Failure Analysis of a Primary Reactor Cooling Pump Using Modal and Vibration Analysis

Thomas J. Hazelwood and Blake W. Van Hoy

Oak Ridge National Laboratory

1 Bethel Valley Road

Oak Ridge, TN 37831

Telephone: (865) 540-3010

hazelwoodtj@ornl.gov

Abstract

Four pumps redundantly supply primary cooling water to the reactor of the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL). All four pumps underwent maintenance during a recently scheduled downtime. During preliminary evaluation following maintenance, one pump, PU-1A, exhibited higher vibration levels compared to the other three pumps. The pump, being a safety class item, underwent further performance testing to rule out potential damage resulting from the higher vibration. Vibration analysis and modal analysis including steady state spectrum, operational deflection shape, run up transients, and modal impact have been utilized to identify dynamic characteristics that could contribute to the increased vibration levels. This report will cover the testing setup, methodology, analysis results, and recommendations.

Keywords

Condition monitoring, fault analysis, failure prevention, signal analysis, diagnostics

Purpose of Data Acquisition and Analysis

Pump PU-1A, one of four original, primary cooling pumps for the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL), continued to exhibit a vibration velocity greater than the other three pumps after maintenance. Due to the pump being a safety class item, several dynamic measurements were made to identify the root cause of the increased vibration and determine if this vibration might create a potential to cause damage to the pump, its motor, or its associated piping.

Data Acquisition Setup

An eight-channel data acquisition system was utilized for this measurement combined with a modal hammer and seven single axis laboratory grade accelerometers. Five of the accelerometers were epoxied in a single column and oriented radially along the pump's vertical axis. Two of the accelerometers where epoxied onto the attached piping a few feet from the pump. Table 1 lists these sensors, their location, and their software nomenclature.

Table 1 Acquisition Channels

Channel Number	*Sensor Type*	*Placement*	*Geometry Nomenclature*
1	Modal Hammer	Varied	Varied
2	Accelerometer	Top of Pony Motor, Radial	col.1.x
3	Accelerometer	Motor, Upper Bearings, Radial	col.2.x
4	Accelerometer	Motor, Lower Bearings, Radial	col.3.x
5	Accelerometer	Pump, Upper Flange, Radial	col.4.x
6	Accelerometer	Pump, Lower Flange, Radial	col.5.x
7	Accelerometer	Piping, Suction	suc.1.x
8	Accelerometer	Piping, Discharge	dis.1.x

Pump Information

The rated rotational speed of the 600-horsepower motor is 1775 rpm, but it runs at 1781 rpm or 29.68 Hz. Multiple orders of this rotational speed, noted in Table 2, are expected to be present within the measurement with amplitudes depending on system characteristics such as imbalance, misalignment, and looseness.

Table 2 Frequency of Orders

Order	**1**	**2**	**3**	**4**	**5**	**6**	
f (Hz)	29.688	59.376	89.064	118.752	148.44	178.128	
Order	**7**	**8**	**9**	**10**	**11**	**12**	**13**
f (Hz)	207.816	237.504	267.192	296.88	326.568	356.256	385.944

Some detectable vibration was expected originating from the rolling element bearings at frequencies noted in Table 3, but they were minimal due to the recent maintenance.

Table 3 Bearing Frequency

	Upper Guide Bearing SKF 6226C3		*Upper Thrust Bearing SKF 29326EJ*		*Lower Bearing 2x SKF 7222-BEGAM*	
	Order	f (Hz)	Order	f (Hz)	Order	f (Hz)
Rolling Element and Cage Assembly	0.41	12.17	0.45	13.36	0.43	12.77
Rolling Element About Own Axis	2.75	81.64	3.42	101.53	2.66	78.97
Over Rolling Inner	5.29	157.05	11.5	341.41	8.56	254.13
Over Rolling Outer	3.71	110.14	9.53	282.93	6.44	191.19
Over Rolling One Point On Ball	5.49	162.99	6.84	203.07	5.32	157.94

It was expected that an increased vibration would be noted at five times the rotational speed due to the pump's five vanes. The pump is positioned vertically in the following arrangement from top to bottom: pony motor, main motor, flange, pump housing. The motor and flange are depicted in Figure 1. Part of the pony motor can also be seen at the top of Figure 1. The pump assembly is anchored with four large bolts to an elevated steel platform. The flange, pump, and anchor bolts are depicted in Figure 2.

