)	2.5 mils (0.06 mm)	1.5 mils (0.04 mm)	2.0 mils (0.05 mm)	2.5 mils (0.06 mm)	3.0 mils (0.08 mm)
Filtered - 1X				1.2 mils (0.03 mm)	1.5 mils (0.04 mm)	2.0 mils (0.05 mm)	2.5 mils (0.06 mm)
Filtered - 2X				0.5 mils (0.01 mm)	1.0 mil (0.03 mm)	1.5 mils (0.04 mm)	1.7 mils (0.04 mm)
Filtered - 2ƒ				0.5 mils (0.01 mm)			

*This table has been updated by EASA from its original printing to reflect changes in NEMA MG 1.

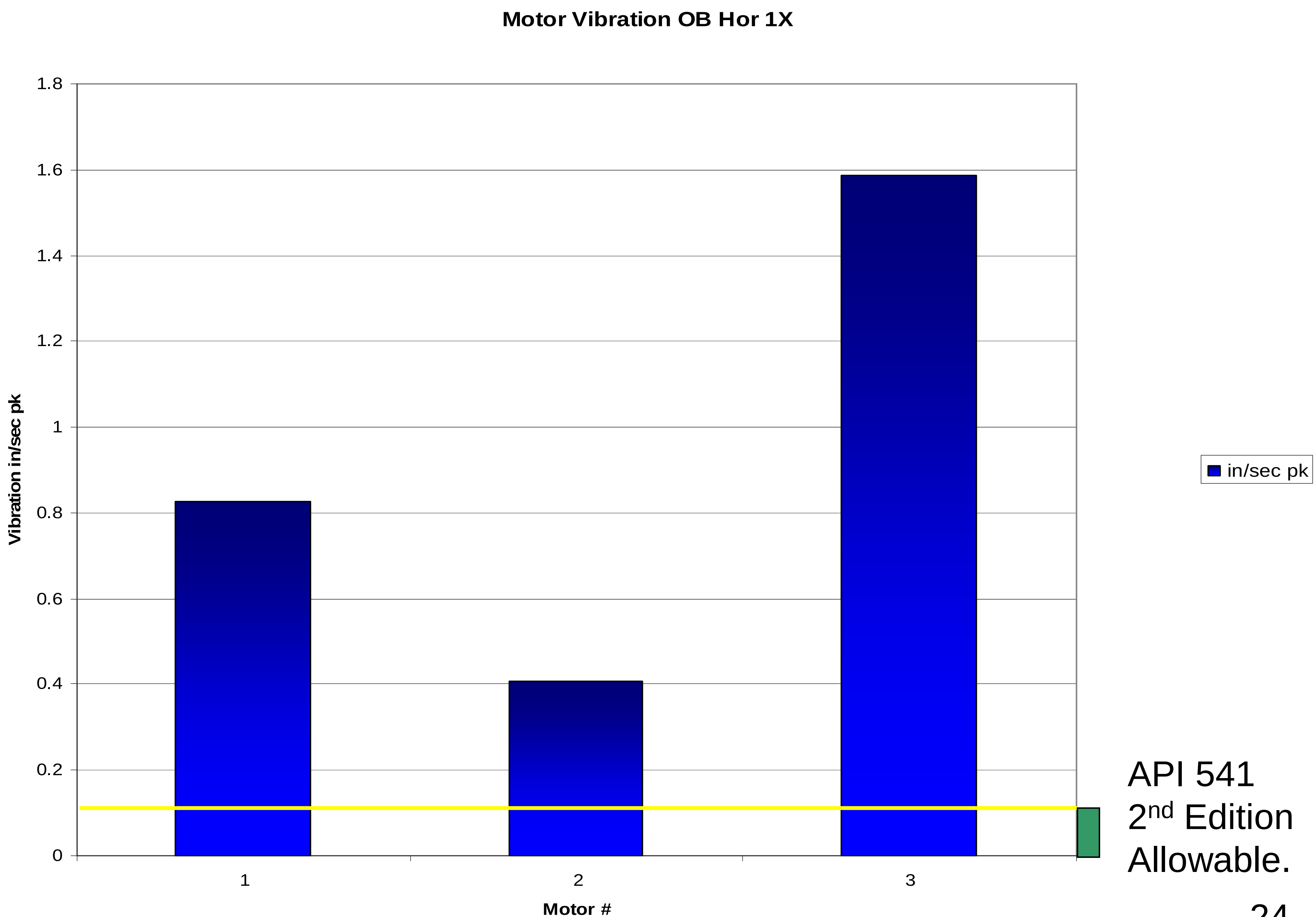
Comparing Industry Motor Housing Vibration Limits Showed That the Motor Vibration Exceeded All of These Limits.

Vibration Data

Findings:

- Motor OB Bearing Housings in Horizontal Direction Had Highest Vibration.
    - **Motor 1**
        - OB Hor 1X 0.713 in/sec pk ~ 14.4 mils, pk-pk
        - OB Ver 1X 0.059 in/sec pk
        - Ratio of Horizontal to Vertical Vibration = 12:1 - Indication of Resonance, Looseness and/or Support Flexibility.
    - **Motor 2**
        - OB Hor 1X 0.408 in/sec pk ~ 8.2 mils, pk-pk
    - **Motor 3**
        - OB Hor 1X 1.586 in/sec pk ~ 31.95, mils pk-pk

Vibration Data



API 541 2nd Edition Allowable.

Vibration Data

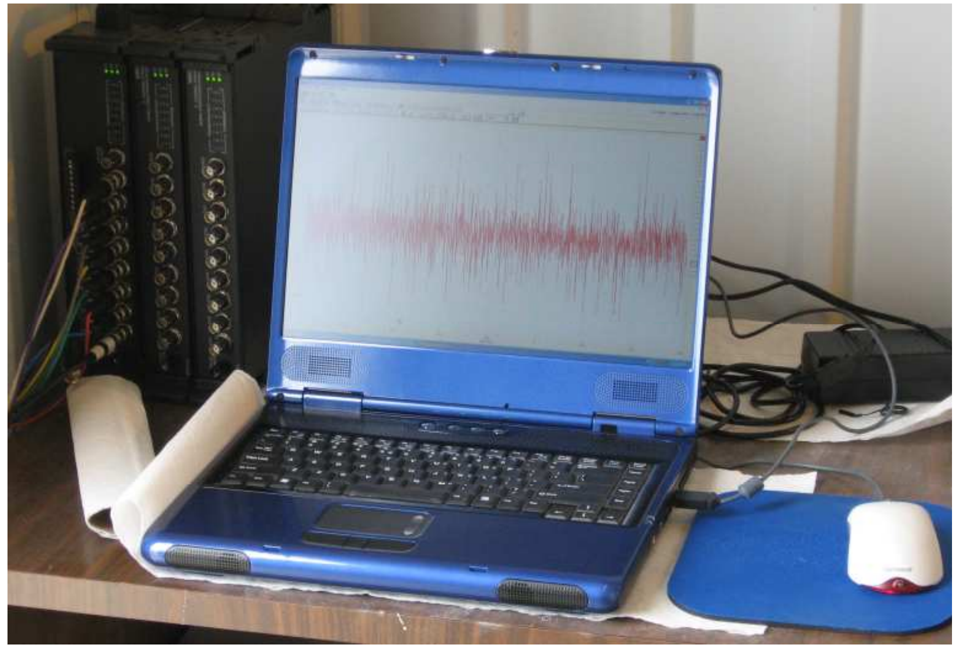
Findings:

- Pump Vibration was Lower than the Motor with Most Motion in Horizontal Direction.

- Pump #1
  - Pump IB Hor 0.269 in/sec pk
  - Pump IB Ver 0.050 in/sec pk
  - Vibration Ratio Hor to Ver of 5.38:1

Continuous Vibration Acquisition During Speed Change

Vibration data measured with multi-channel ZonicBook 618E analyzer.



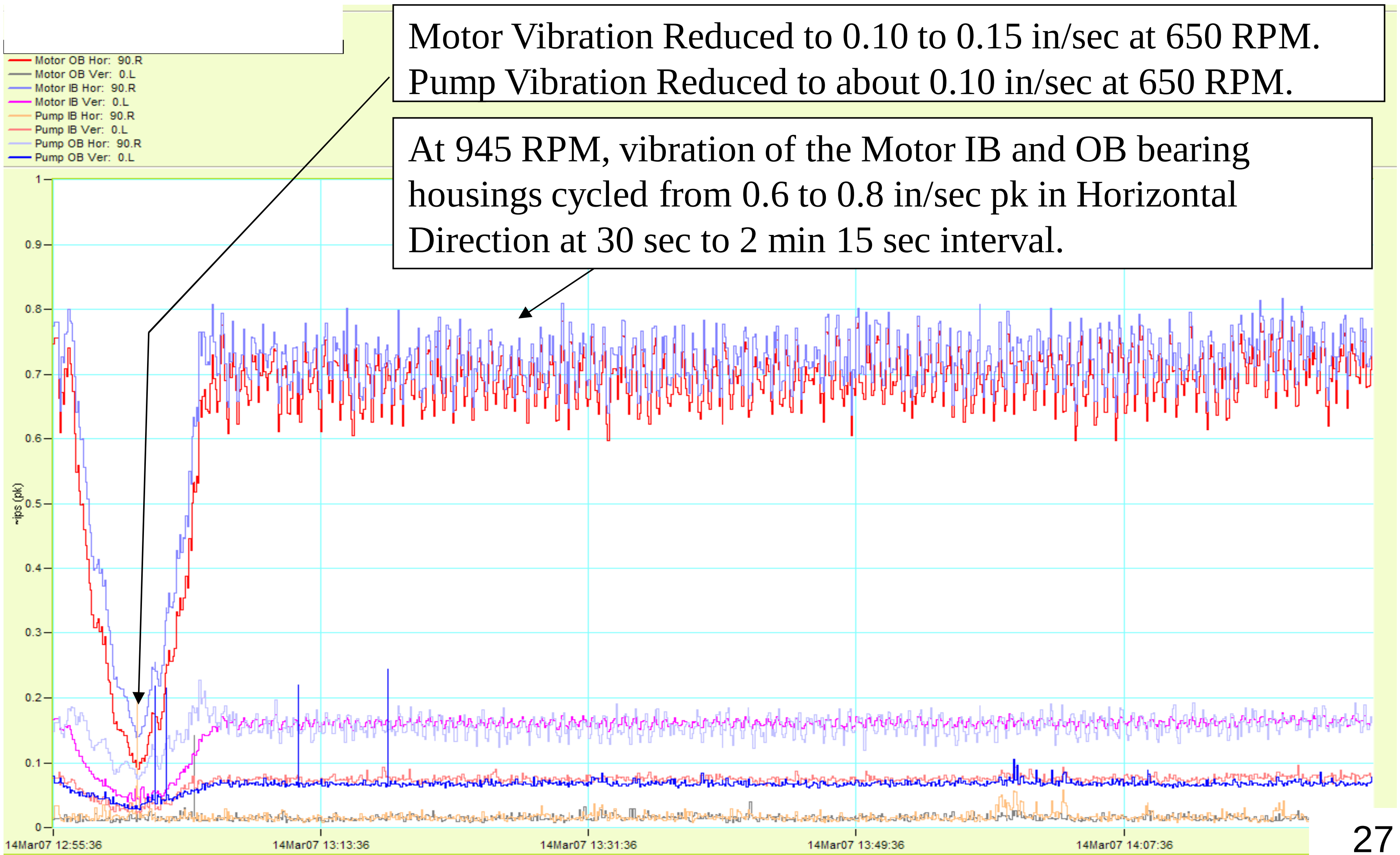
Accelerometers were mounted on Unit #1 Motor and Pump bearing housings.

Operating speed was 945 RPM.

