POWER HOUSE FD & ID FANS
ANALYZING CONCRETE FOUNDATION RESONANCE

Ken Singleton

Manager
KSC Consulting LLC, Bristol VA
ksingleton@vibrationconsulting.com

Bob McGinnis, P.E.
McGinnis Engineering LLC, Kingsport TN

Abstract: A request was received to investigate high amplitude vibration of forced draft (FD) and induced draft (ID) fans at a coal fired power plant. Operating deflection shape analysis (ODS) and experimental modal analysis (EMA) were specifically requested. Of most concern was reported vibration amplitude over 0.40 in/sec pk on the ID Fan A outboard bearing. Steel bracing had been bolted to the ID Fan's outboard pedestals in an attempt to reduce vibration. In-place balancing had been performed but was not effective in reducing the primarily axial direction vibration. Vibration data on the motor and fan bearing housings was monitored by a System 1 online acquisition system acquiring data from velometers. Proximity probes were not installed at the fluid film bearings.

During three days onsite, test data was measured that included standard vibration data, ODS, EMA and multi-channel continuous data acquisition. Natural frequencies of the outboard pedestal of ID Fan A, inadequate hold down bolt tightness, inadequate and improper bracing and weak foundations were some of the problems identified. Recommendations were provided to increase stiffness of the ID and FD fan's outboard pedestals by redesigning braces to bolt to a large concrete mass, correcting bearing housing, pedestal and motor bolting issues and checking journal alignment to the babbitted bearings.

Keywords: Bearing housing, experimental modal analysis, hold down bolts, operating deflection shape analysis, pedestal, resonance.

Background: The power plant went into commercial service June 2008. The two ID Fans were direct coupled to 3950 HP, 1196 RPM motors using grid couplings. Concrete foundations were poured then the fan pedestals and motor pedestals poured later. The fan rotors were supported in Dodge Sleevoil babbitted bearings. The ID Fan rotors weighted 30,000 lbs. Rotors were reported balanced to ISO 1940-1 balance quality G 2.5 which calculated to 57 oz-in at the drive end and 55 oz-in opposite drive end. ID Fan motor bearings were babbitted while the FD Fan motors were equipped with rolling element bearings.

Visual Inspection: Before any vibration data was taken, a thorough visual inspection was made of all fans. This inspection identified several items as follows:

- The ID Fan bearing housings were bolted to fabricated steel bases which were bolted to soleplates. The soleplates were bolted and grouted to the concrete pedestals. The pedestals appeared undersized for the 30,000 lb_f fan rotors.

- The two ID Fans were located end-to-end with the outboard pedestals 12' 6" apart. ID Fan A is shown in **Figure 1**. This fan had the highest reported vibration amplitude of the outboard bearing housing axial direction.

Figure 1. ID Fan A.

Vibration had reportedly exceeded 0.40 in/sec pk. A Steel brace had been installed in an attempt to reduce the bearing housing axial vibration. The brace was fabricated of 8" square tubing and bolted to both ID Fan's outboard pedestals, as shown in **Figures 2 & 3**.

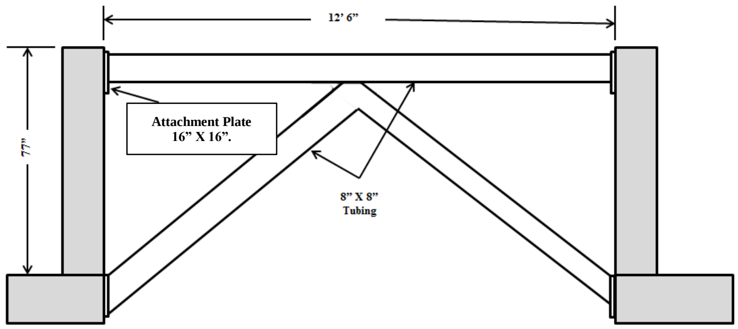

Figure 2. Brace of 8" Square Tubing Bolted to ID Fan Outboard Bearing Concrete Pedestals.

Figure 3. ID Fan A & B, Outboard Pedestals, Steel Bracing Bolted to Each Pedestal.

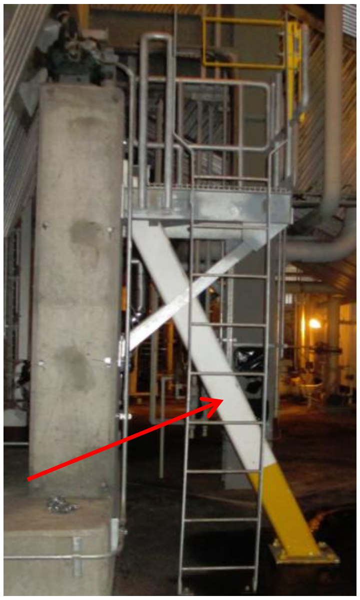

Figure 4: ID Fan A Outboard Bearing Pedestal Single Brace 30 Deg Angle.

- Bracing was also installed on the FD Fan outboard fan pedestals, **Figure 4**. These braces were also fabricated of 8" square tubing and installed at a steep 25 degree angle. Access to the bearings was by ladder. Brace plates were bolted to the concrete pedestal and concrete floor. The brace was not completely effective in reducing vibration to acceptable amplitudes.

- ID fan's concrete foundations had many cracks that appeared to extend deep within the foundations, **Figure 5**. The quality of the concrete appeared substandard.

- ID and FD Fan concrete pedestals did not appear bonded to the concrete foundations although rebar likely extended from the foundations up into the pedestals. Drawings were not available to verify construction details. The joint was cracked at the interface of the pedestals and foundation, shown by photo of ID Fan A outboard pedestal, **Figure 6**.

Figure 5. ID Fan A Foundation Crack.

- FD Fan A Motor OB Bearing was not accessible from the platform.

- No proximity probes were installed in the Dodge Sleevoil bearings. Vibration monitoring was by GE Bently System 1 acquiring data from velometers magnetically attached to the bearing housings or stud mounted to brackets bolted to the housings.

- ID Fan bearing housing hold down bolts used thin washers under the bolt heads. The slotted holes in the bearing housings for hold down bolts were very large, see **Figure 7**. Much thicker washers were needed to insure adequate clamping force without yielding of the washers.

- ID Fans A & B Motor hold down bolts to a fabricated base used tapped holes in 1" thick steel instead of through bolting with washers and nuts, **Figure 8**.

Figure 6. ID Fan A, OB Concrete Pedestal & Foundation Interface.

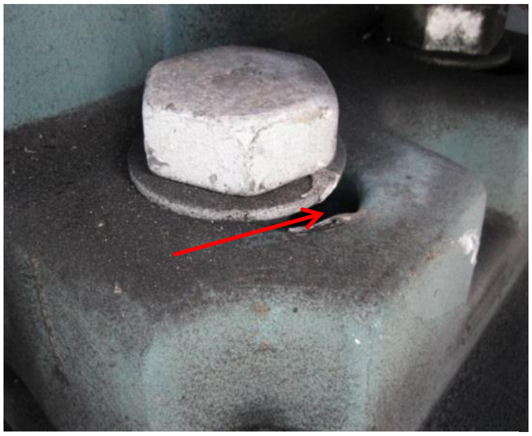

Figure 7. ID Fan A, Inboard Bearing Housing Hold Down Bolt – Washer Was Too Thin.

Figure 8. ID Fan A & B Motor Hold Down Bolts Used Tapped Holes in Fabricated Steel Base.

Initial Vibration Data on ID & FD Fans: The initial vibration survey of the ID Fan's A & B motor and fan bearing housings showed highest amplitude vibration at the fan's outboard bearing housings at 2X rotor rotational frequency.

FD Fan A motor drive end bearing housing vibration data indicated a rolling element bearing defect. Per verbal information, a bearing had failed previously at this location and that motor was out for repair.

The frequency spectrum and waveform data for ID Fan A outboard bearing housing, axial direction is shown in **Figure 12**. Note the bubble of energy at the base of the 2X frequency which typically is an indicator of resonance. The lower frequency portion of the spectrum plot with log magnitude scaling is shown in **Figure 13**. This plot more clearly shows indication of resonance near the 2X frequency.