Figure 1 Motor and Flange

Figure 2 Flange and Pump

Modal Analysis

Modal analysis was performed on the pump using the single input multiple output (SIMO) roving modal hammer technique. This measurement captures system characteristics such as mass, stiffness, and damping to determine the natural frequencies and mode shapes of the system. Increased vibration amplitude is expected when these natural frequencies are excited due to motor rotation during normal operation. This interaction will be described in the steady state section of this document. It is worth noting that the pony motor was in operation, rotating the shaft and impeller, during this measurement. The system's driven rotation will distort the frequency response function (FRF) to some extent because force inputs are being provided by both the rotation and as the modal hammer.

Frequency Response Function

Four primary radial natural frequencies were identified at approximately 11, 88, 145, and 292 Hz and can be seen in Figure 3. The last three of these correlate with three, five, and ten times the rotational speed. The proximity of the fifth order, approximately 148 Hz, to the modal peak at 145 Hz should result in greater amplitudes due to the five vanes of the pump impeller. The top of the pony motor exhibited the highest amplitude throughout the modal analysis.

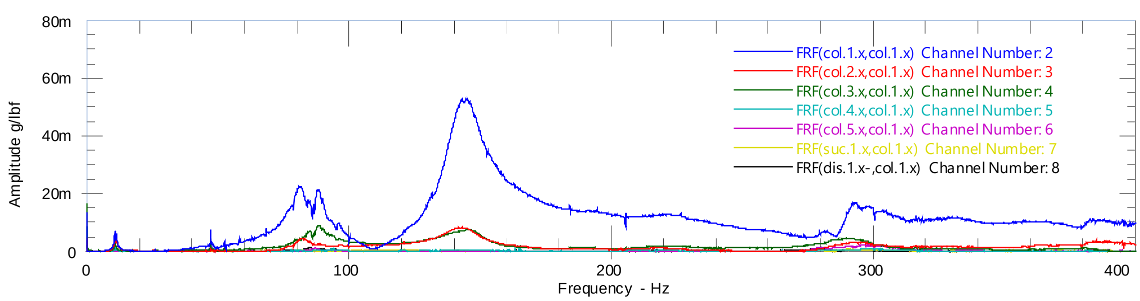

Figure 3 Modal Frequency Response Functions

Mode Shape

The following mode shapes were calculated using a single degree of freedom curve fitter. Mode shapes can be used to visualize the data from the FRF to depict the vibrations of the system. These shapes can be compared against the operational deflection shapes of the pump during normal operation to visualize possible interaction locations and intensities. Note that the amplitude of the first mode, in Figure 4, was quite low. The top of the pony motor exhibited the most motion in the remaining modes. Mode two, in Figure 5, includes motion at the lower bearings of the motor as well.