Speed was reduced to 650 RPM in 1% increments; then increased back to 945 RPM. Purpose of speed change was to determine if vibration changed with speed, indicating possible resonance.

Continuous Vibration Acquisition During Speed Change

Vibration dropped dramatically with speed reduction from 945 to 650 RPM.



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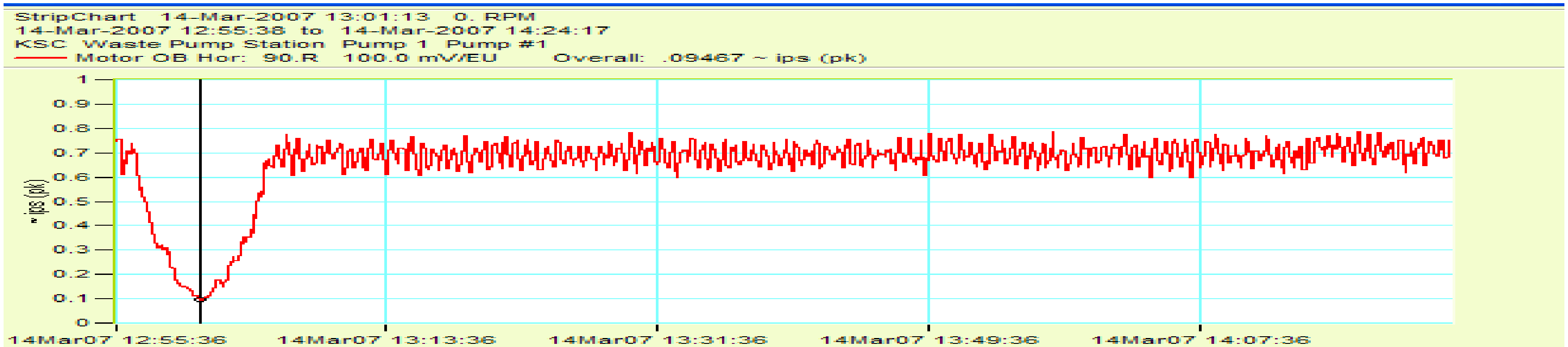
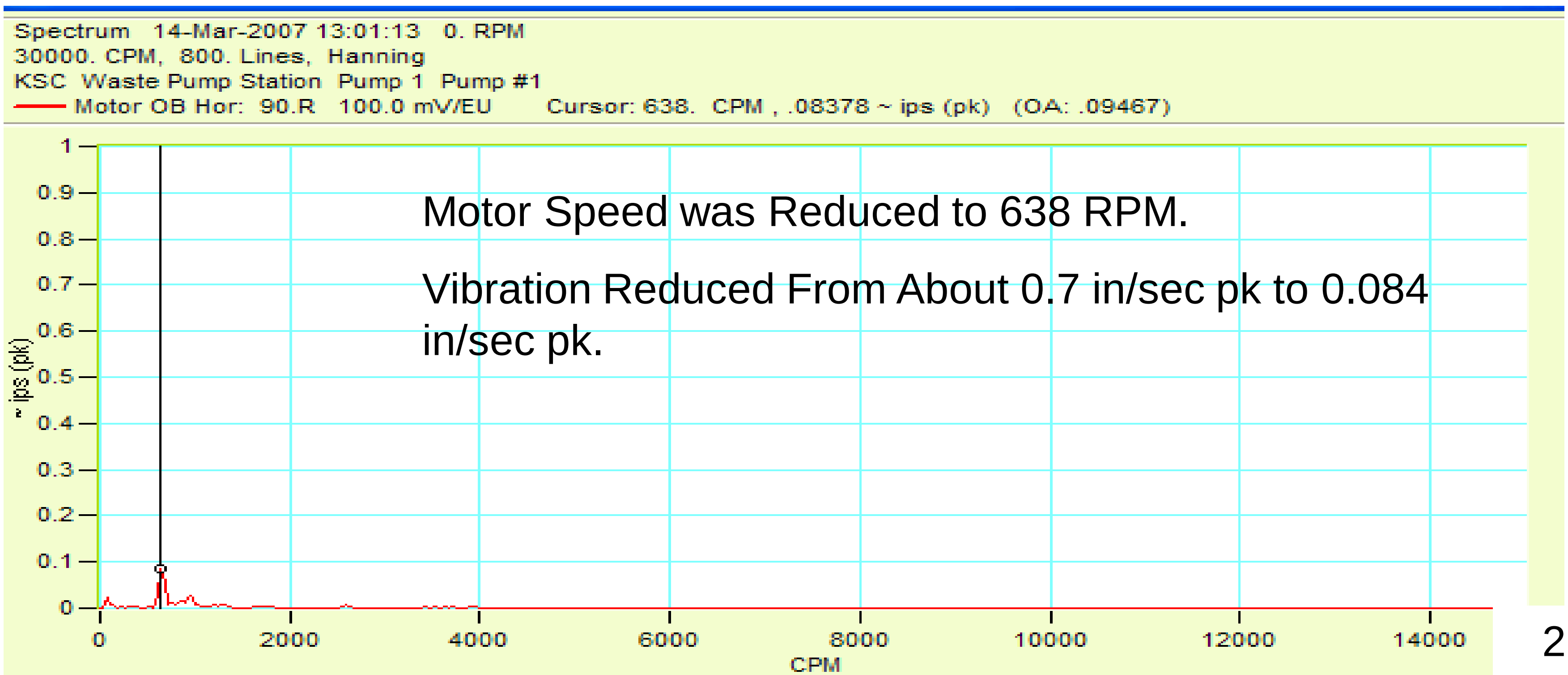
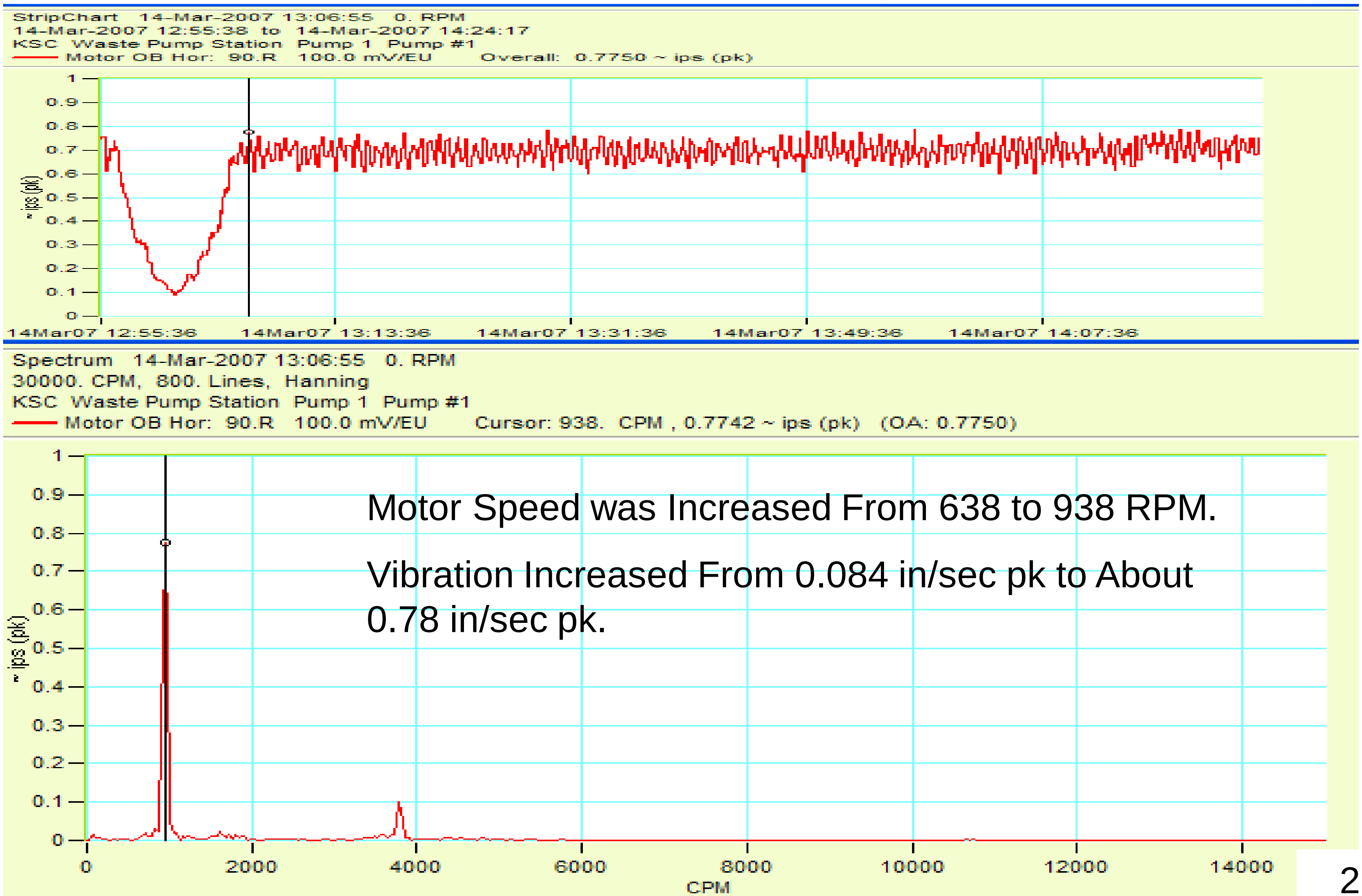




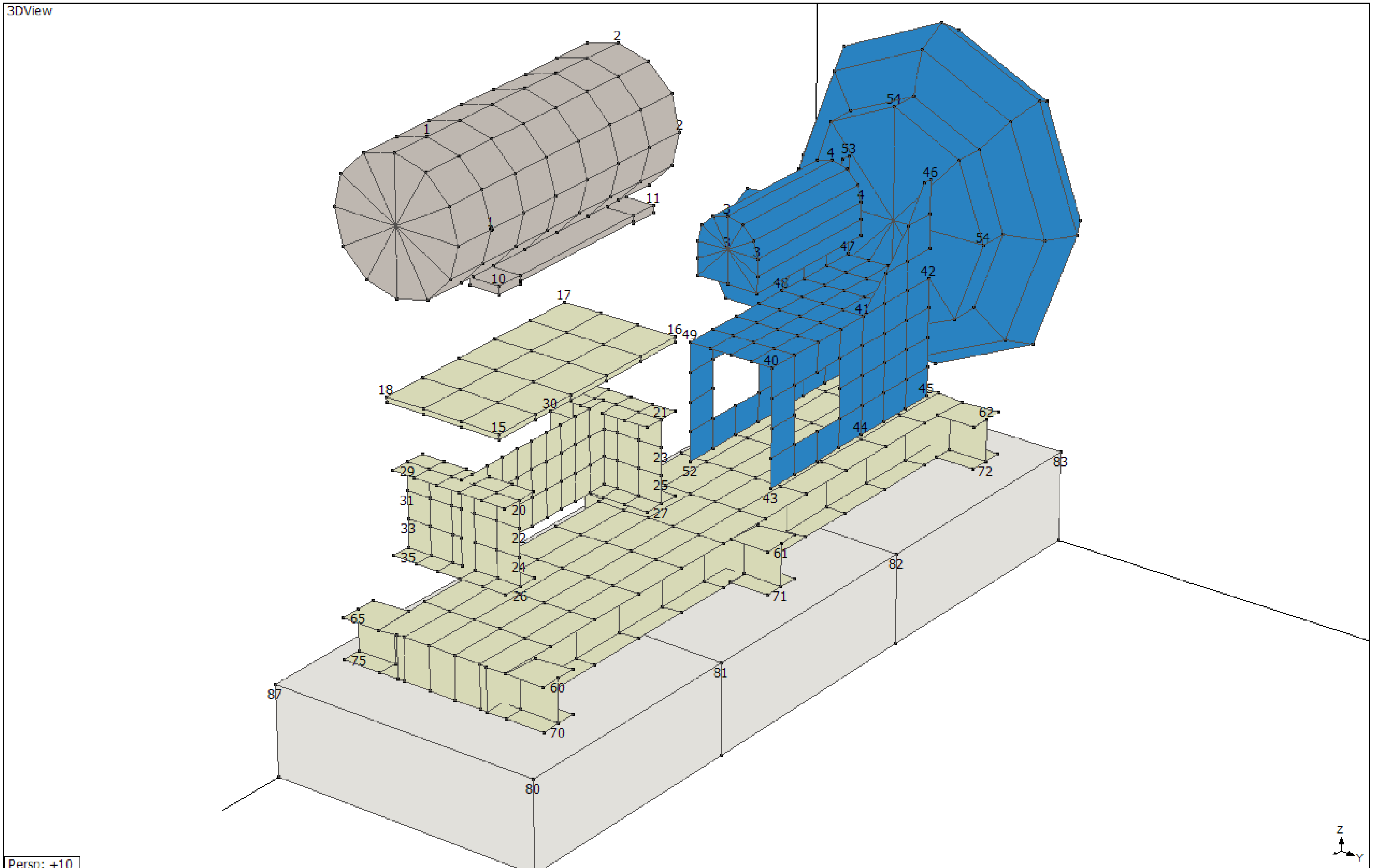
Continuous Vibration Acquisition During Speed Change

Vibration levels returned to the same levels as before the speed reduction.