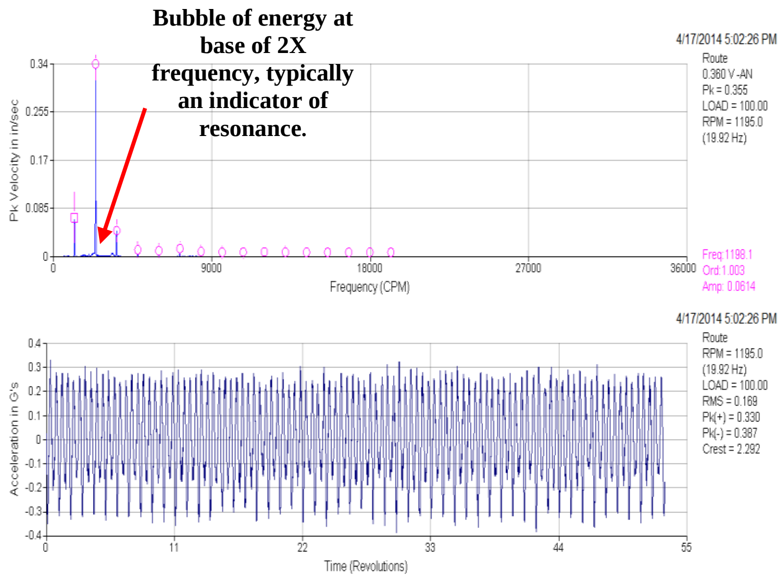

Figure 12. ID Fan A, Outboard Bearing, Axial Direction in/sec pk.

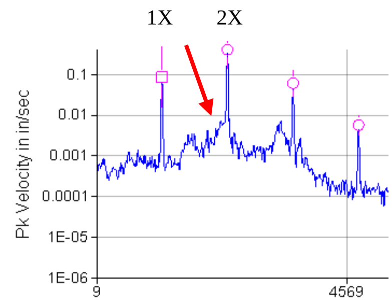

Figure 13. Log Mag Scaling of Lower Frequencies Shows More Clearly Resonance Indication.

Data is plotted in **Figures 14-19** for the ID and FD fans Overall, 1X and 2X vibration. Note that the charts show AMCA Alarm Filter Out (overall) for Startup (Green), Alarm (Yellow) and Shutdown (Red) applicable to these fans. AMCA does not specify a vibration limit for 2X so estimated limits are shown.

Data showed that ID Fan B, see **Figure 14**, had higher overall amplitude vibration than ID Fan A. The overall vibration amplitudes for the outboard bearing housing horizontal measured 0.252 in/sec pk. Axial vibration at the top of the bearing housing measured 0.492 in/sec pk (well above Shutdown Limit). ID Fan A had lower levels but vibration amplitude of the outboard bearing housing axial direction was at Alarm level.

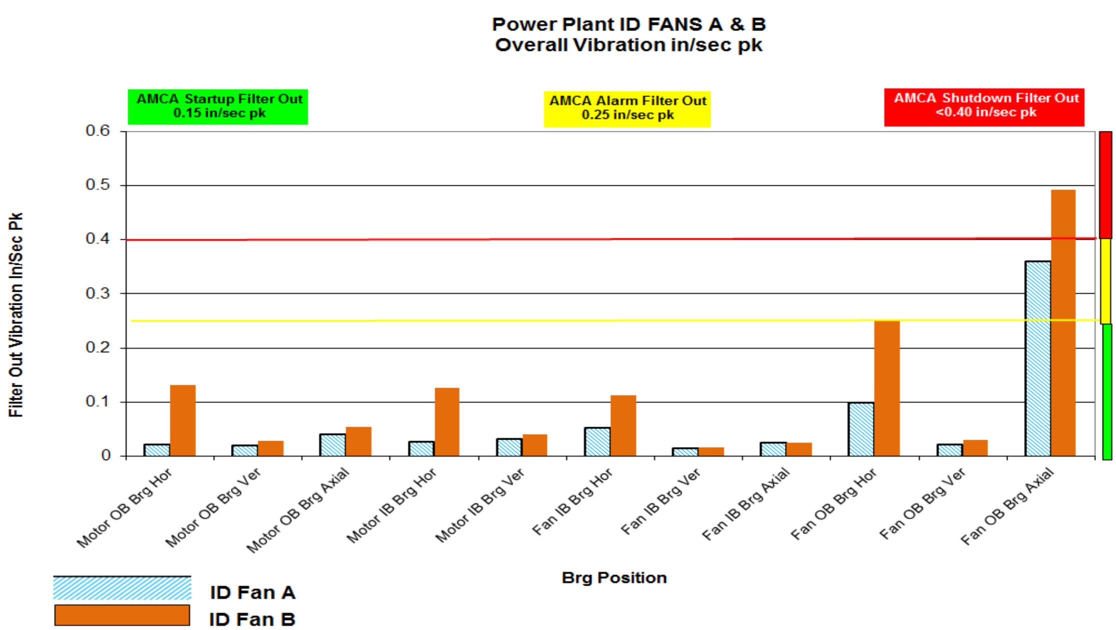

Figure 14. ID Fan's Overall Vibration in/sec pk.

The ID Fan's 1X vibration is shown in **Figure 15**. ID Fan B had much higher amplitude vibration than ID Fan A. ID Fan B outboard fan bearing housing amplitudes were above recommended Shutdown levels and some points were above Alarm Level. Misalignment of the Dodge Sleevoil bearing to the journal was considered likely as well as amplification of the vibration by structural natural frequencies. Amplitude in the axial direction of ID Fan B outboard bearing housing was 0.333 in/sec pk

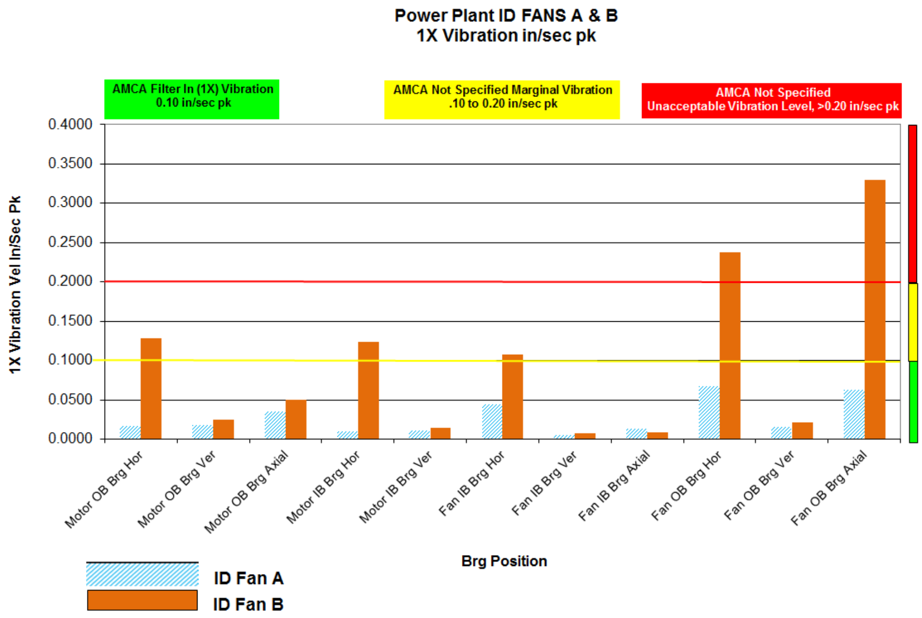

Figure 15. ID Fan's A & B Vibration at 1X, in/sec pk.

ID Fans A & B vibration measured at 2X is shown in **Figure 16**. Both ID Fan's outboard fan bearing housings had very high amplitude vibration at 2X rotor run speed.

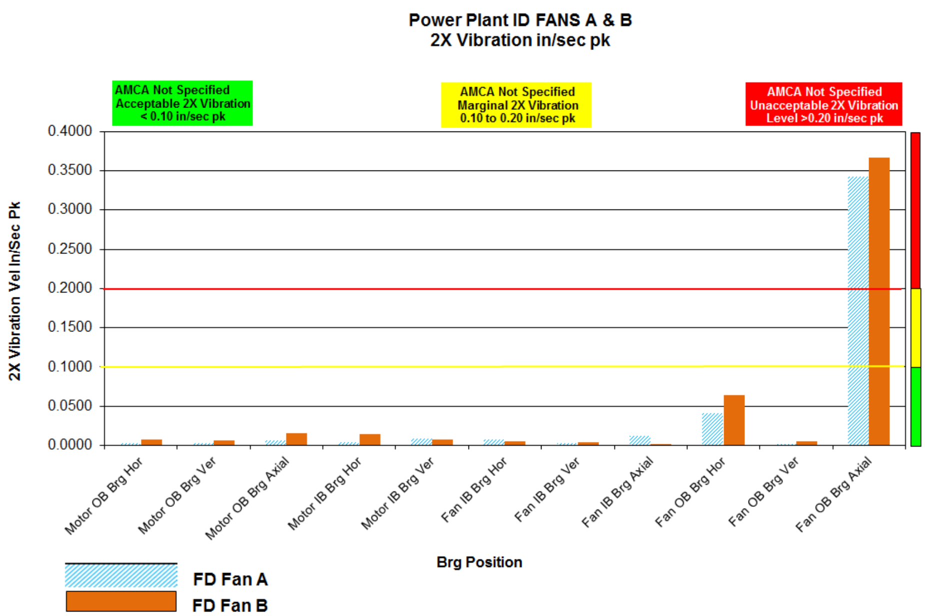

Figure 16. ID Fan's A & B Vibration at 2X, in/sec pk.