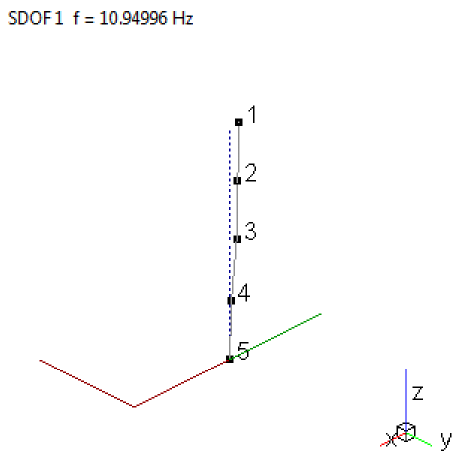

Figure 4 Mode Shape 1

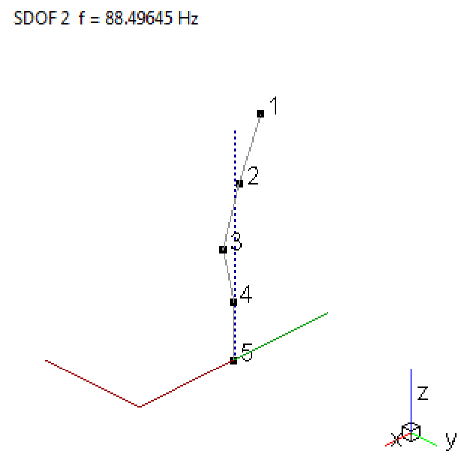

Figure 5 Mode Shape 2

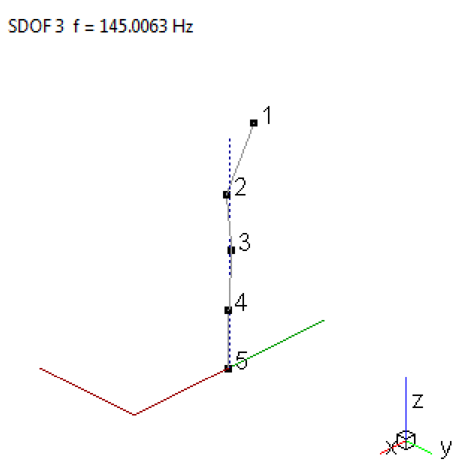

Figure 6 Mode Shape 3

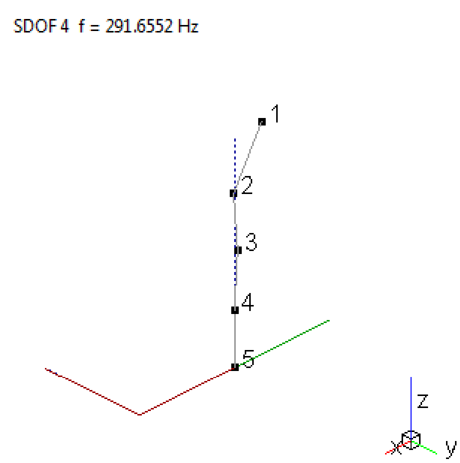

Figure 7 Mode Shape 4

Steady State

About ten minutes of data, or 596.48 seconds, was taken with seven accelerometers while the pump was at its full operating speed. Two hundred and thirty-three fast Fourier transforms (FFT) were calculated and averaged into one spectrum data set for each of the sensors. This data is displayed within this section as a two-dimensional spectrum plot and operational deflection shapes.

Spectrum

Within the spectrum data displayed in Figure 8, five frequencies of interest exhibit elevated amplitudes of vibration. These frequencies closely correlate with the first, second, third, fifth, and tenth orders of rotational speed. The amplitudes of each of the sensors at these frequencies are presented in Table 4. As expected from the Modal Analysis section, the peak associated with the fifth order at 148.83 Hz exhibited the highest amplitude at 0.295 g rms.