Operating Deflection Shape Analysis

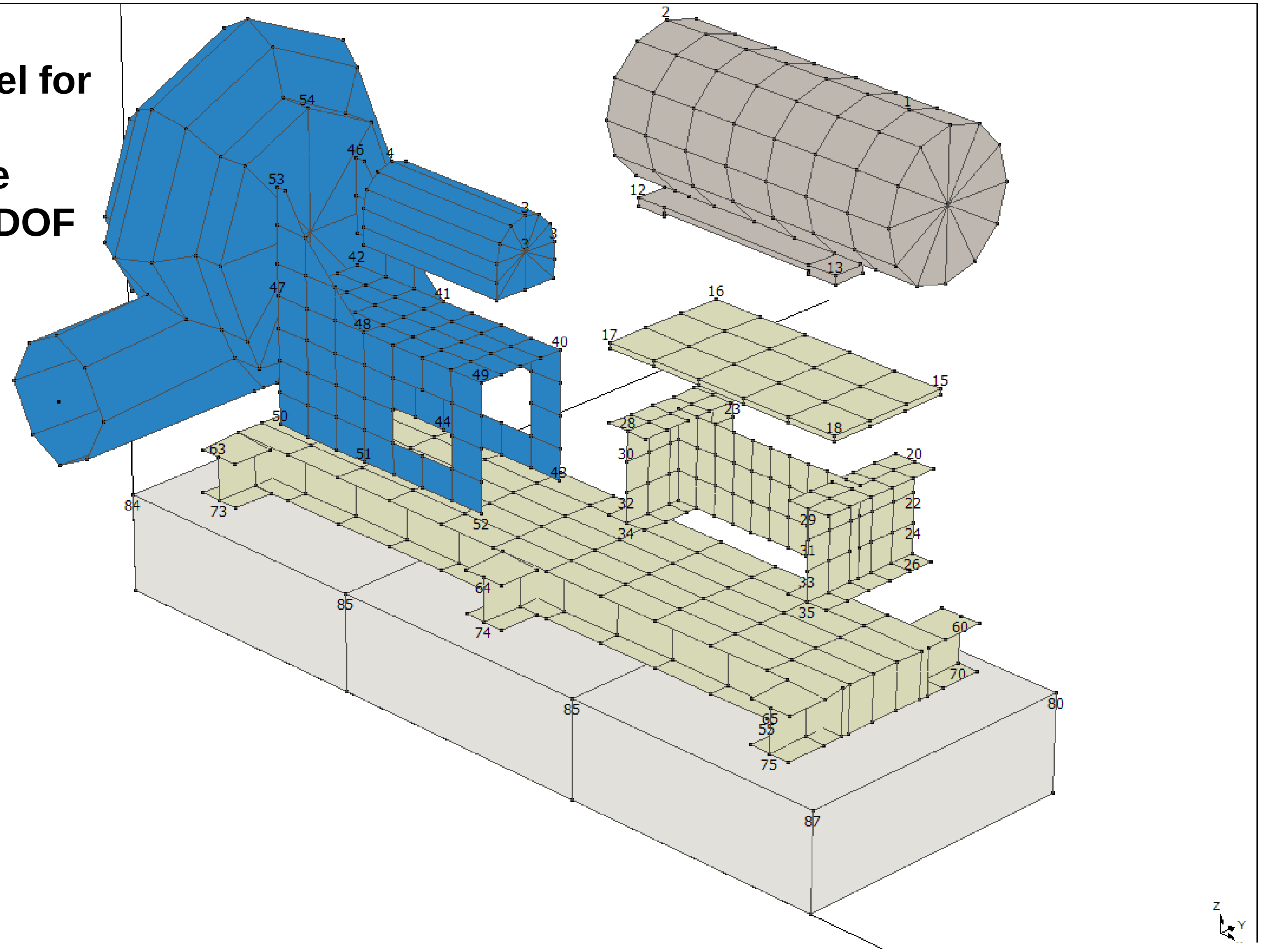
Individual objects used to develop the model in ME'scopeVES V4



Operating Deflection Shape Analysis

Measurement locations for the ODS.

Printing the Exploded Model for use in the field helps show the measurement DOF more clearly.

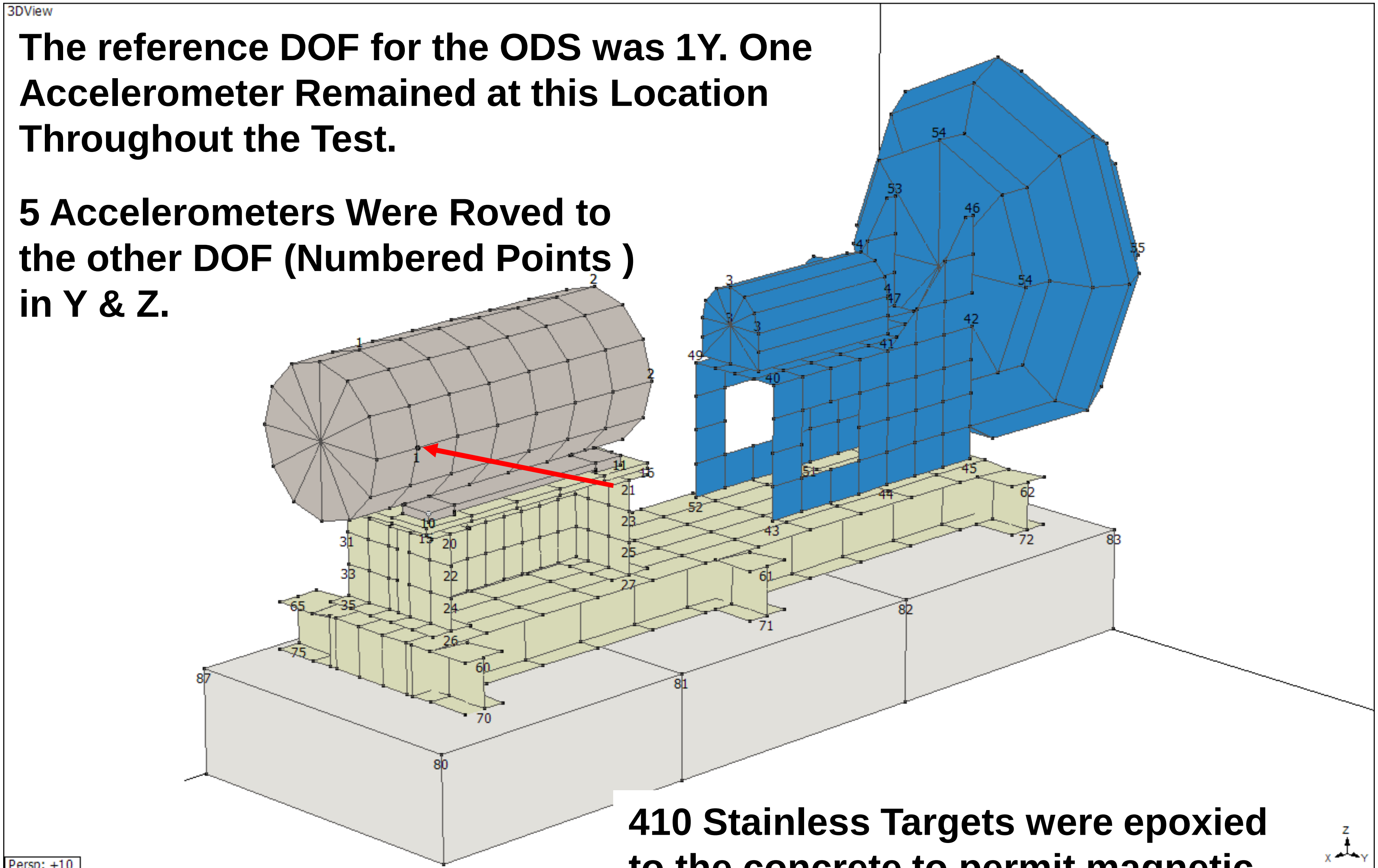


Operating Deflection Shape Analysis

Model with objects in correct position.

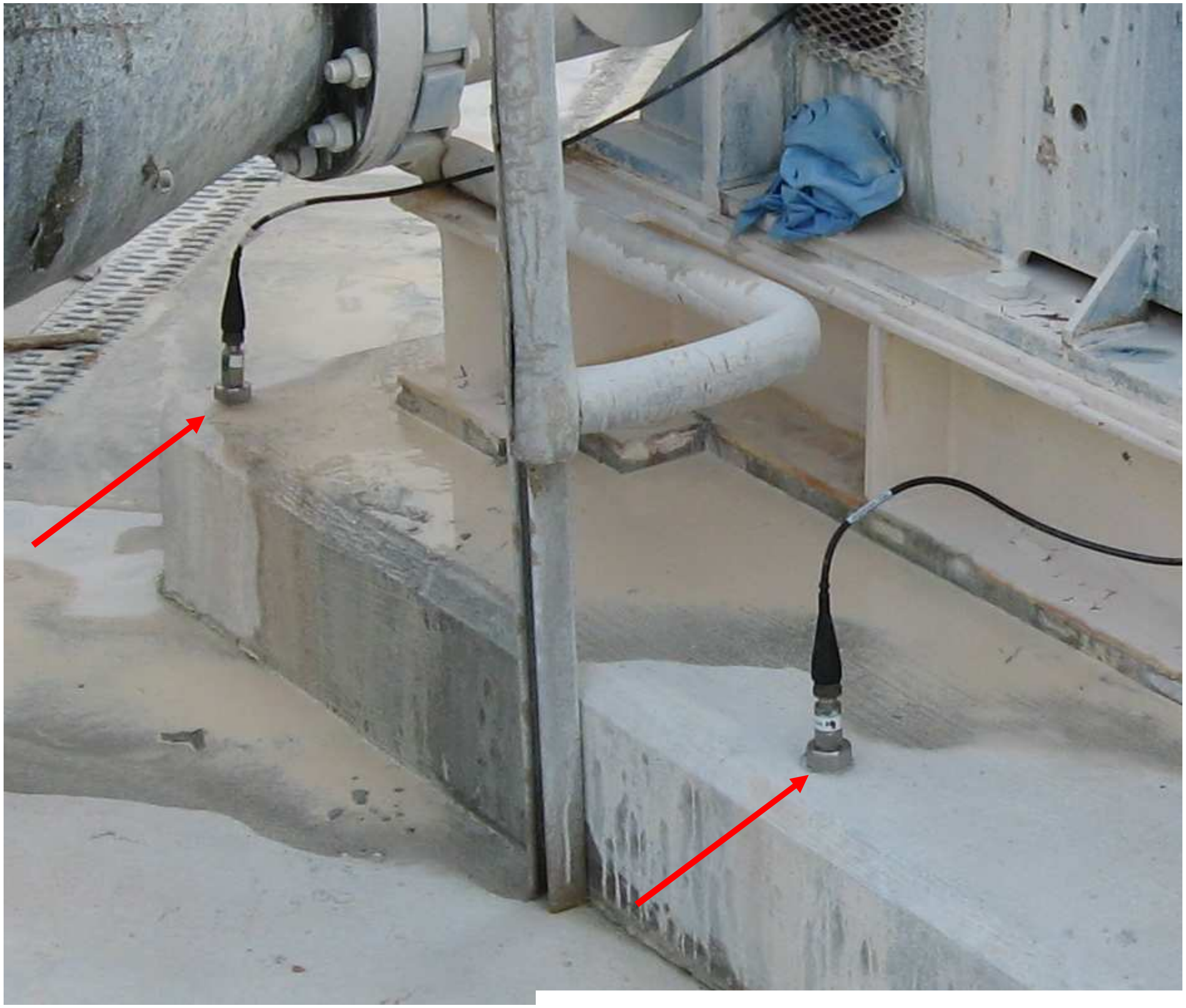
The reference DOF for the ODS was 1Y. One Accelerometer Remained at this Location Throughout the Test.