FD Fans A & B overall vibration is shown in **Figure 17**. All points were below AMCA recommended Startup amplitude of 0.15 in/sec pk. The client reported that the FD Fans had experienced high amplitude of vibration in the past.

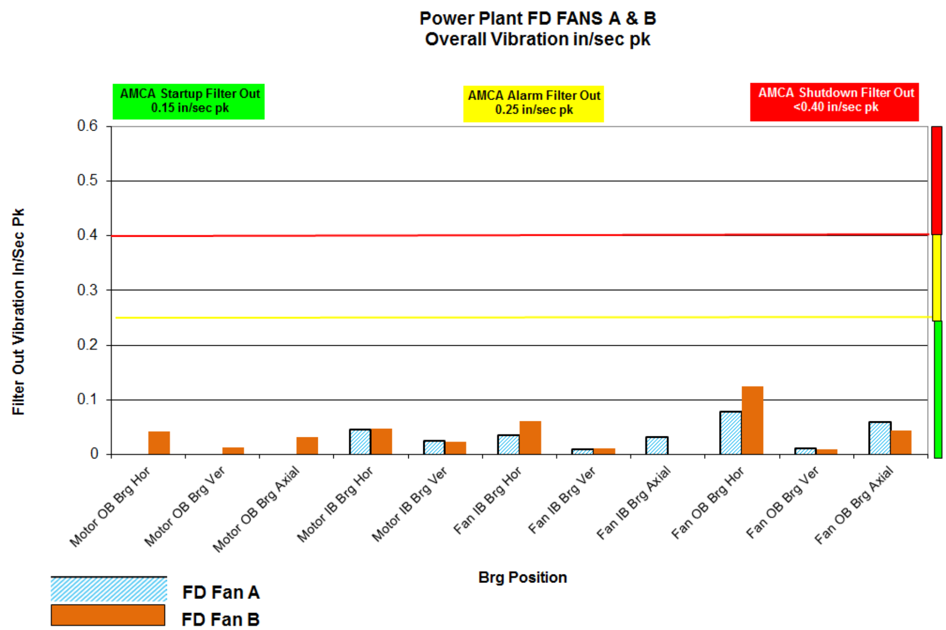

Figure 17. FD Fan's A & B Overall Vibration in/sec pk.

Vibration amplitude at 1X for FD Fans A & B was well below AMCA Startup level with except of one point on FD Fan B, outboard bearing housing horizontal direction, see **Figure 18**.

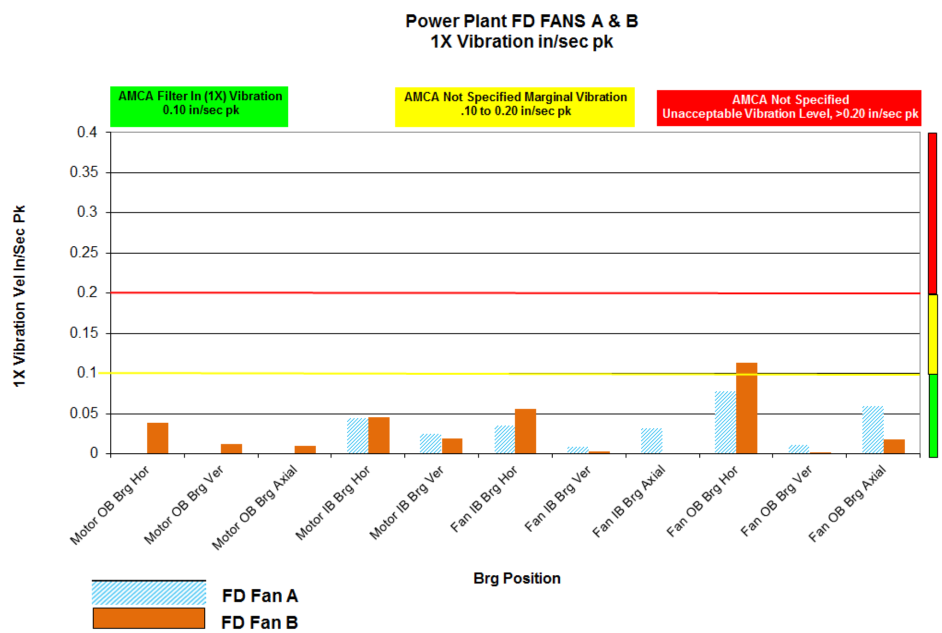

Figure 18. FD Fan's A &B 1X Vibration in/sec pk.

FD Fans A & B vibration at 2X is shown in **Figure 19**. Although AMCA does not specify a vibration tolerance the amplitudes were not considered excessive.

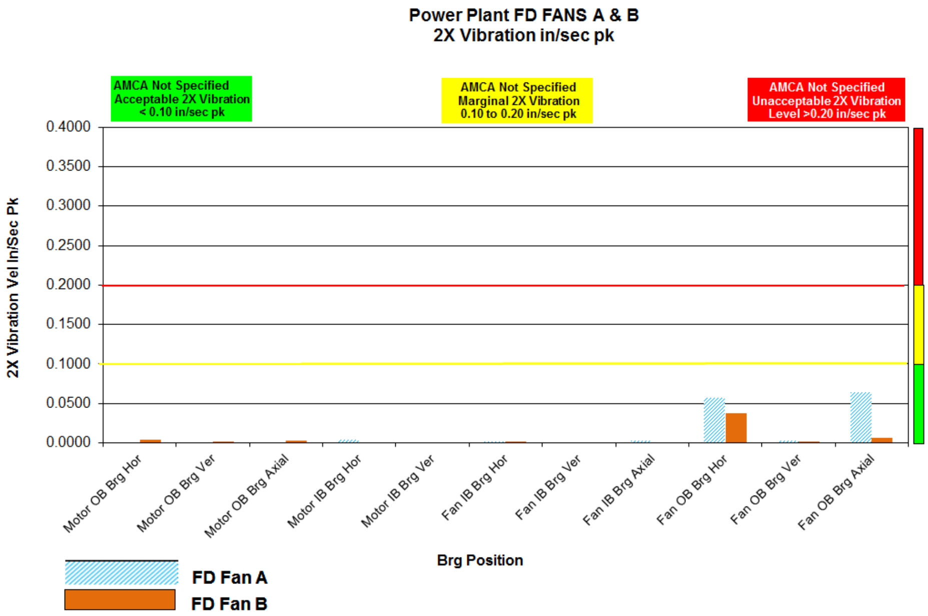

Figure 19. FD Fan A & B Vibration at 2X, in/sec pk.

ODS Analysis: The ODS Model was developed using ME'scopeVES [Ref 2]. The 3D computer model included the concrete foundation, concrete pedestals, motor, fan bearing housings, fabricated steel base supporting the fan bearing housings and soleplates, see **Figure 20**. ME'scopeVES provides drawing tools to develop very realistic models. Our models are typically drawn to scale as was this model.

The overall dimensions of the concrete foundation were 386" X 199". The fan concrete pedestals were 67" wide X 18" thick X 77" tall. The model was drawn using individual components so that any relative motion

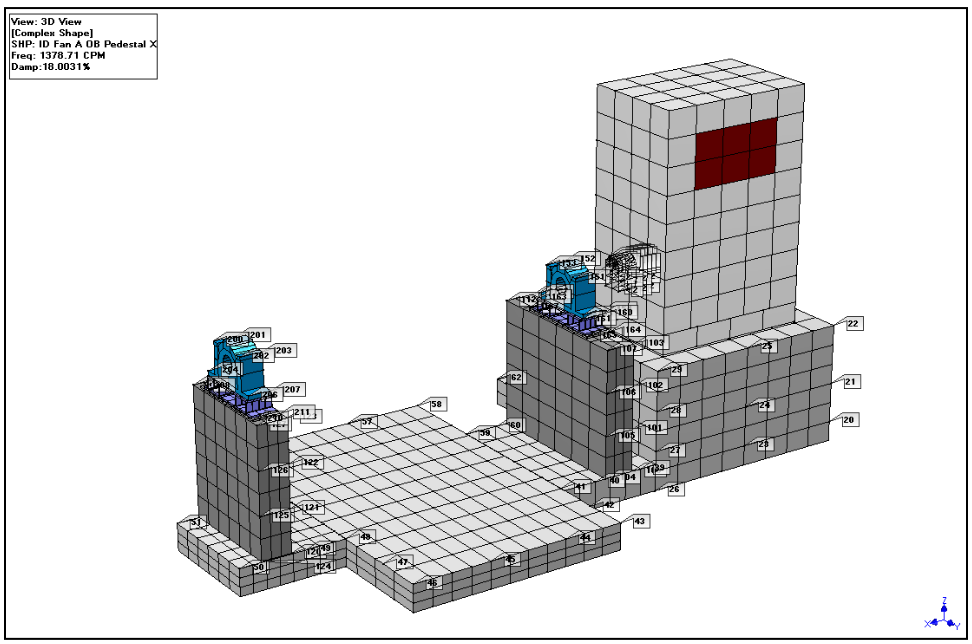

Figure 20. ME'scopeVES Model of ID Fan A.

could be displayed when animated. It is important to generate the model animation equations correctly in order to accurately show any relative motion between the bearing housings, fabricated bases, soleplates, pedestals, etc. A close up view of the outboard bearing and pedestal model is shown in **Figure 21**.