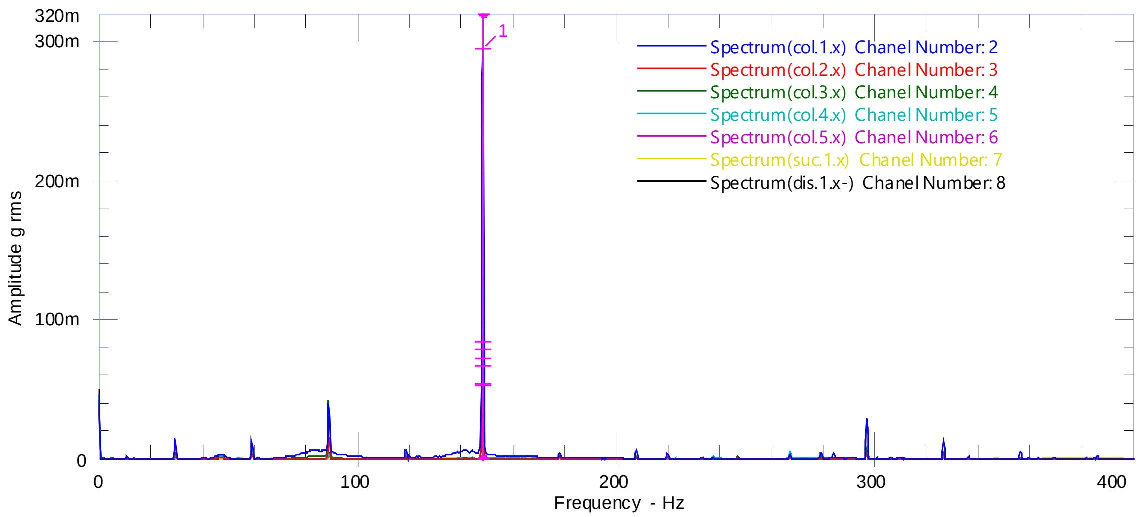

Figure 8 Steady State Spectrum, All Sensors

Table 4 Steady State Acceleration Ampitudes

Location	*29.688 Hz*	*59.375 Hz*	*89.063 Hz*	*148.83 Hz*	*297.27 Hz*
col.1.x (g rms)	0.016	0.013	0.041	0.295	0.030
col.2.x (g rms)	0.012	0.004	0.018	0.053	0.003
col.3.x (g rms)	0.006	0.005	0.043	0.055	0.007
col.4.x (g rms)	0.004	0.012	0.004	0.084	0.029
col.5.x (g rms)	0.002	0.009	0.005	0.068	0.027
suc.1.x (g rms)	0.004	0.009	0.006	0.073	0.010
dis.1.x (g rms)	0.000	0.006	0.002	0.080	0.015

The steady state spectrum data of the accelerometer on top of the pony motor is displayed in Figure 9. All orders of run speed within the range from 0 to 400 Hertz are present, but five times run speed stands out as the maximum excitation at almost 0.3 g rms.

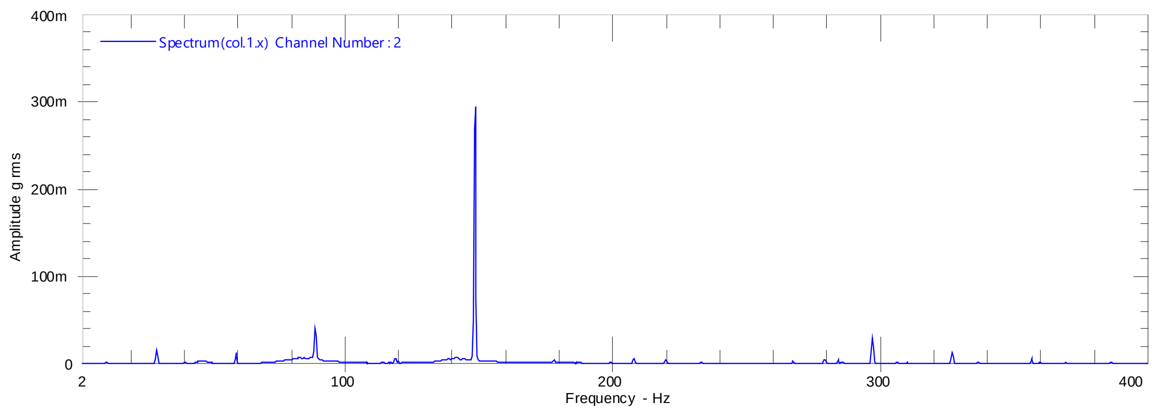

Figure 9 Steady State Spectrum, Top of Pony Motor

The steady state spectrum data of the accelerometer on the lower bearing area of the motor is displayed in Figure 10. Again, all orders of run speed are present. The five times run speed peak was still the maximum, but its amplitude was much lower at around 0.055 g rms. The next highest peak was at three times run speed with an amplitude of about 0.043 g rms, which is the maximum excitation for this frequency.