5 Accelerometers Were Roved to the other DOF (Numbered Points) in Y & Z.



410 Stainless Targets were epoxied to the concrete to permit magnetic mounting of accelerometers.

Operating Deflection Shape Analysis



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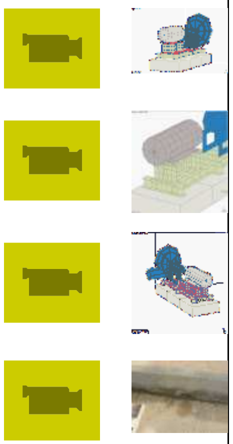
Operating Deflection Shape at Running Speed



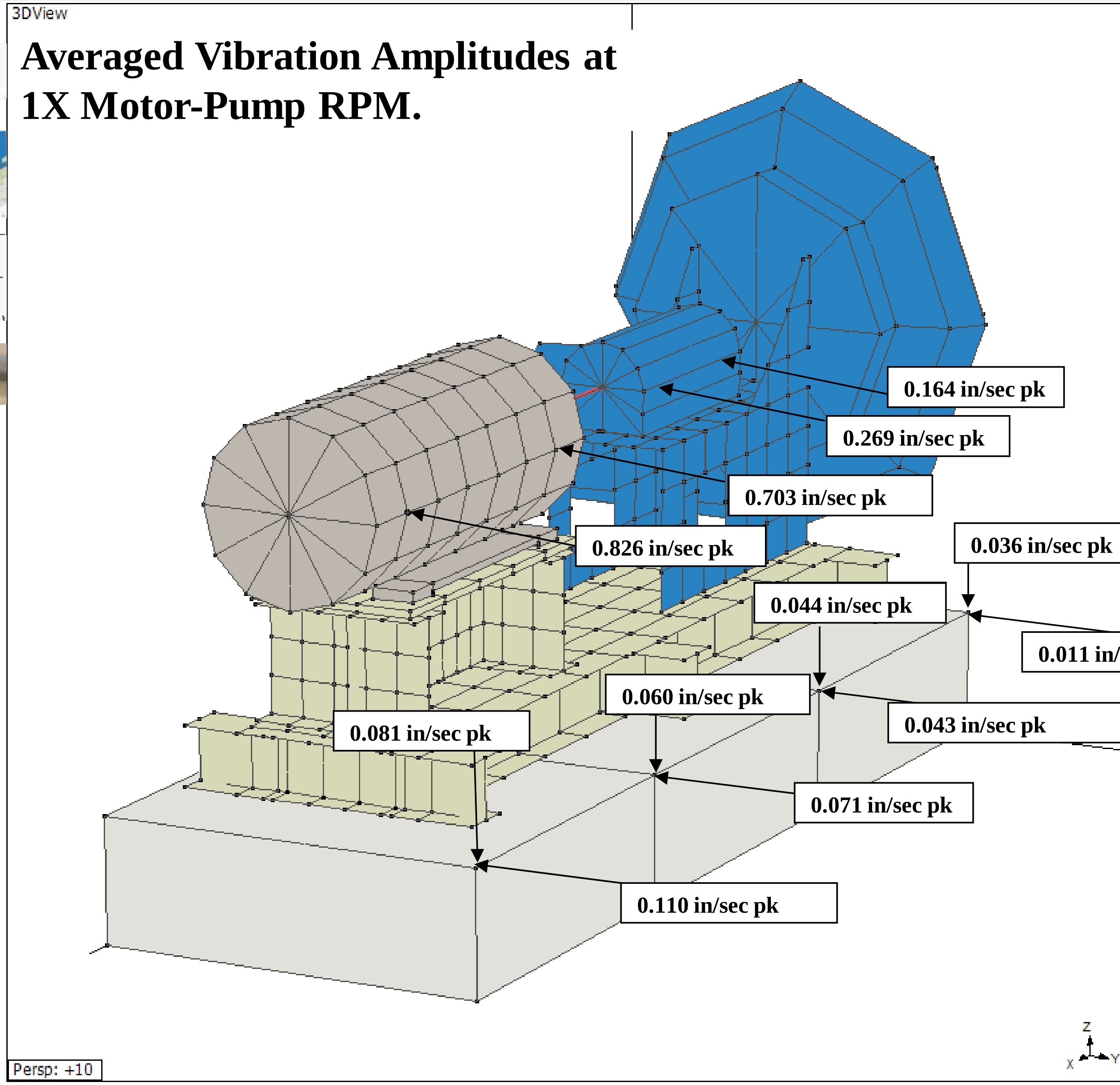
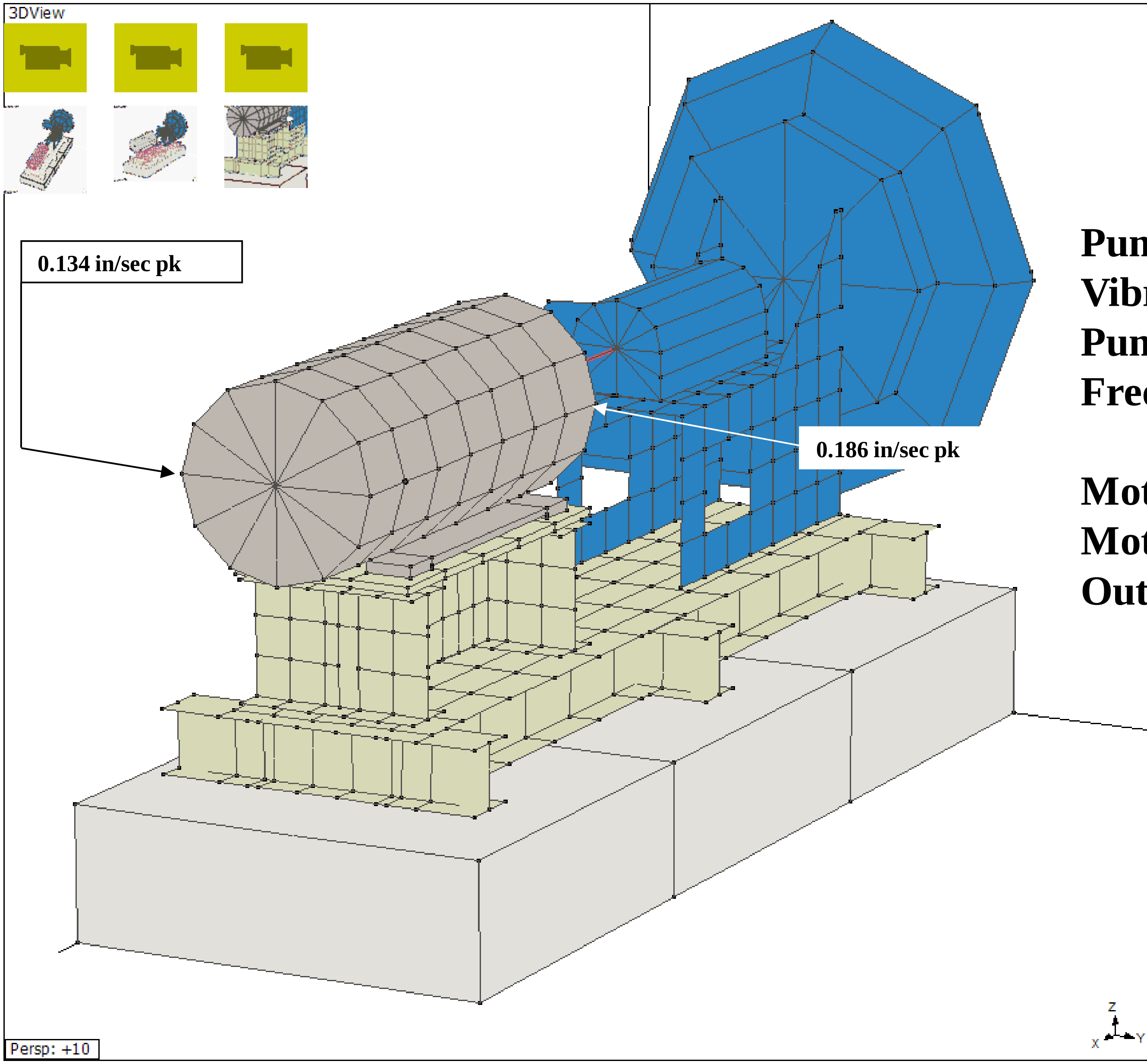


Figure 7. Average Vibration Amplitudes for Operating Deflection Shape at Running Speed Frequency.

Operating Deflection Shape at Vane Passing



Pump 1: Averaged Vibration Amplitudes At Pump Vane Passing Frequency.

Motion at Each End of Motor was 180 Degrees Out of Phase.

Operating Deflection Shape Test

ODS Findings:

1X Run Speed – Side to side flexure of the motor pedestal.
- Flexure of the skid.
- Relative motion between the skid and concrete base.
- Side to side rocking motion of the concrete base, but low amplitude.

Vane Passing – Twisting of the motor pedestal about the Z axis.