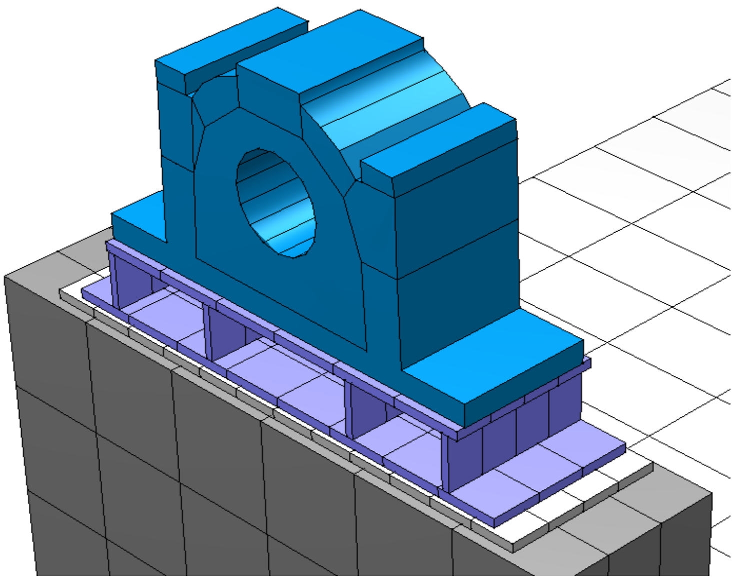

Figure 21. Detail of Fan Outboard Bearing, Fabricated Base, Soleplate and Concrete Pedestal.

Concrete Foundation and Pedestal Vibration Measurements: Prior to measuring vibration data at the DOFs on the concrete, targets of 410 SS were epoxied at DOF coordinates measured using a steel tape. A recently introduced epoxy, Loctite Epoxy Metal/Concrete [Ref 1], with high strength bonding in 5 to 10 minutes was used. Approximately one hundred twenty five targets were epoxied to the concrete foundation and pedestals. ID Fan A outboard pedestal, East side is shown in **Figure 22** with epoxied targets.

Figure 22. ID Fan A Outboard Pedestal With 410 SS Targets Epoxied.

The ODS FRF Data was measured using a two channel CSI 2130 Analyzer and low frequency CTC AC133 500 mV/g accelerometers [Ref 5]. Flat rare earth magnets were used to attach the accelerometers to the 410 SS targets, as shown in **Figure 23**. Data was also measured on the motor, fan bearing housings, fabricated supports and soleplates. After uploading the data to the Emerson AMS software, the ODS FRF were exported to ME'scopeVES for generation of 3D structural animations.

Since high amplitude vibration of ID Fan A was of most concern to the client, ODS data was only measured on this fan. But, the findings were applicable to ID Fan B and the FD Fans which were of similar construction.

A Note About ODS FRF: The ODS FRF has advantages over Transmissibility when viewing the frequency plots. Transmissibility is a ratio measurement (amplitude & phase) that measures relative vibration of the roving sensor or sensors to the vibration of the fixed sensor at the reference DOF or reference point. The Transmissibility therefore does not contain peaks in the frequency plot and does not provide the true vibration amplitude (just the ratio). An ODS FRF is calculated like an FRF and has magnitude and phase for each bin of the FRF. The ODS FRF magnitude is the Auto Spectrum of the Roving response and its phase is the difference between the phases of the Roving Response and the Reference Response sensors. The ODS FRF therefore looks like a frequency spectrum and the correct amplitude is displayed in the magnitude trace, Ref [6].

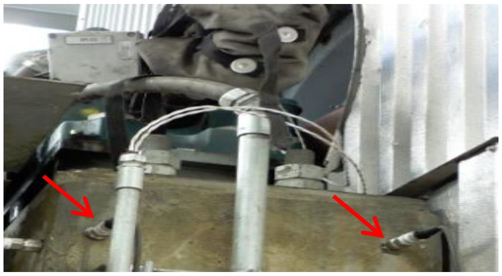

Figure 23. Flat Rare Earth Magnets Attached 500mV/g Low Frequency Accelerometers.

Analysis of the ODS animations for ID Fan A indicated the following:

- IB bearing housing fabricated steel base and soleplate showed low amplitude slippage relative to the concrete pedestal. Inadequate tightness of the anchor bolts was indicated.
- IB bearing housing low amplitude relative slippage to the fabricated steel base. Bearing housing hold down bolts inadequate preload or stretch was indicated.
- OB bearing pedestal rocking side-to-side (Y Axis) and axially (X Axis) with highest amplitude vibration at 2X run speed. There was low amplitude vibration of the pedestal relative to the concrete foundation. There was bearing housing slippage on the fabricated steel base which indicated inadequate bolt preload or stretch.

The vibration amplitudes at some DOF for 1X run speed frequency on ID Fan A outboard pedestal are shown in **Figure 24**. The amplitudes were not considered excessive.

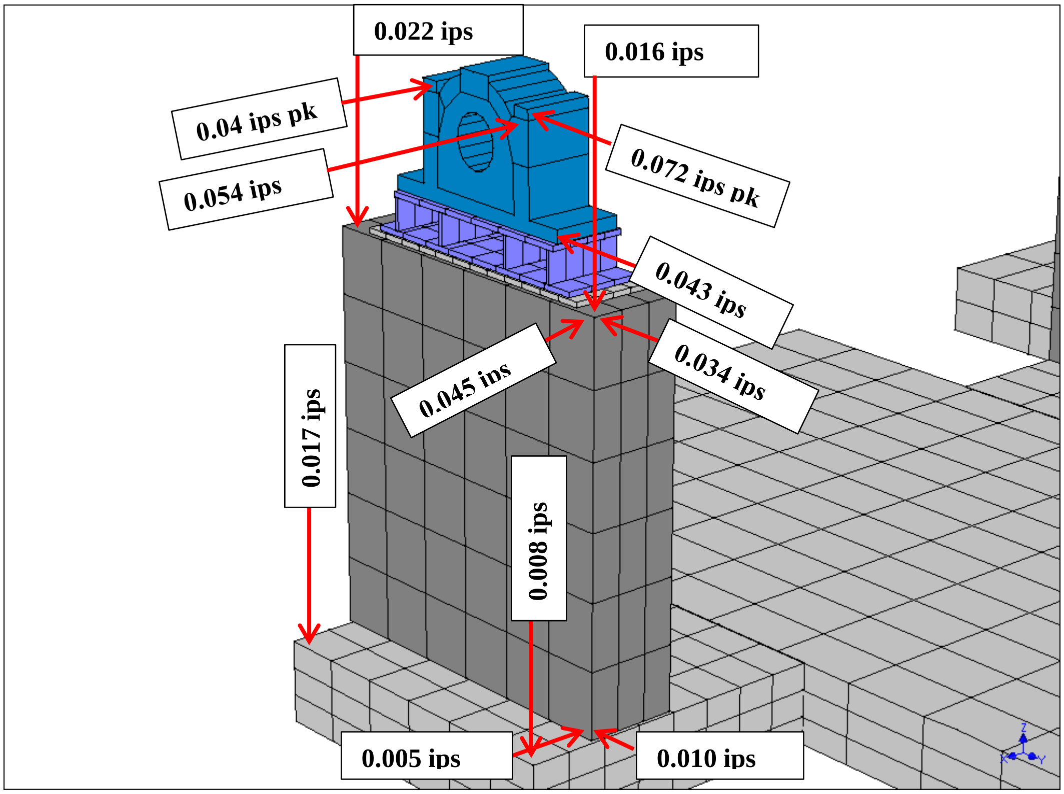

Figure 24. ID Fan A OB Pedestal Vibration at 1X Run Speed Frequency.

A photo of the Dodge Sleevoil bearing and pedestal at the fan outboard position is shown **Figure 25**.