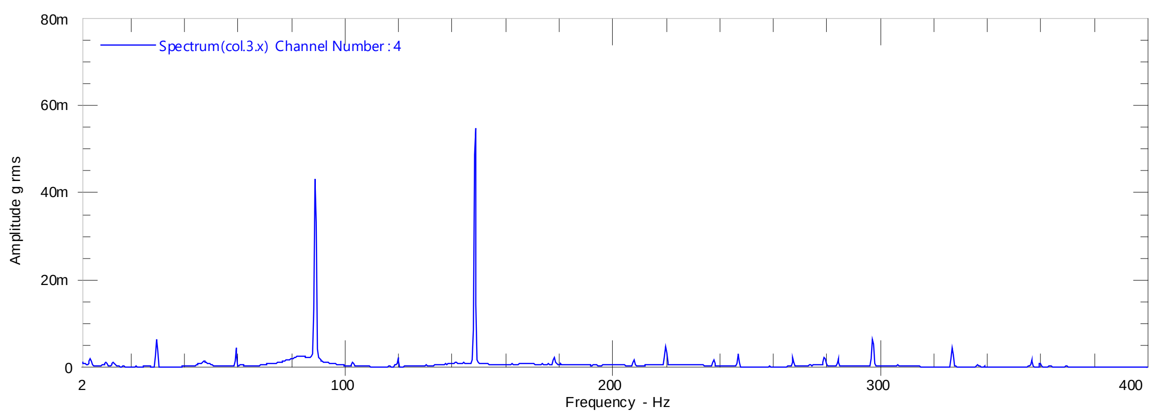

Figure 10 Steady State Spectrum, Motor Lower Bearings

The steady state spectrum data of the accelerometers of the suction and discharge piping are displayed in Figure 11 and Figure 12 respectively. As in the cases for the motor and pump accelerometers, all orders of run speed are present within the depicted range and five times run speed has the maximum amplitude.

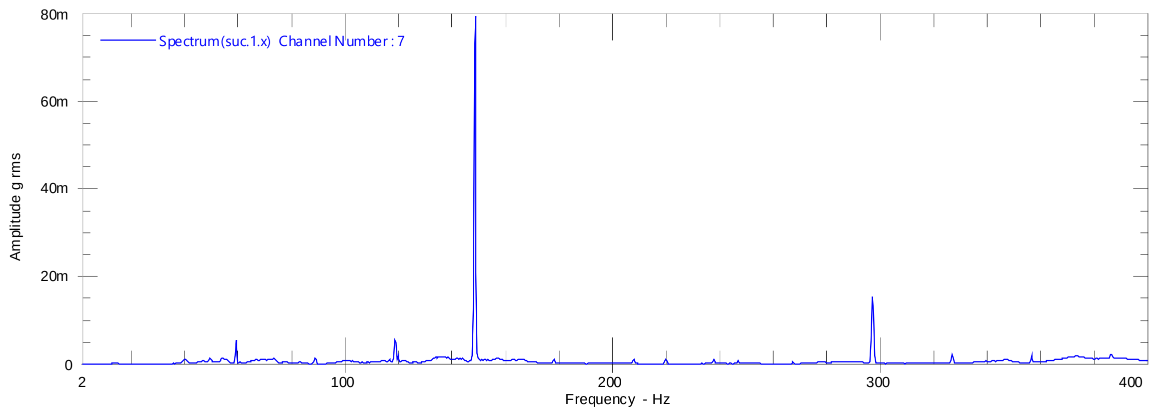

Figure 11 Steady State Spectrum, Suction piping

The amplitude of five times run speed of both piping accelerometers are both about 0.080 g rms. The next highest peak is at ten times run speed at about 0.015 g rms.