Modal Test

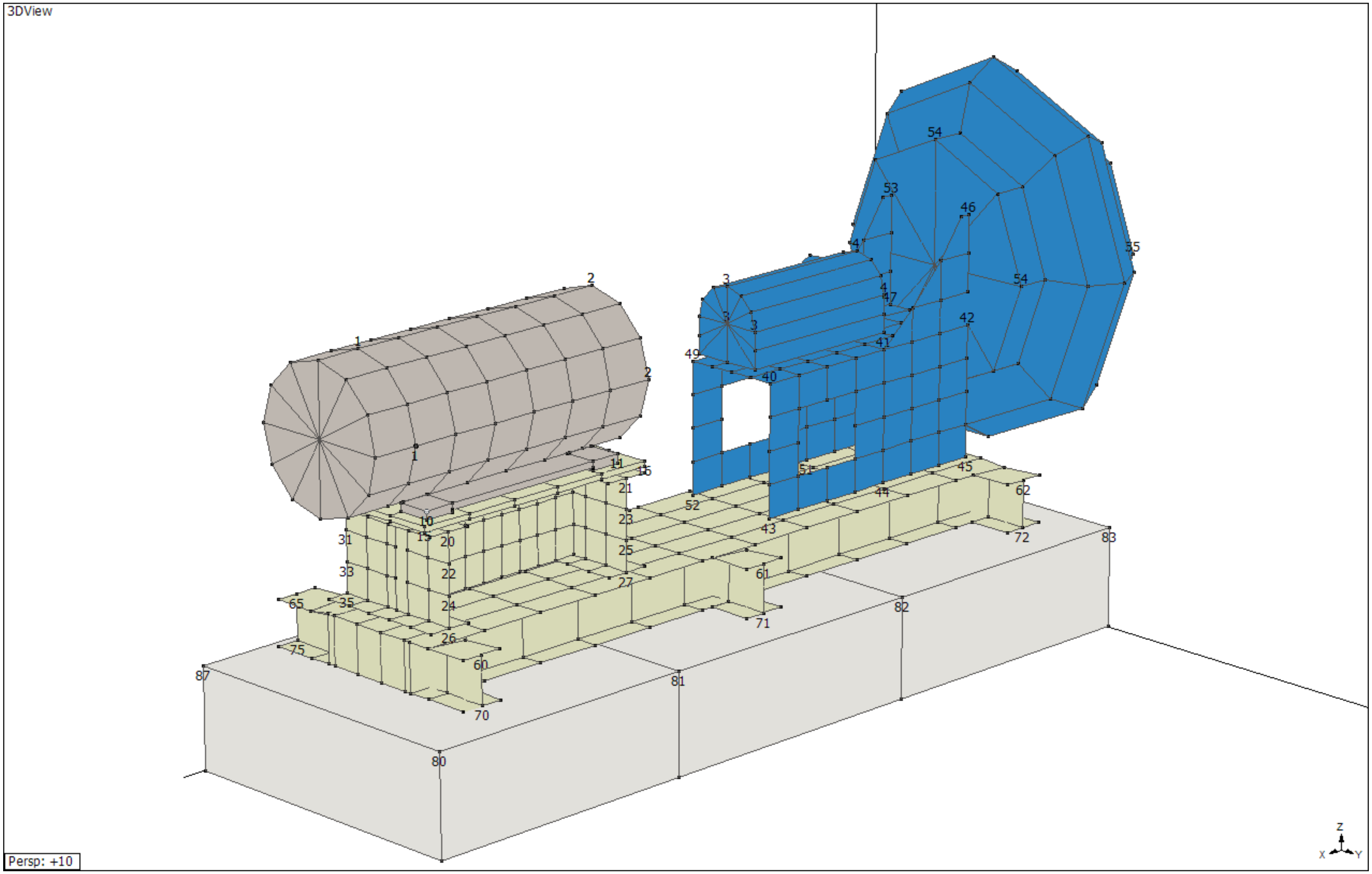
- **Modal Sledge Hammer used to Excite the Natural Frequencies of Pump-Motor & Skid.**

- **Zonicbook 618 Analyzer and eZ-analyst Software acquired data.**

- **Driving Point Location (Point of Hammer Impact during the Modal Test) at Motor Outboard Bearing Housing in Horizontal Direction.**

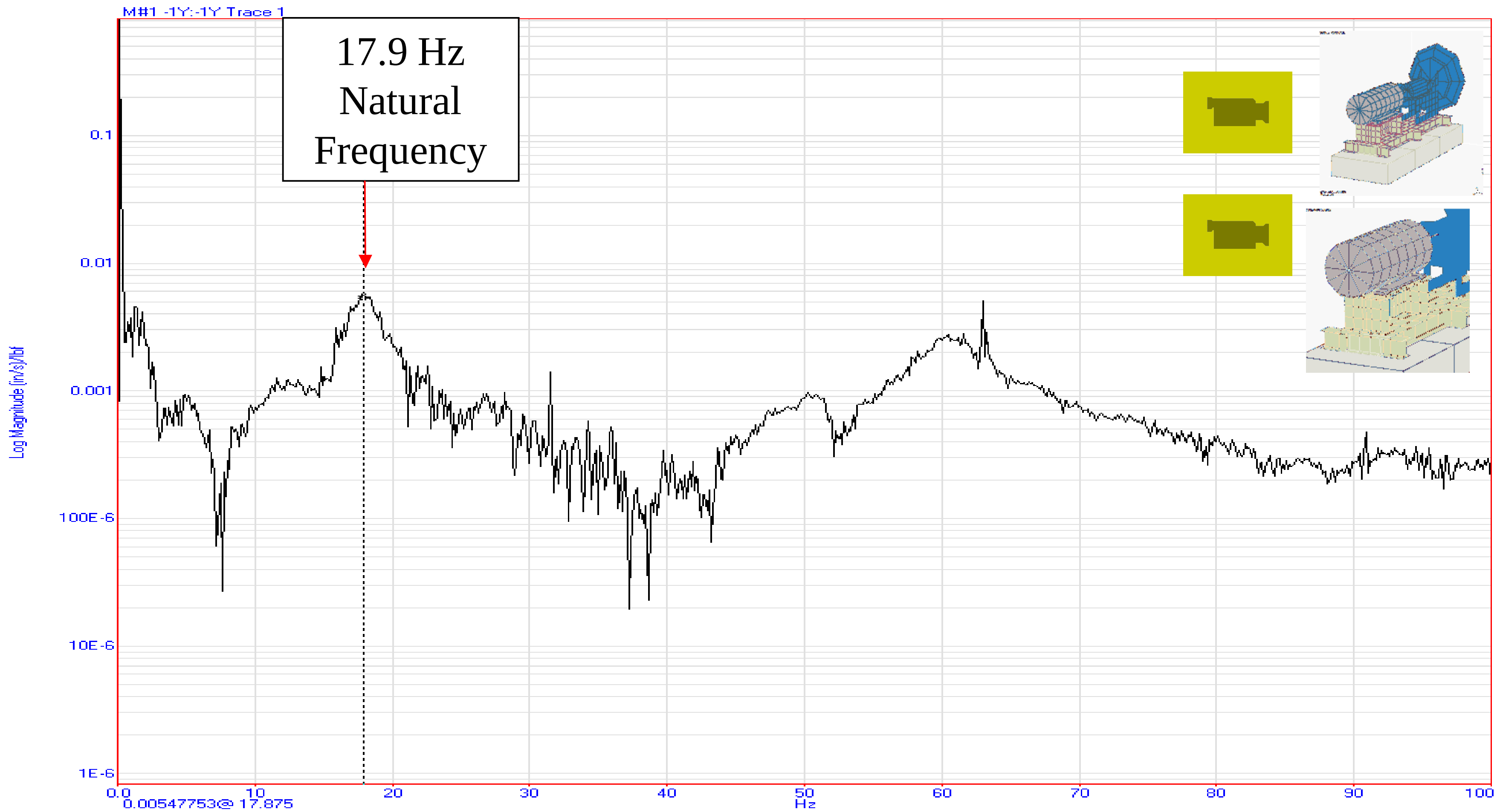
Modal Test

Modal DOF (Degrees of Freedom) were same as used for the ODS.



Modal Test

17.9 Hz ~ 1074 CPM natural frequency near pump operating speed. Mode shape was side-to-side motion of the motor with flexure in the supporting structural steel pedestal and skid frame. Very little participation of the concrete base in the mode shape.



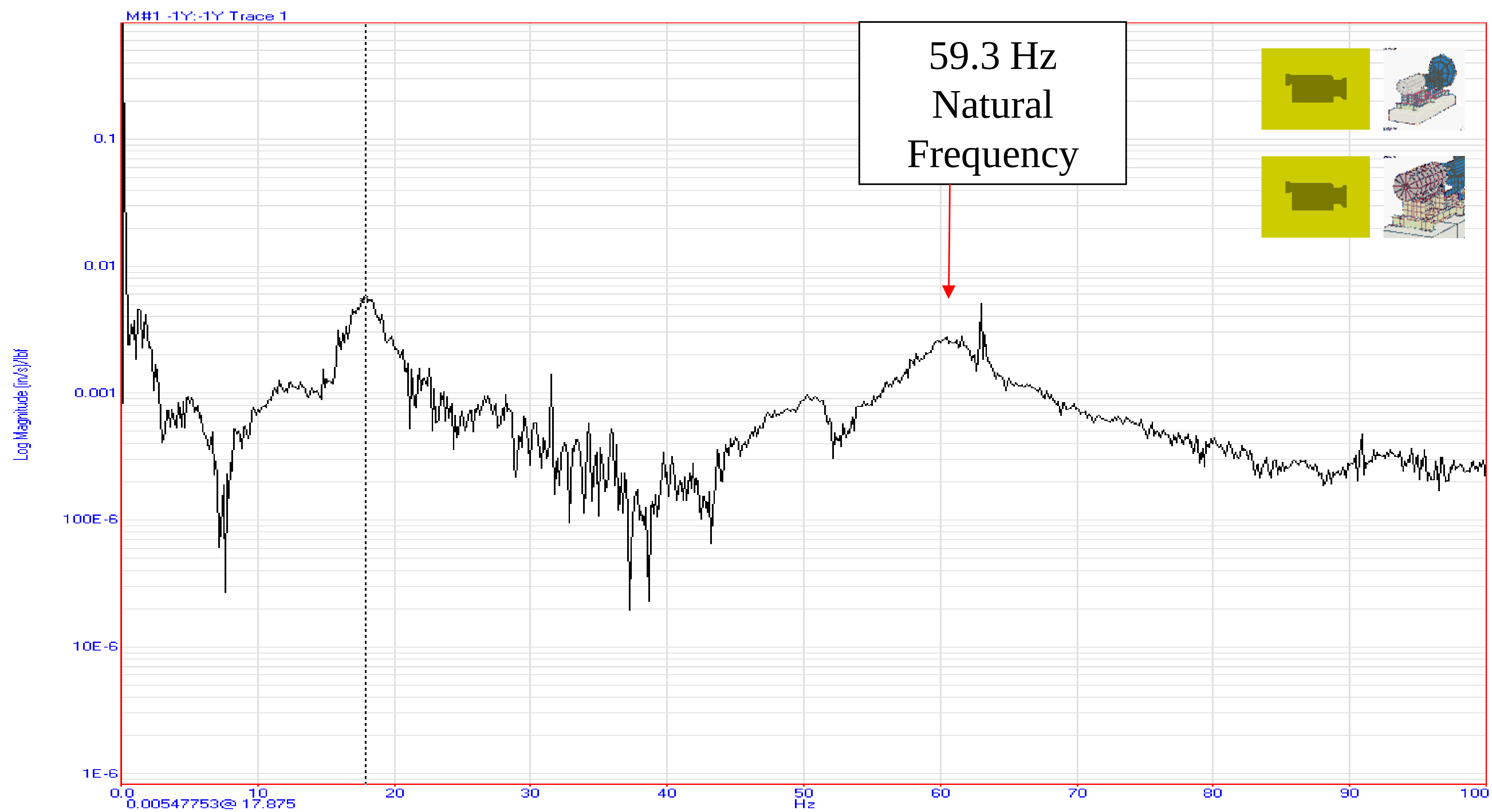
Driving Point Frequency Response Function at Motor Outboard End Horizontal.

Modal Test

59.3 Hz ~ 3558 CPM Natural Frequency near Pump Vane Passing Frequency.

Mode shape:

- Twisting of the motor and pedestal about the Z axis.
- Flexure of the 16” wide flange beams. Bending in Z axis of the skid frame.



Modal Test

The modal driving point (FRF) and Vibration Spectrum was used to calculated an estimate of the dynamic force.