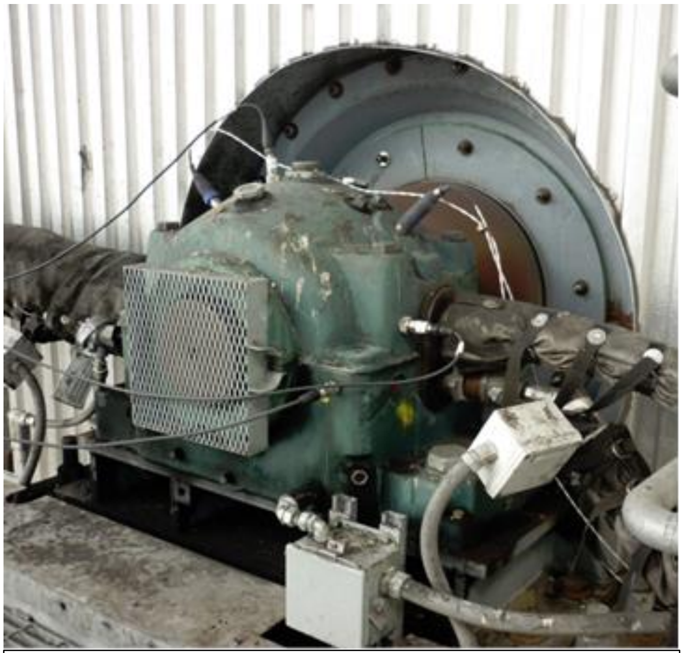

Figure 25: ID Fan A, Outboard Bearing Housing.

The ODS model of the inboard bearing housing, fabricated base, soleplate and pedestal are shown in **Figure 26**. Some DOF are labeled with vibration amplitude at 1X. Low amplitude slippage of the bearing housing on the fabricated steel base was indicate by the ODS data. However, very little relative vibration of the soleplate to the concrete was indicated.

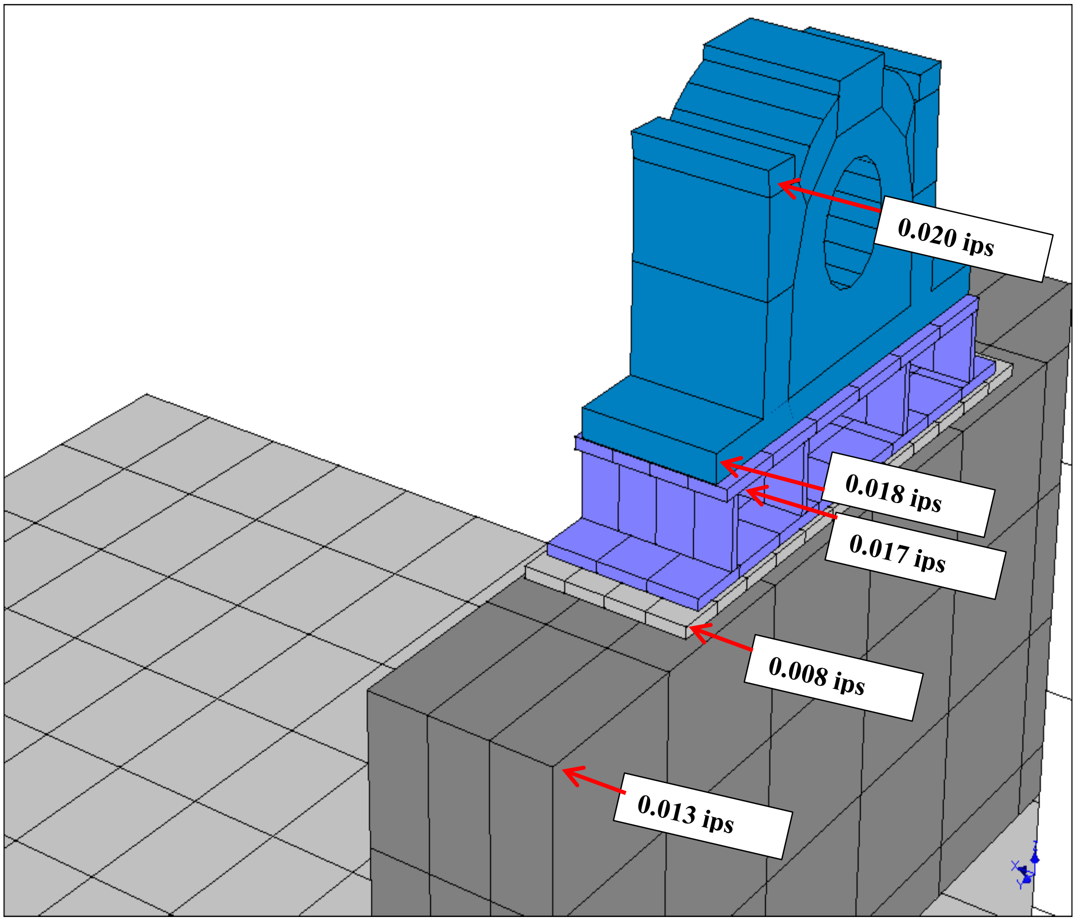

Figure 26. ID Fan A, IB Brg Housing, Support and Pedestal. ODS Amplitude at 1X Shaft Rotational Frequency.

A photo of the inboard bearing housing is shown in **Figure 27**.The laser tachometer used to generate a once per revolution signal for our multi-channel data acquisition system is also shown. A piece of reflective tape had been attached to the shaft by a previous consultant and we were able to obtain a stable once per revolution trigger.

Figure 27. ID Fan A Inboard Bearing.

ODS Analysis of Vibration at 2X: ODS data at 2X rotor run speed showed much higher amplitude vibration of the outboard bearing housing and pedestal. The ME'scopeVES model is shown in **Figure 28** with some DOF labeled with vibration amplitudes. Slippage of the soleplate on the concrete pedestal was indicated which could be caused by inadequate tightness of the anchor bolts. Continual slippage would wear the grout.

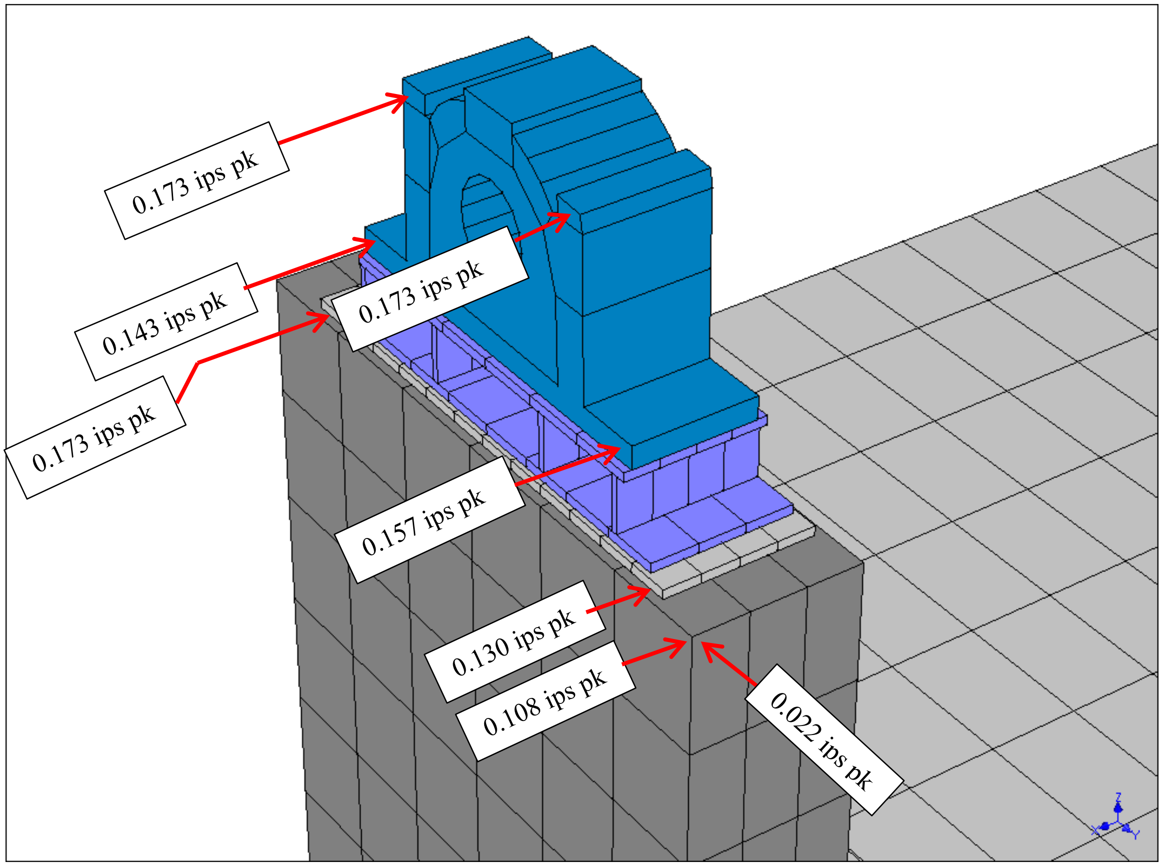

Figure 28 ID Fan A OB Bearing & Pedestal With Some DOF Vibration Amplitude Labeled at 2X Run Speed.

A view of the ODS Model for ID Fan A OB Pedestal to concrete foundation interface is shown in **Figure 29**. The pedestal had a rocking motion. Low amplitude slippage at 2X was indicated by the data although the vibration amplitudes were very low.