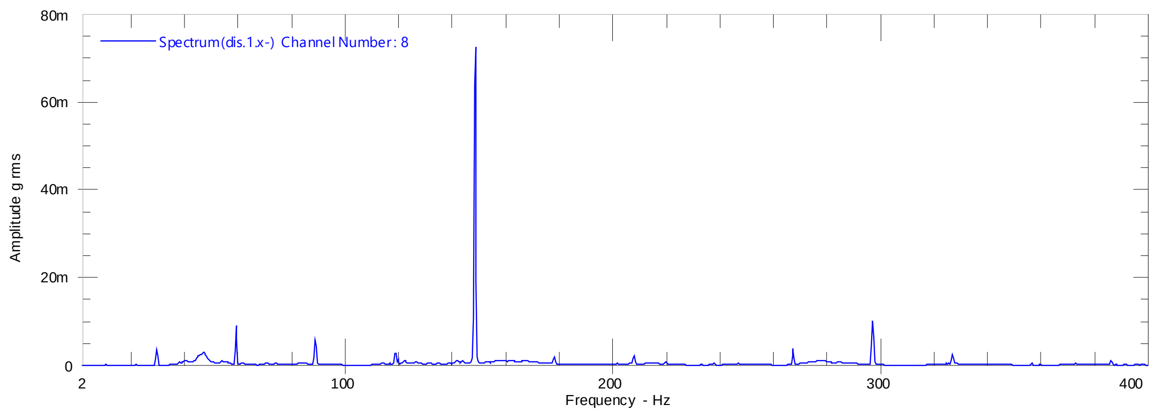

Figure 12 Steady State Spectrum, Discharge Piping

Operational Deflection Shape

The following operational deflection shapes (ODS), shown in Figures 13 though 17, depict the pump during normal operation. The deflections are normalized to the largest amplitude at that frequency.

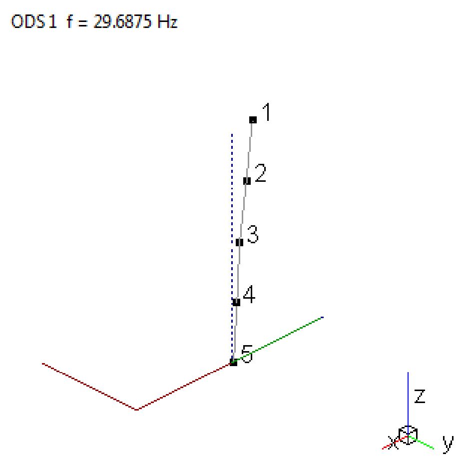

Figure 13 ODS 1

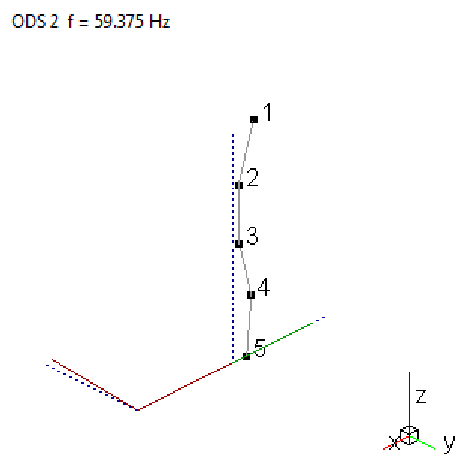

Figure 14 ODS 2

Operational deflection shapes three, four, and five, shown in Figures 15, 16, and 17, exhibit modal interaction with mode shapes two, three, and four respectively, shown in Figures 5, 6, and 7. Operational deflection shape four, shown in Figure 16, at five times run speed, exhibits the largest vibration amplitude.

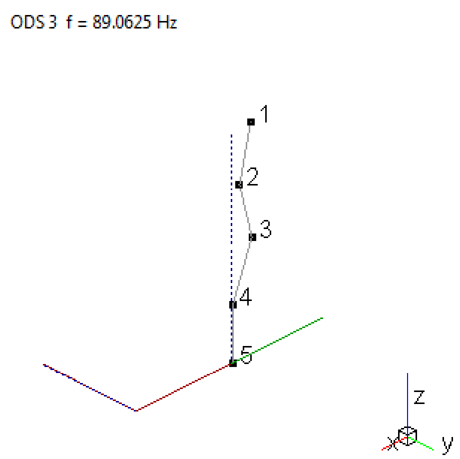

Figure 15 ODS 3

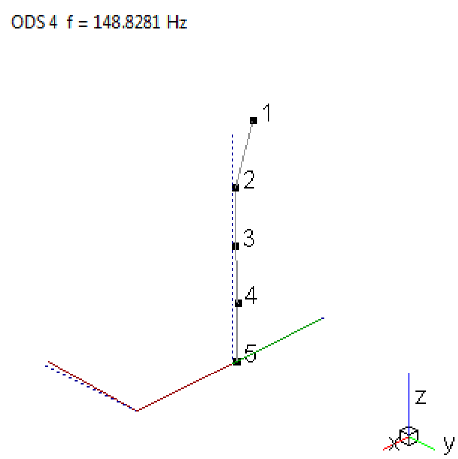

Figure 16 ODS 4

Operational deflection shape five, shown in Figure 17, at ten times run speed, differs from mode shape four, shown in Figure 7, by having a larger response from the accelerometers on the pump and flange as well as some motion in the piping.