The force at the #1 Motor Outboard bearing Housing in the horizontal direction was calculated as follows:

$$F_{lbf\,1X\,Run\,Speed} = \frac{Vibration_{in/\sec}}{FRF\ Mobility_{in/\sec/lbf}} = lbf$$

$$F_{lbf\,1X\,Run\,Speed} = \frac{1.586_{in/\sec}}{0.00219_{in/\sec/lbf}} = 722\ lbf$$

Modal Test

This force level was reasonable for a rotor with an estimated weight of 3,000 lbs operating at 938 RPM balanced to between G-2.5 and G-6.3.

If balanced to ISO 1940-1 G-2.5, the unbalance force was calculated as follows:

$$\omega_{rad/\sec} = \frac{2\pi(RPM)}{60} = \frac{2 \bullet \pi \bullet 938}{60} = 98.23\, rad/\sec$$

$$Disp_{mm\ rms} = \frac{Velocity}{rad/\sec} = \frac{2.5\, mm/\sec}{98.23\, rad/\sec} = 0.001\, mm, rms$$

$$Disp_{inch\ op} = \frac{0.001\, mm\ rms}{25.4\, mm/in} x 1.414 = 0.0014\, in, pk$$ or Mass Eccentricity

$$F_{lbf} = 1.77 \bullet oz \bullet in \bullet \left(\frac{RPM}{1000}\right)^2$$

$$F_{lbf} = 1.77 \bullet (3{,}000 lb \bullet 16 oz/lb) \bullet 0.0014 in \bullet \left(\frac{938}{1000}\right)^2$$

$$F_{lbf} = 105.9\, lbf$$

Modal Test

This force level was reasonable for a rotor with an estimated weight of 3,000 lbs operating at 938 RPM balanced to between G-2.5 and G-6.3.

If balanced to ISO 1940-1 G6.3, the unbalance force was calculated as follows:

$$Disp_{mm\ rms} = \frac{Velocity}{rad/\sec} = \frac{6.3\,mm/\sec}{98.23\,rad/\sec} = 0.064\,mm, rms$$

$$Disp_{inch\ op} = \frac{0.064\,mm\ rms}{25.4\,mm/in} \bullet 1.414 = 0.0036\,in, pk$$

$$F_{lbf} = 1.77 \bullet oz \bullet in \bullet \left(\frac{RPM}{1000}\right)^2$$

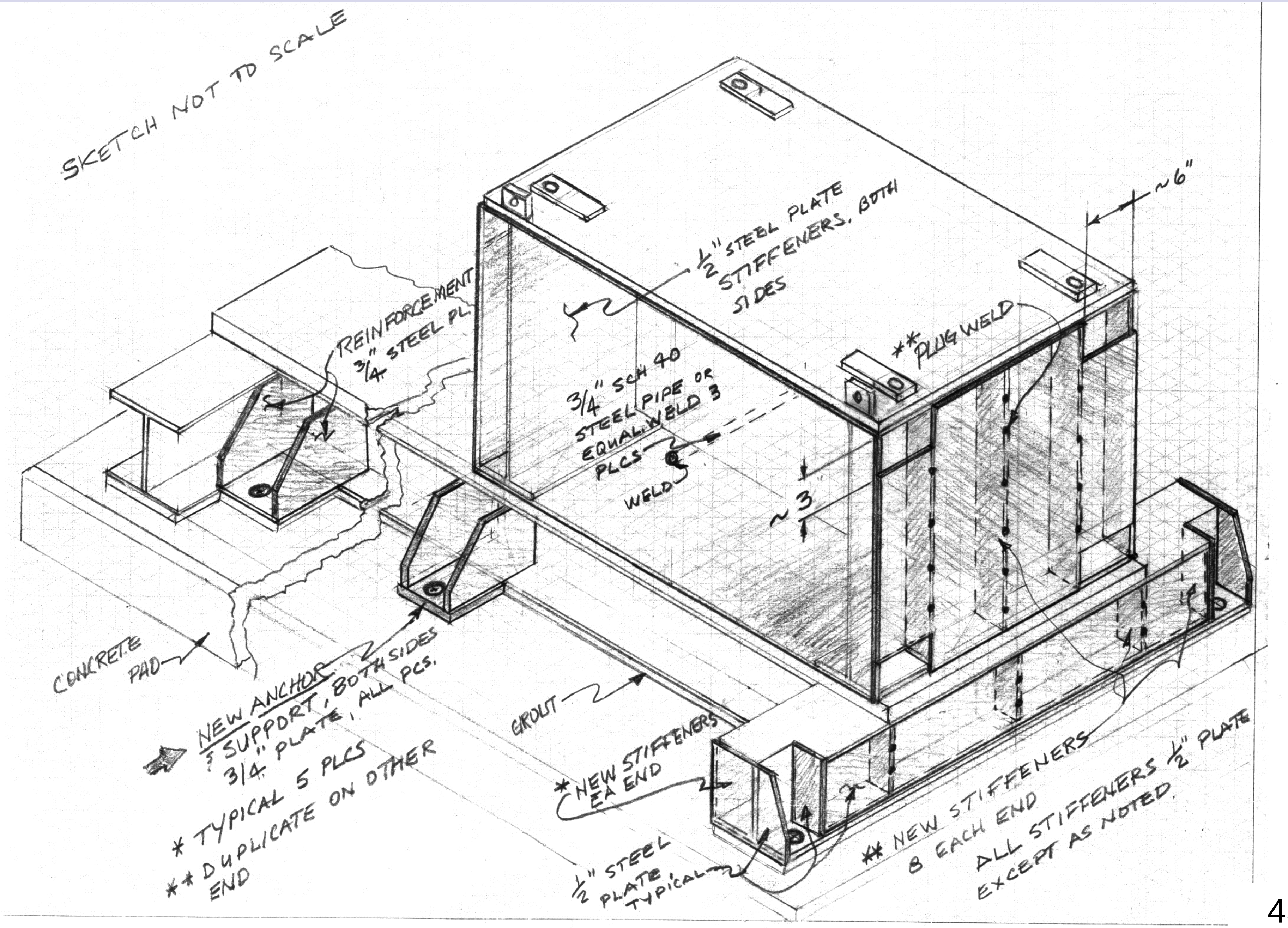
$$F_{lbf} = 1.77 \bullet (3{,}000\,lb \bullet 16\,oz/lb) \bullet 0.0036\,in \bullet \left(\frac{938}{1000}\right)^2$$

$$F_{lbf} = 266.9\,lbf$$

Recommendations

1. Stiffen each skid and the motor pedestal (to increase horizontal natural frequency above the running speed and pump vane passing frequency).
2. Install two additional anchor bolts at the Motor Inboard Skid location to reduce flexure of the skid.
3. Weld gussets to the left side of the pump skid at the pump end to increase stiffness of the skid at the anchor bolt location.

Recommended Skid Modifications



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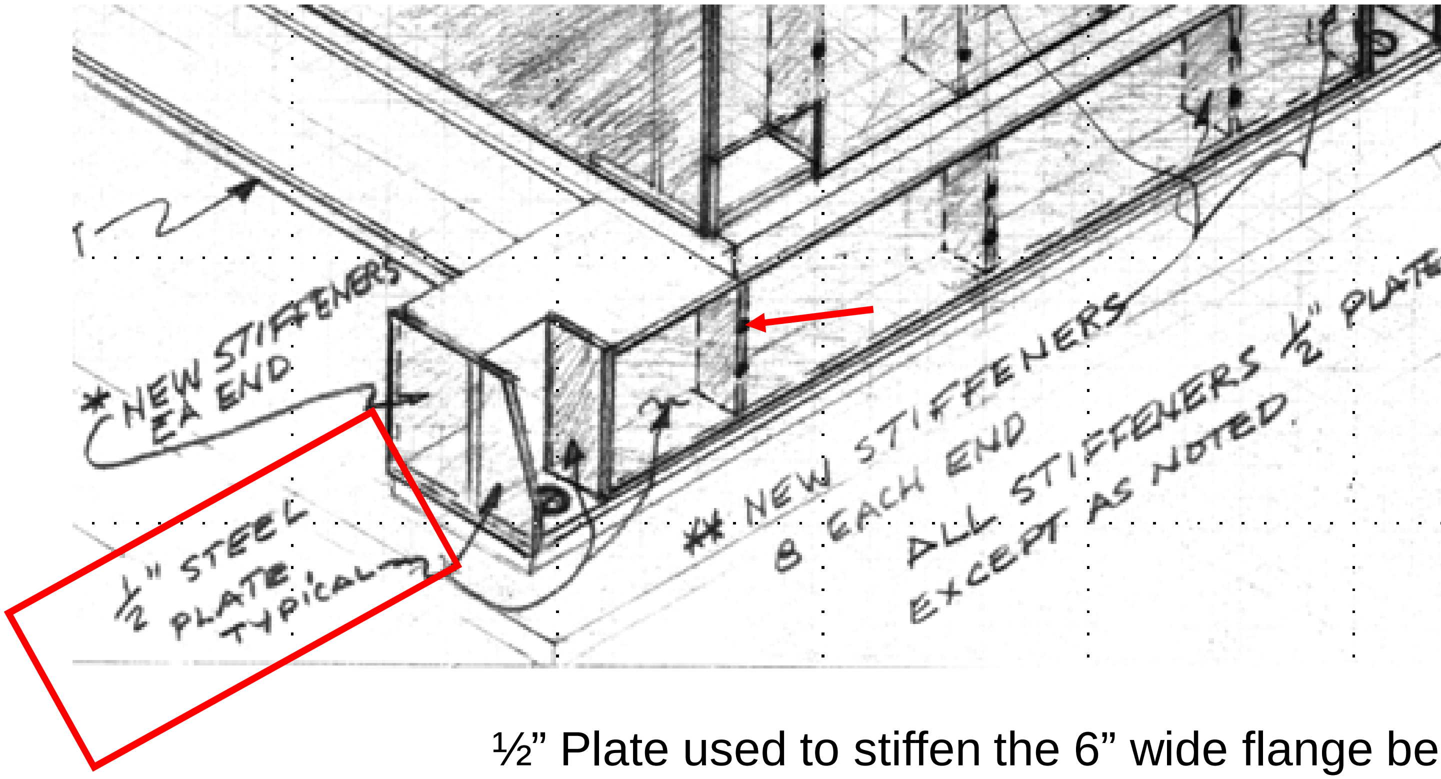
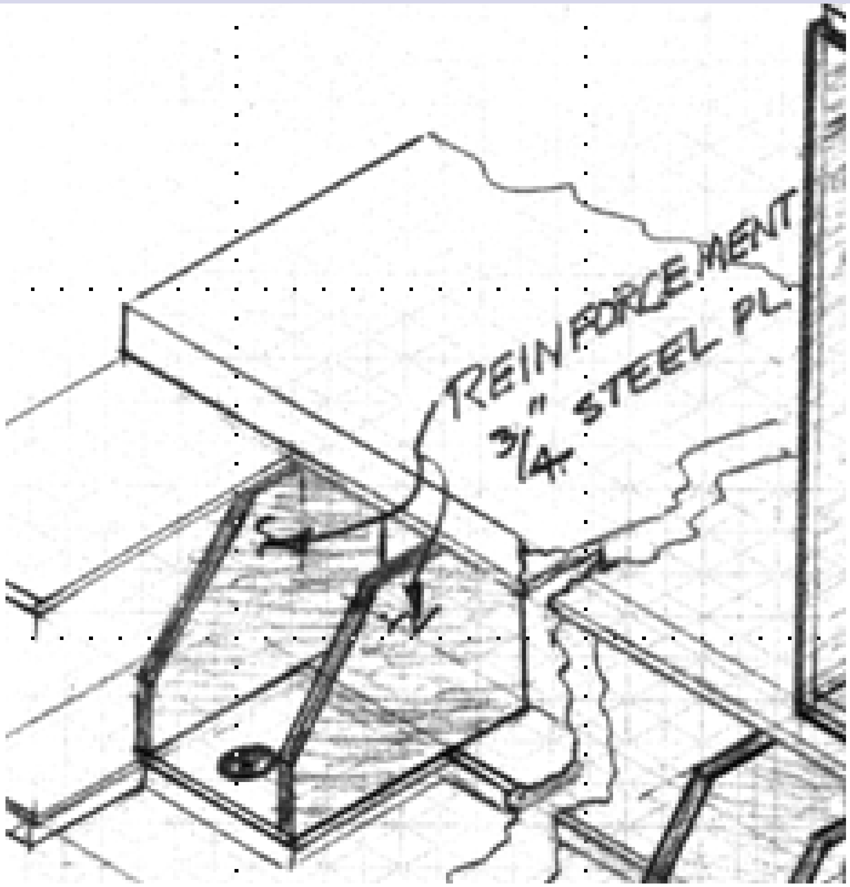


½” Plate used to stiffen the 6” wide flange beams.