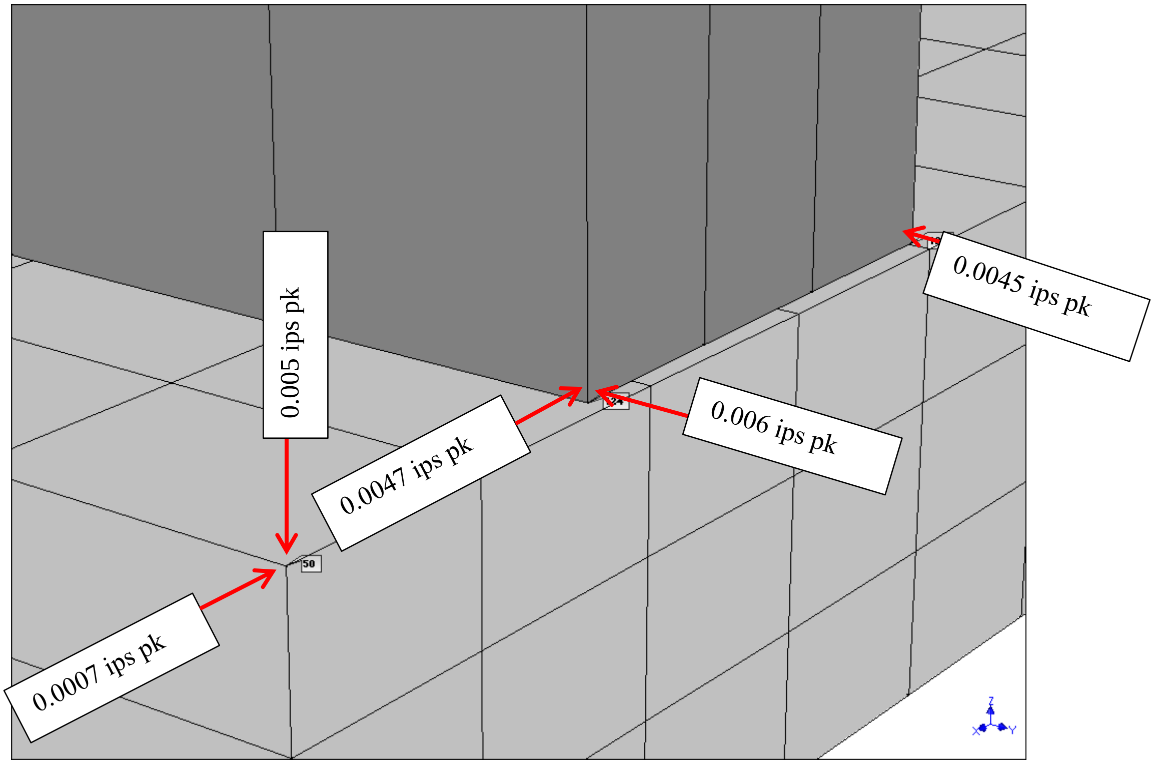

Figure 29. ID Fan A, OB Bearing Pedestal Interface to Concrete Foundation.

ID Fan A Outboard Bearing Pedestal Modal Test: The outboard bearing pedestal was modal tested using a 130 lb_f steel ram with a 50,000 lb_f force head stud mounted. A soft grey tip was attached to the force head to limit the excitation frequency band width from about 0 to 10,000 CPM. The ram was supported by Nylon slings and a motorized man lift, see **Figure 30 & 31**.

The pedestal modal test in the Y (side-to-side) direction was conducted by impacting with the force head at the top of the concrete pedestal at one corner. Impacts were on the left side (as viewed from the motor). Response was measured with low frequency CTC AC133 500 mV/g accelerometer magnetically attached to the 410 SS targets. Eight FRF were measured along both sides of the pedestal taking five averages for each DOF. The magnitude portion of the FRF driving point g/lb_f is shown in **Figure 32**. The cursors in the plot are located at the fan 1X and 2X frequencies. Curve fitting the data found the following:

- Natural frequency at 1432.84 CPM with 14.59 % of critical damping.
- Natural frequency at 2508.71 CPM with 3.20 % of critical damping.

Figure 30. Author **(Singleton) With Steel Ram Equipped With 50,000 lb$_f$ Force Head Supported by Nylon Slings.**

Figure 31. ID Fan A, OB Bearing Pedestal. Modal Test in Y Direction (Side-to-Side).

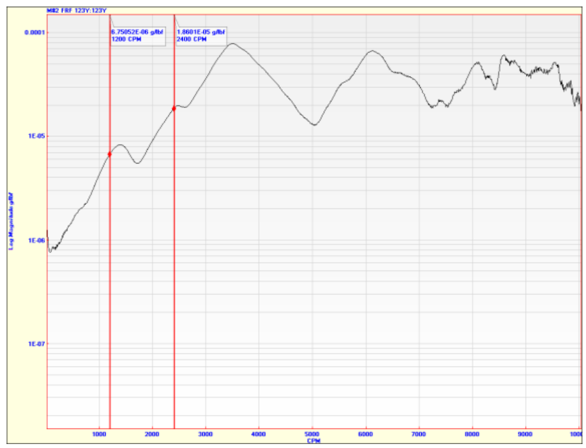

Figure 32. ID Fan A Driving Point FRF in Y, 123Y:123Y.

The modal test in the axial direction (X) was conducted by impacting the base of the bearing housing since the concrete pedestal was not accessible, see **Figure 34**. The driving point FRF is shown in **Figure 33**. The cursors are located at the fan's 1X and 2X run speed frequencies. Curve fitting the FRF data found the following:

- 1378.71 CPM 18.0 % of Critical Damping (Just above 1X)
- 5107.24 CPM 3.85 % Critical Damping

The driving point FRFs measured on the outboard pedestal were used to calculate the dynamic stiffness or modal stiffness as follows:

- Horizontal (Y Axis) 6,058,920 lb$_f$/in at 1200 CPM 8,795,430 lb$_f$/in at 2400 CPM.
- Axial (X Axis) 6,258,190 lb$_f$/in at 1200 CPM 2,102,690 lb$_f$/in at 2400 CPM.

The FRF response would have been affected by the steel bracing between the OB Pedestals of ID Fan A & B. Also note that the fan shaft was not rotating which would also affect the FRF measurements. Based on the modal and vibration test data, the estimated dynamic force at ID Fan A outboard bearing pedestal and bearing housing calculated as follows:

- 1X Run Speed Top of Pedestal Horizontal (X) 2754 lb_f
- 2X Run Speed Top of Pedestal Horizontal (X) 1120 lb_f

- 1X Run Speed Bearing Housing Axial (Y) 2634 lb_f
- 2X Run Speed Bearing Housing Axial (Y) 2326 lb_f

The fans were AMCA Class BV 4. ANSI/AMCA Standard 801-01 (R2008) recommended balance quality grade was G2.5 for Class BV 4 ID/FD Fans.

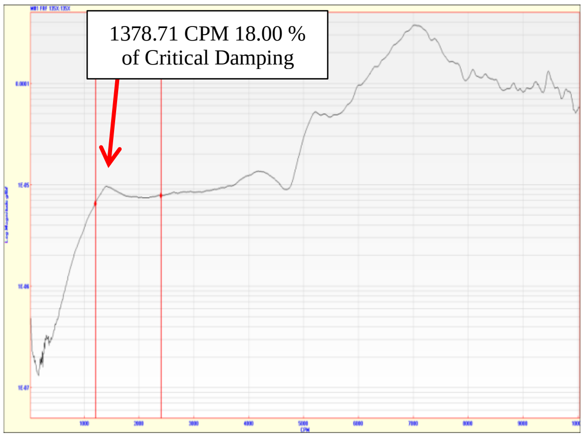

Figure 33. ID Fan A, OB Pedestal FRF Reference DOF 135X:135X.

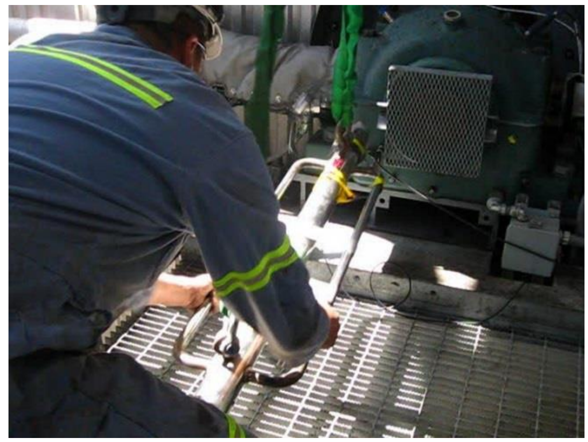

Figure 34. ID Fan A, OB Bearing Pedestal Modal Test in X Direction (Axial). Impact Location was at base of the Bearing Housing since Concrete Pedestal Was Not Accessible.

Curve fitting the modal test data and animating the ME'scopeVES model of the outboard bearing pedestal showed rigid body rocking mode shapes in X and Y directions. The mode shapes are plotted in **Figures 35-38**.