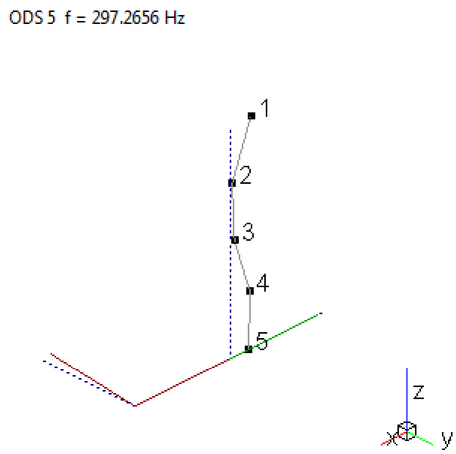

Figure 17 ODS 5

Transient Analysis

An additional ten minutes of data was taken for transient analysis. The main motor was off during the first two minutes of this acquisition and the pump was driven by the pony motor. The pump quickly came up to speed when the main motor powered on. No electrical grounding issues are apparent within the transient data. The portion of this data collected while the main motor was running closely matches the steady state spectrum section. The top of the pony motor, shown in Figure 18, and the suction piping, shown in Figure 19, were chosen as representative transient data.

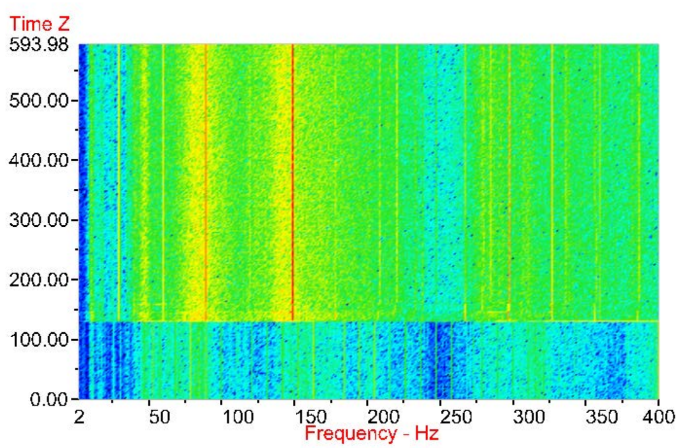

Figure 18 Transient, Top of Pony Motor

No broadband noise was present in the piping or pump; therefore, cavitation does not seem to be present in the system. Further, there were no indicators of looseness in the system.

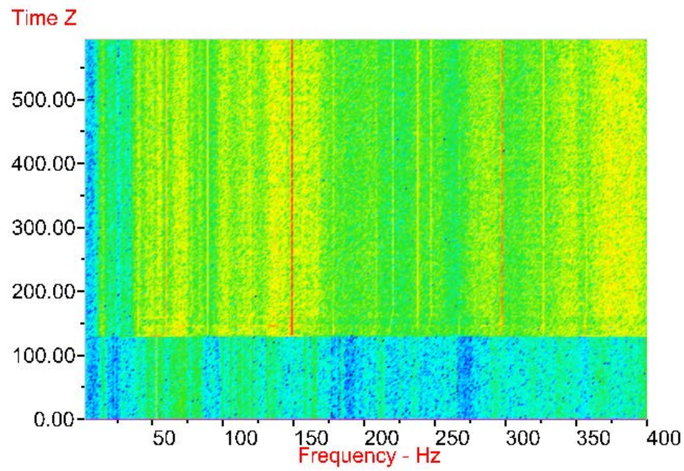

Figure 19 Transient, Suction Piping

Pony Motor Only Steady State Spectrum

About two minutes of data was taken with the main motor off while the pump is being driven by the pony motor. Fifty FFT where calculated and averaged into one spectrum data set for each of the sensors, shown in Figure 20. The top of the pony motor exhibited the most motion, just as with normal operation, but all the levels were expectedly lower. The largest amplitude was 0.0044 g rms at 78.9 Hz.