Vertical gussets of ½” plate and ½” plate plug welded to the 6” wide flange and the vertical gussets to increase stiffness in the vertical (Z) direction.

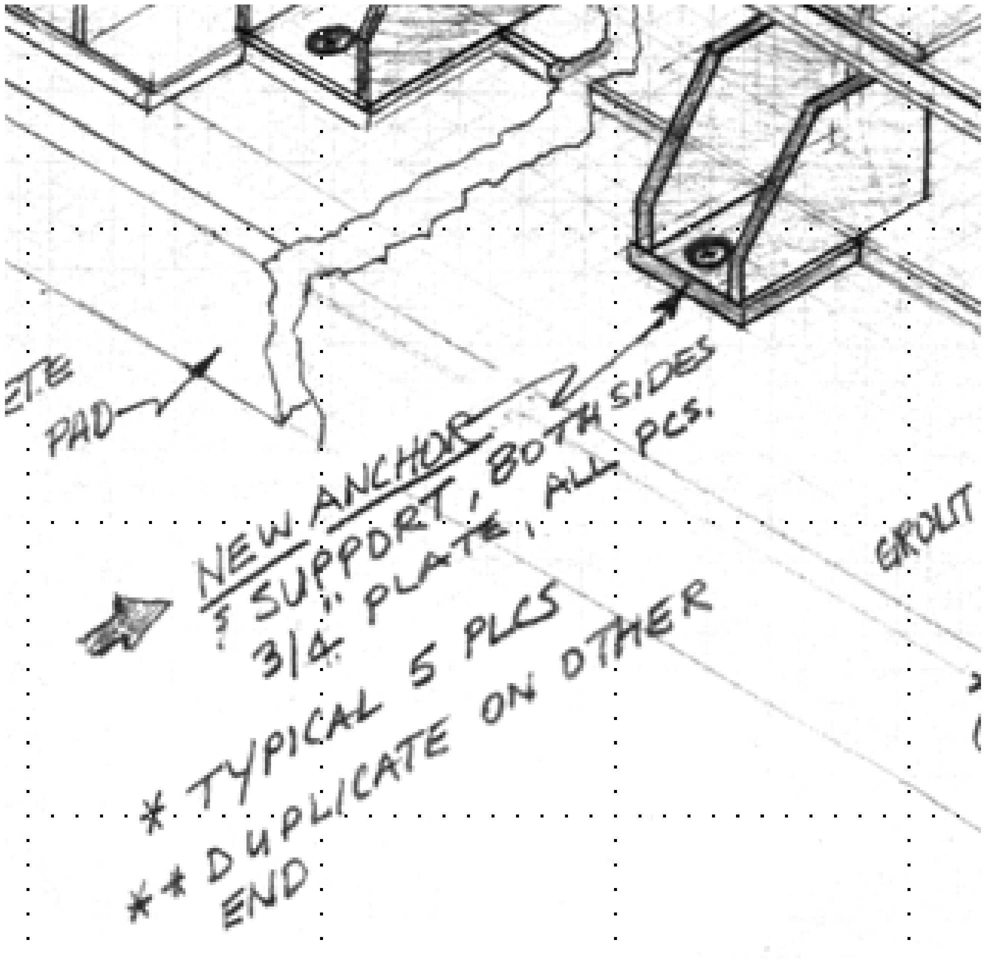
Recommended Skid Modifications



Pump End of Skid:

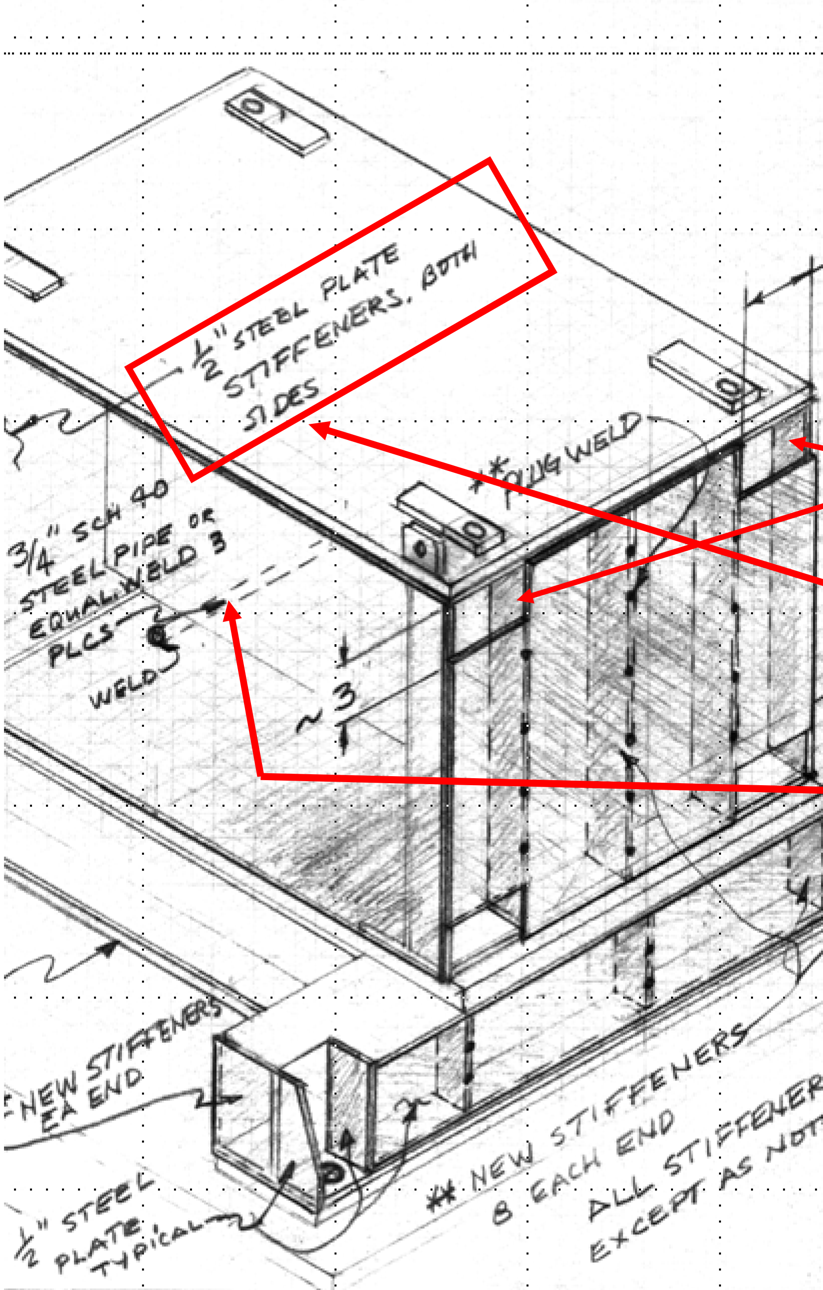
¾” Plate Reinforcement for Anchor Bolt.

Recommended Skid Modifications



At Motor IB End: Both Sides of Skid, New Anchor Bolt Supports of ¾" Plate.

Recommended Skid Modifications



Motor Support Modification

Vertical stiffeners of ½" plate and ½" plate plug welded to the stiffeners and the 16" wide flange beams, both ends.

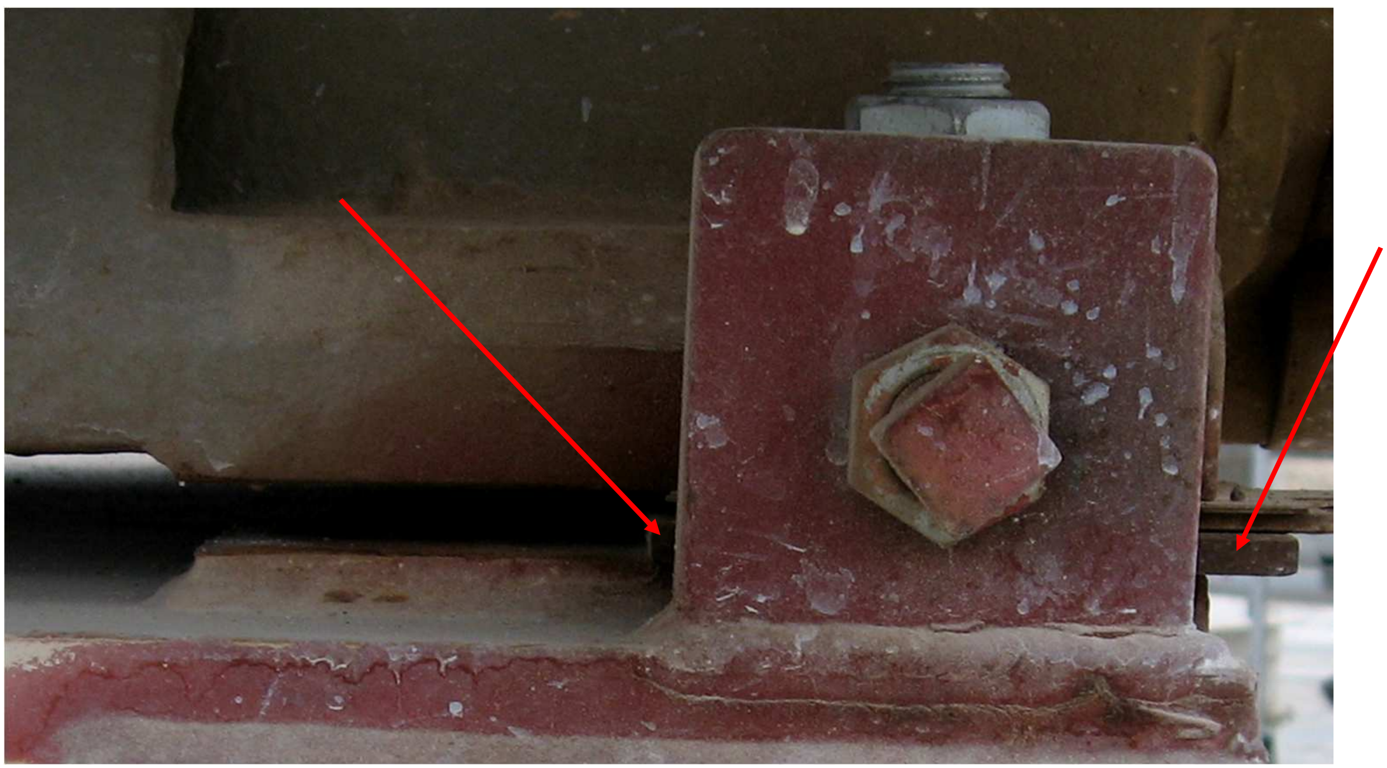
3" openings to access motor hold down bolts.

½" plate stiffeners welded to both sides.

¾" SCH 40 Pipe stiffeners welded three places to stiffen the plate to avoid low frequency bending natural frequencies of the plate.

Recommendations

4. Remove the carbon steel shims from the motor shim stack and replace with ground stainless steel shims. Limit shim stack to 5 shims.