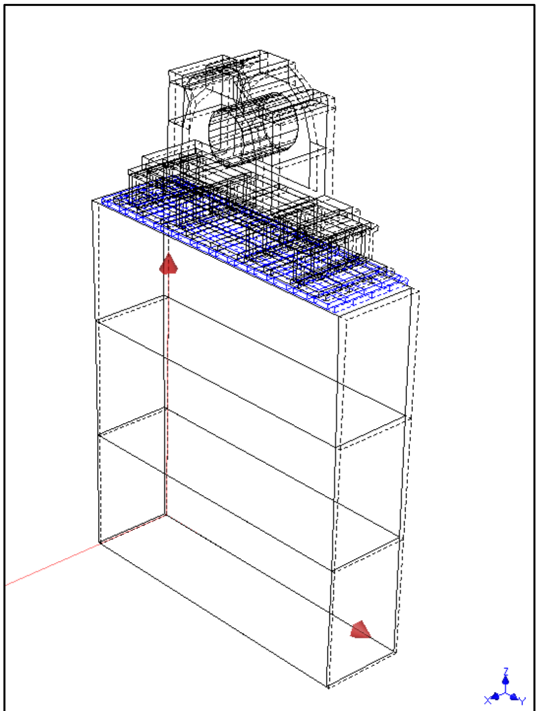

Figure 35. ID Fan A Outboard Bearing Pedestal Modal Test, Mode Shape 1401 CPM Rocking Side-to-Side in Y.

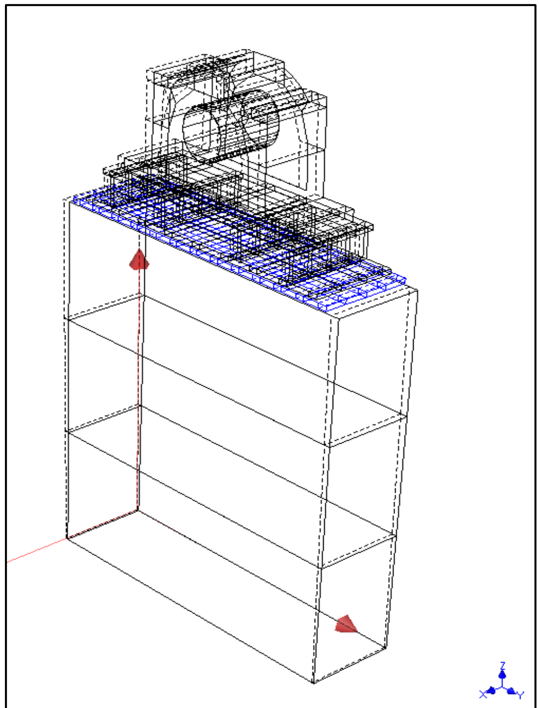

Figure 36. ID Fan A Outboard Bearing Pedestal Modal Test, Mode Shape 2509 CPM Rocking Side-to-Side in Y.

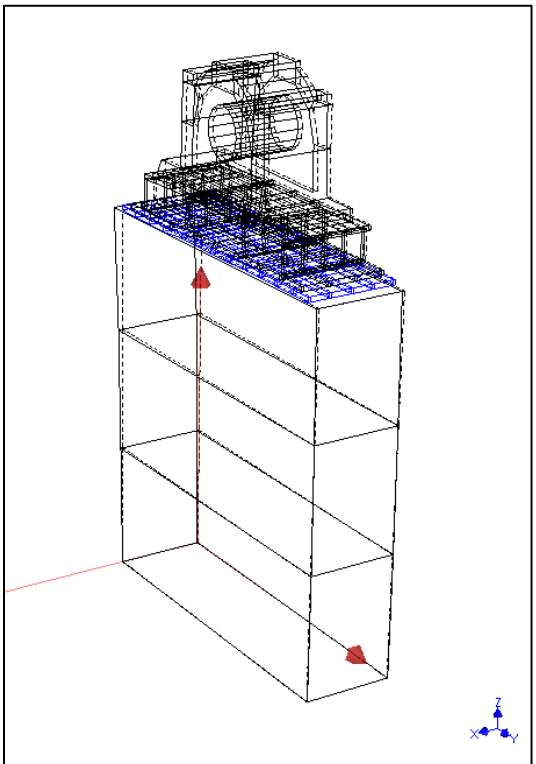

Figure 37. ID Fan A Outboard Bearing Pedestal Modal Test, Mode Shape 1378 CPM Rocking in X (Axial).

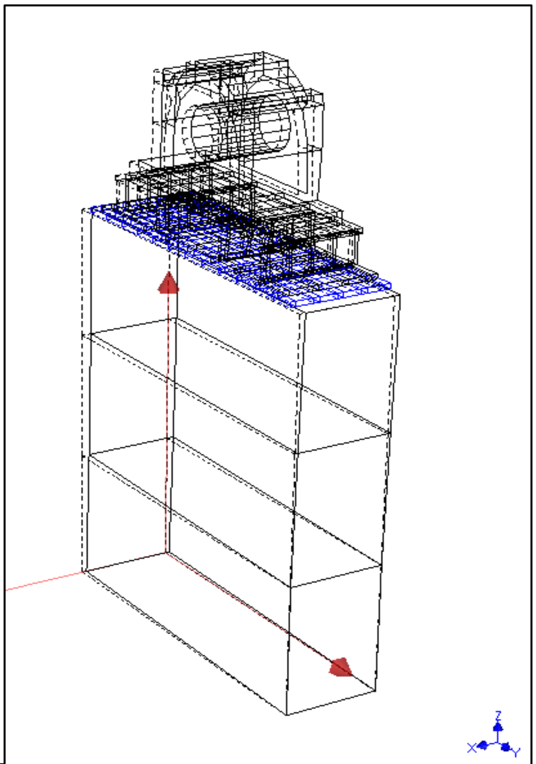

Figure 38. ID Fan A Outboard Bearing Pedestal Modal Test Mode Shape 5107 CPM Rocking in X (Axial).

Conclusions:

1. Visual inspection the FD & ID Fans identified several potential problems as follow:

- The fan concrete pedestals were undersized and lacked mass and rigidity to support the 30,000 lb_f fan rotors. Removing the pedestals and pouring massive pedestals was discussed with the client but not doable in the short time frame available for the outage.
- ID Fan Motors were bolted to a fabricated steel base using tapped holes in 1" thick steel. Through bolting using Grade 8 bolts with thick washers and nuts would have been preferred.
- ID fan concrete foundations had many cracks that appeared to extend deep within the foundations. The quality of the concrete appeared substandard.
- ID and FD Fan pedestals did not appear bonded to the concrete foundation.
- ID Fans A & B outboard pedestals were connected by a steel brace fabricated of 8" square tubing. Brace steel plates were bolted to the concrete pedestals. These plates had a thickness to width ratio which allowed flexing between the attaching bolts and the 8"square tubing. This was also contributing factor to excessive vibration.
- FD Fan A & B outboard pedestals were braced in the axial direction at 25 degree angle with fabricated 8" square tubing. Brace steel plates were bolted to the concrete floor and concrete pedestals. High amplitude axial vibration was reported to have occurred although vibration data we measured was low amplitude.
- FD Fans A & B outboard bearing platform design used ladder access.
- FD Fan A Motor OB Bearing was not accessible from the platform.
- FD Fan B - Motor drive end bearing housing, possible bearing defect frequencies indicated. Bearing numbers were not available to calculate the fault frequencies.

2. ODS Data measured on ID Fan A indicated the following:

- Fan IB Bearing Position:
  - Bearing housing steel fabricated base and soleplate showed low amplitude slippage relative to the concrete pedestal. Inadequate tightness of the anchor bolts was indicated.
  - Bearing housing low amplitude slippage on the steel fabricated base indicated inadequate tightness of the bearing housing hold down bolts.
- Fan OB Bearing Position:
  - Bearing pedestal rocking side-to-side (Y Axis) and axially (X Axis) with highest amplitude vibration at 2X run speed.
  - Bearing pedestal low amplitude vibration relative to the concrete foundation.
  - Bearing housing relative slippage to the steel fabricated base indicating inadequate bolt tightness.

3. Experimental modal test data measured on ID Fan A outboard bearing pedestal indicated the following:

- Pedestal natural frequencies in the Y Axis near 1X and 2X fan run speed frequency frequencies.
- Pedestal natural frequency in the X Axis near 1X fan run speed frequency.

4. Based on modal and vibration test data the dynamic forces acting on the fan outboard bearing pedestal in horizontal direction at 1X run speed = 2754 lb_f.

Residual unbalance for G2.5 Balance Quality calculated as follows:

- Drive End Journal 56.98 oz-in Calculated Unbalance Force 156 lb_f
- Opposite Drive End Journal 55.36 oz-in Calculated Unbalance Force 142 lb_f

ID Fan A rotor residual unbalance forces at the outboard bearing calculated to 19.4 times G2.5.