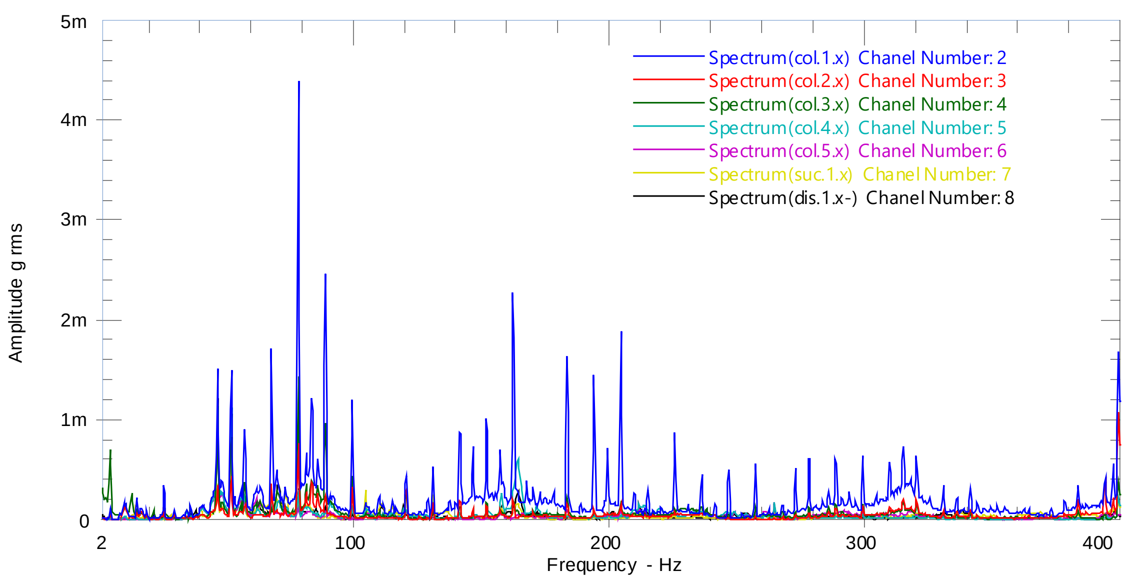

Figure 20 Pony Motor Only Steady State Spectrum, All Sensors

Analysis Results

Modal interaction was exhibited during the third, fifth, and tenth orders. The fifth order is excited further due to the five-vane pump. There is no evidence of electrical grounding, cavitation, looseness, misalignment, or imbalance within the data collected. Some bearing frequencies are present, but they are not elevated; therefore, it is concluded that the bearings have not experienced excessive wear or damage.

This pump is categorized as an integrated drive, rigid foundation, pump larger than 15 kW, or Group 4. Per ISO 10816 vibration standard, the motor falls within Zone C, which designates that the pump is considered unsatisfactory for long-term continuous operation. The standard states that the pump may be operated for a limited time until remedial action is performed. This categorization is a result of the high vibration found at the top of the pony motor of 0.295 g rms at 148.83 Hz for a 600 HP (447 kW) motor.

Using the same standard for the vibration measured from the piping at about 0.080 g rms at the same frequency categorizes the piping section within Zone A, which designates a newly commissioned machine. The piping accelerometers move a maximum distance of 0.125 mils peak to peak at the rotational speed of the pump. This indicates that piping damage due the measured vibration is not expected.

Recommendations

The rotational speed adjustment to decrease the excessive vibration would need to be significant due to the frequency width of the excited mode, which does not appear to be an option. It is suggested to perform vibration and modal analysis on the other three reactor cooling pumps to determine what differentiates PU-1A from the others. It is likely that a structural component is different between them, such as a brace, bolt, weld, flange, or joint. It is probable that with this information, PU-1A could be modified to increase the system's stiffness specifically at the top of the motor and pony motor to reduce the high vibrational amplitudes as compared to the other three pumps.

Reference

International Organization for Standardization. (2009). *Mechanical vibration -- Evaluation of machine vibration by measurements on non-rotating parts -- Part 3: Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15 000 r/min when measured in situ (Standard No. 10816-3).* Retrieved from https://www.iso.org/standard/50528.html

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