Recommendations

1. Stiffen each skid and the motor pedestal (to increase horizontal natural frequency above the running speed and pump vane passing frequency).
2. Install two additional anchor bolts at the Motor Inboard Skid location to reduce flexure of the skid.
3. Weld gussets to the left side of the pump skid at the pump end to increase stiffness of the skid at the anchor bolt location.
4. Remove the carbon steel shims from the motor shim stack and replace with ground stainless steel shims. Limit shim stack to five shims.
5. Replace the motor hold down bolt washers with washers a minimum of ½” thickness and hole size no more than 1/16” larger than the bolts.

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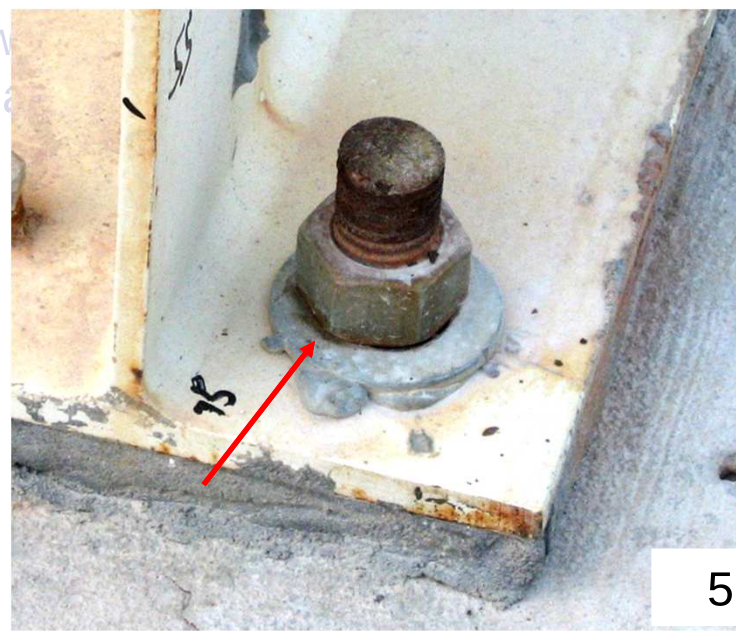
5. Replace the motor hold down bolt washers w
   thickness and hole size no more than 1/16" la
6. Replace anchor bolt washers with washers a minimum ½" thick and hole size no more than 1/16" larger than the bolts.



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4. Remove the carbon steel shims from the motor shim stack and replace with ground stainless steel shims. Limit shim stack to five shims.
5. Replace the motor hold down bolt washers with washers a minimum of ½” thickness and hole size no more than 1/16” larger than the bolts.
6. Replace anchor bolt washers with washers a minimum ½” thick and hole size no more than 1/16” larger than the bolts.
7. To correct the relative movement between the concrete base and concrete pad, injection of epoxy grout should be considered. If stiffening of the structural steel is successful, then grout injection may not be required.

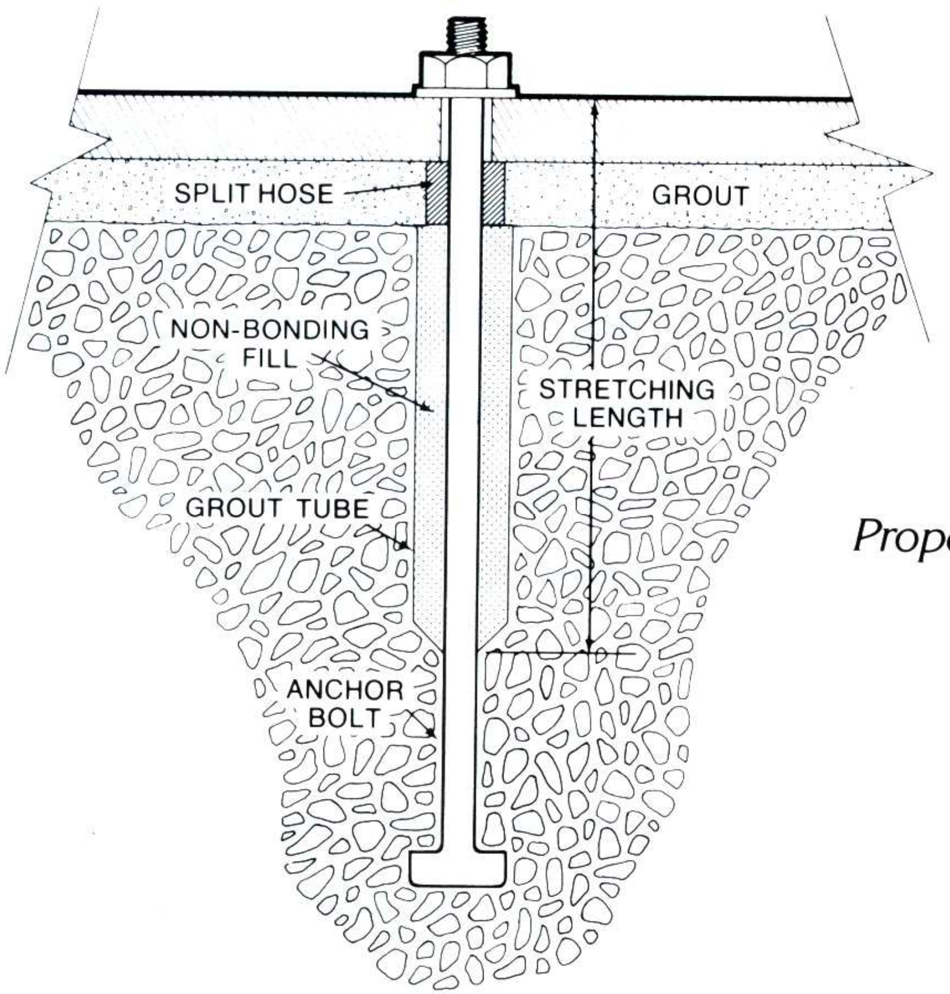
Recommendations

1. Stiffen each skid and the motor pedestal (to increase horizontal natural frequency above the running speed and pump vane passing frequency).
2. Install two additional anchor bolts at the Motor Inboard Skid location to reduce flexure of the skid.
3. Weld gussets to the left side of the pump skid at the pump end to increase stiffness of the skid at the anchor bolt location.
4. Remove the carbon steel shims from the motor shim stack and replace with ground stainless steel shims. Limit shim stack to five shims.
5. Replace the motor hold down bolt washers with washers a minimum of ½” thickness and hole size no more than 1/16” larger than the bolts.
6. Replace anchor bolt washers with washers a minimum ½” thick and hole size no more than 1/16” larger than the bolts.
7. To correct the relative movement between the concrete base and concrete pad, injection of epoxy grout should be considered. If stiffening of the structural steel is successful, then grout injection may not be required.
8. Confirm that the anchor bolt installation method used a sleeve to provide adequate stretch length of the bolts.

Recommendations

Recommended Anchor Bolt Installation

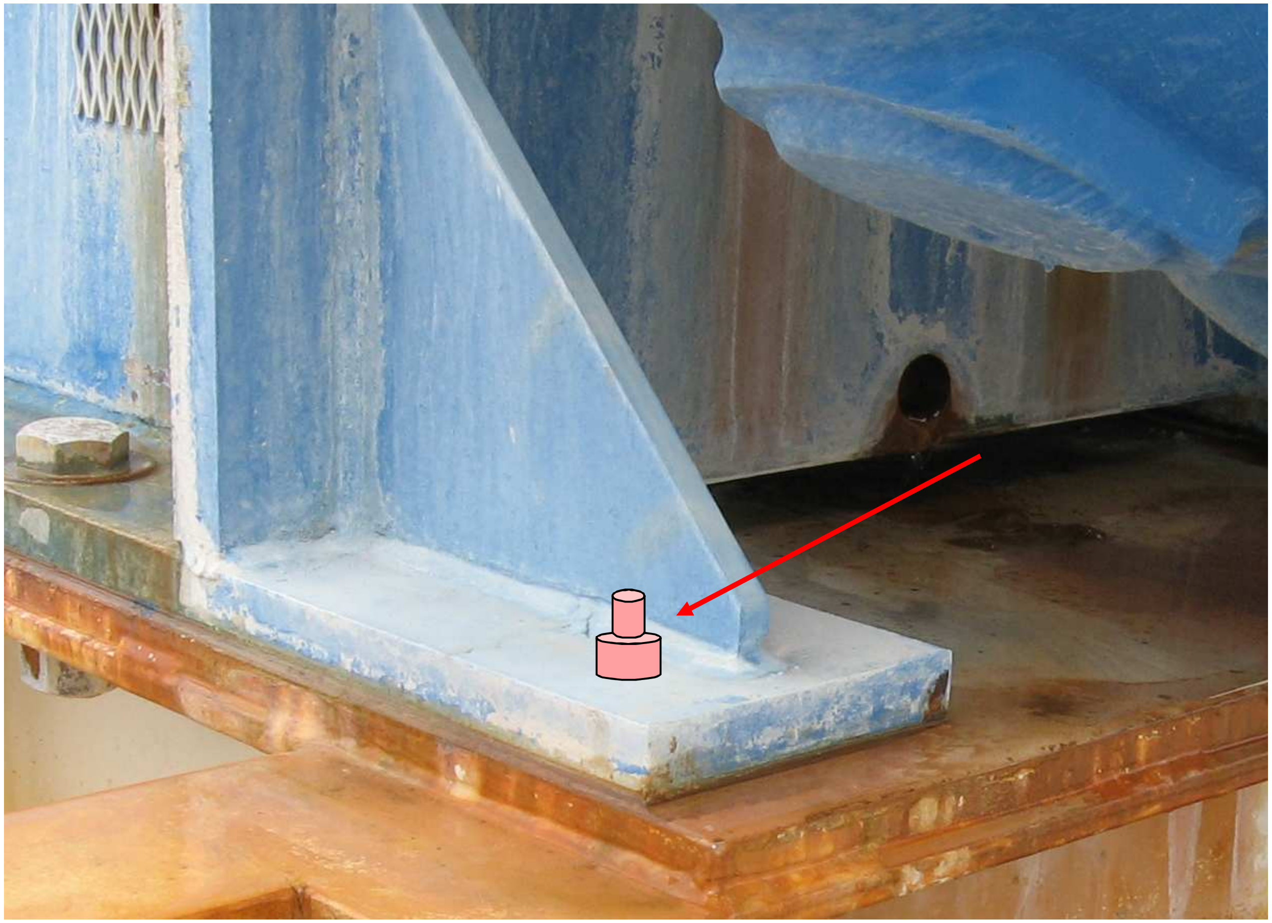
Reference Escoweld 7505E/7530 Machinery Grout.



Proper method of installing anchor bolts.

Recommendations

9. Install Hold Down Bolts Through Pump Base and Skid Both Sides.



Recommendations

9. Installing Hold Down Bolts Through Pump Base and Skid Both Sides.

10. After modification to the skid and motor pedestal, realign the motor to the pump to generally accepted industry guidelines for 1200 RPM

Motor Speed, RPM	Parallel Offset (mils)		Angular Misalignment (mils)	
	Excellent	Acceptable	Excellent	Acceptable
1200	+/- 1.25	+/- 2.0	0.5	0.8
1800	+/- 1.0	+/- 1.5	0.3	0.5
3600	+/- 0.5	+/- 0.75	0.2	0.3

Table 2. Industry Generally Accepted Shaft Alignment Tolerances.

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11. Following the modifications, retake vibration data to confirm the natural frequencies were shifted a sufficient amount away from the exciting frequencies and that vibration amplitudes are acceptable.

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During discussions later with the client a few months later, we were advised that the recommendations were implemented and the vibration problem was resolved and they were very pleased.

We have not had opportunity to return to the site to take vibration data and review the implementation of the recommendations.

End