5. The steel brace between outboard pedestals of ID Fans A & B provided a vibration transmission path. The result was a beat frequency caused by the RPM difference of the two fans at the time of testing 1.97 RPM = 0.0328 Hz = 30.45 Sec. A result of this would be difficulty balancing the fan rotors in-situ since most spectrum analyzers cannot resolve frequencies this close using a once-per-revolution trigger signal.

Recommendations:

1. ID Fans A & B: Inspect the fan outboard bearings for unusual wear pattern of the babbitt and for correct alignment of the bearings to the journal. Replace the babbited bearing if necessary.

   Consider using the following process to insure bearing alignment to the shaft.

   - A feeler gage is inserted at each end and both sides of the bearing bottom half and the journal. The feeler gage should insert exactly to the same depth at the four locations.
   - Plastigage is then laid over the journal at each end of the bearing. Shim stock of 0.005 inch thickness is placed at the bearing split line surfaces. The top half of the bearing is installed on to the bottom half (dowel pins guide bearing top half). Bearing cap bolts and the plunger are torqued to recommended values. Then, the top half is removed and the plastigage checked for proper alignment of the top half of the bearing to the journal.

2. Consider modifying the ID Fan's motor hold down bolts to through bolts with washers and nuts. Grade 8 bolts, nuts and washers should be used.
3. Insure that the fan bearing sole plate anchor bolts and correctly torqued.
4. Insure that the fan bearing housing hold down bolts are properly lubricated and correctly torqued. A minimum ½ inch thick washers and Grade 8 bolts should be used. Thread lubricant should be applied to the threads, bolt heads and nut faces.
5. Insure that the Dodge Sleevoil Bearing plunger bolts are torqued to 3600 in/lb_f = 300 ft/lb_f as stamped on the plunger stud.
6. Remove the steel bracing connecting the ID Fan A & B outboard pedestals. Replace with individual bracing bolted to massive concrete pad per drawing, see **Figure 40**. Install the pedestal reinforcing plates per **Figure 39**.

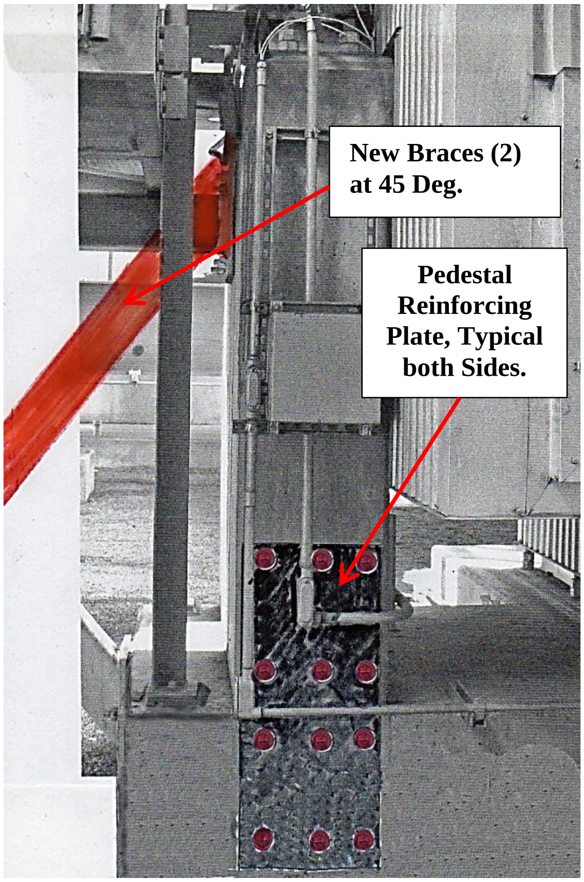

Figure 39. Remove Existing Steel Braces and Install Two Braces at 45 Deg. Bolt Plate to Each Side of Pedestal & Concrete Foundation.

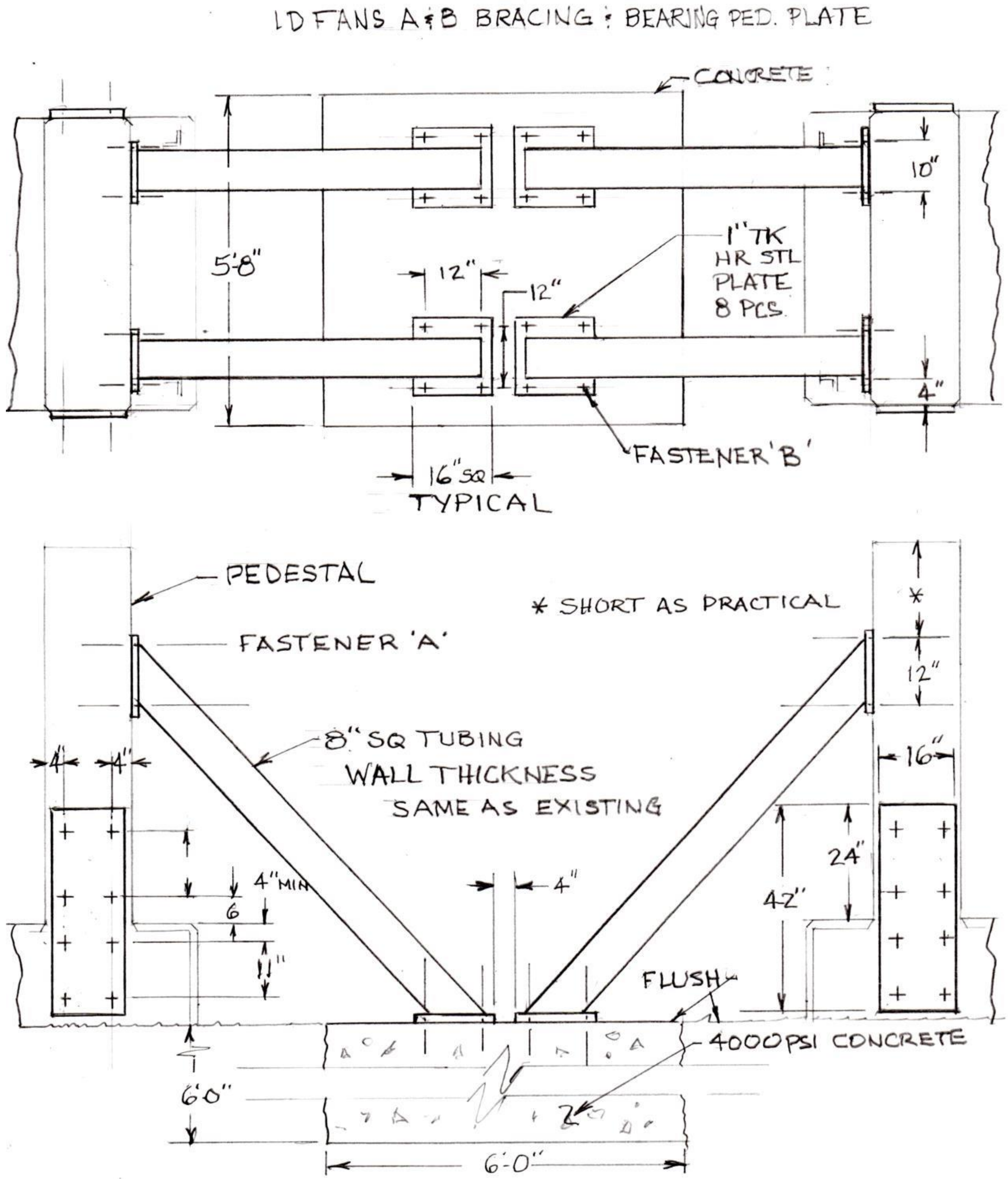

Figure 40. ID Fans A & B Revised Bracing and Pedestal Plate Support.

7. FD Fan A & B

- Consider replacing the bracing of the fan outboard bearing pedestal per **Figure 41**.
- Consider modifying the fan outboard pedestal ladder access with platform and stair access.

Figure 41. FD Fan A OB Pedestal Bracing and Platform Access by Stairs Modification.

8. After replacement of the ID Fan A & B outboard pedestal bracing and all bolting is correctly torqued, plan to balance both rotors to a maximum of G 2.5 residual unbalance. Consider using temporarily mounted proximity probes, [Ref 3] to measure shaft relative displacement to the housing.
9. After replacement of the FD Fan A & B outboard pedestal bracing, plan to balance both rotors to a maximum of G 2.5 residual unbalance.
10. After implementation of the above recommendations, detailed vibration analysis of the ID and FD Fans should be performed to verify that the excessive vibration issue is resolved and that no natural frequencies are near 1X and 2X rotor rotational frequency are present.
11. Consider installing permanent X Y Radial non-contact probes in the ID and FD Fan bearing housings. Two thrust position probes should be installed to monitor the thrust collar position.

We did not return to the job site but during a conversation later with the client, he advised that they had implemented all recommendations.

References:

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