The Truth Behind Misalignment Vibration Spectra of Rotating Machinery

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1. Abstract

Misalignment is probably the most common cause of machinery malfunction. Considering the importance of alignment, the vibration spectra of alignment is not well documented. Various authors have reported different spectra. The goal of this research was to determine the unique vibration signature for misalignment at varying operating and design conditions such as speed, type and level of misalignment, coupling types and machinery dynamic stiffness. The SpectraQuest Machinery Fault Simulator™ was used in the study to create the varying mechanical conditions. Triaxial vibration measurements were taken at each end of the coupling on the motor and rotor bearing housings. Data was collected at several other locations of the Simulator. The results indicate that the speed and the coupling type/stiffness have a strong effect on the vibration spectra. The level and type of misalignment had a significant effect on the vibration signature. Due to inadequate data the effects of machine dynamic stiffness could not be quantified at this time. No guaranteed unique characteristic spectra could be demonstrated during this study, suggesting that further dynamic modeling may be essential to clarifying the issues at hand.

2. Introduction

Misalignment is a common cause of machinery malfunction. A poorly aligned machine can cost a factory 20% to 30% in machine down time, replacement parts, inventory, and energy consumption. A large payback is often seen by regularly aligning machinery. Operating life is extended and process conditions are optimized.

Vibration signatures are widely promoted as a useful tool for studying machine malfunctions. However, the literature on this subject does not present a clear-cut picture of signature characteristics uniquely attributable to misalignment. Different authors report different signatures. There are no reports of systematic, controlled experiments with varying parameters.

This is a report of a systematic series of experiments designed to elucidate the consistent features, if any, of vibration signatures for misaligned machinery. All but two machine-operating parameters were held constant. Systematic variations were introduced in the coupling types, amount of misalignment and the motor speed. The machine was fault-free with the exception of deliberate misalignment, which was varied systematically. Baseline vibration data was recorded for each of the test conditions for comparison purposes.

3. Experimental

All tests were conducted using SpectraQuest's "Machinery Fault Simulator™" (MFS). Figure 1 shows a photo of the MFS along with measurement points.

Vibrations were monitored with accelerometers placed at 6 locations on the MFS. Fourteen channels were used to monitor three directions. Table 1 lists locations, directions, and channel numbers and abbreviated legends used to identify spectra. The tags listed in the tables were used to identify spectra in multiplot comparisons. The tag correlates with the coupling, the two offsets and the actual speed. The actual speed was determined automatically by the software using peaks in the spectra. These deviated slightly from the target speed settings in the experimental design. The X, Y, Z coordinate system was sometimes used to show direction.

The experimental design for this study included three different stiffness couplings. Four levels of offset were used on the left bearing housing to simulate a combination of angular and parallel misalignments. Equivalent offsets on the right bearing housing side gave parallel misalignment. The experimental design had four speeds of rotation. The goal of the study was to determine the effects of coupling stiffness, level and type of misalignment, and the speed of rotation on vibration spectra.

Data was acquired with special custom hardware and software developed in-house. The data was obtained for 500 Hz maximum frequency at 800 lines spectral resolution. Five data blocks were sum averaged to compute spectral functions. Newly developed, in-house software was used to analyze the vibration signatures and get results. Typical spectra are shown in figure 2. It shows the most prominent peak (in Gs.) observed in the group. The figure shows average power spectra computed from four channel measurements.

4. Results

Fourteen channel data was collected at six locations at four different speeds. Since the purpose of this study is to examine the spectra due to misalignment between the motor and the rotor shafts, spectral comparison will be made across coupling measurement points on left bearing housing and the motor. The data will be compared in both vertical and axial directions. The results at 960 and 2,100 RPM did not show a significant vibration. Thus, detailed data analysis and study was limited to the higher speeds of 2,900 and 3,800 RPM only.

Figures 2 to 5 illustrate typical spectra for different operating conditions. Each graph consists of four spectra measured in vertical and axial directions on front top of the motor and top of the left bearing housing. In each figure, the top two graphs are for the motor and the bottom two curves are for the bearing housing. Axial vibration data are on top in each group. Graphs are shifted vertically to elucidate the details and amplitude scales are suppressed purposely. Horizontal scale is frequency in orders of RPM.

A correlation between misalignment and vibration signature could not be discerned. The data for all cases contained several harmonics. Both axial and lateral vibration was present in all cases. The dominant harmonic varied from condition to condition. As a general rule, as expected, increased misalignment yielded increased vibration peaks. However, an exception to this rule was observed.

Speed seems to have the most dominant effect on vibration spectra and severity. It is interesting to note that the level and number of harmonics for data for 960 and 2100 RPM were much smaller than those were at 2900 and 3800 RPM. As a general rule, higher speeds generated increased vibration amplitude and number of harmonics. Often 1X vibration had higher peaks, but in many other cases 2X and 4X seemed to have the largest amplitude. The motor accelerometer revealed more higher frequency vibration than the bearing housing. Some frequency modulation was also noticed at higher harmonics.

Coupling stiffness also appears to have a dramatic effect on misalignment vibration spectra. For a given speed and misalignment level, the steel coupling produced the highest vibration followed by the helical beam and then the rubber coupling. Thus, it can be deduced that at a given condition a stiffer coupling produces more vibration than a softer coupling. Also, the correlation does not seem to be linear and simple.

The effect of the amount of misalignment was not as significant except for the steel coupling. For the helical beam coupling, the vibration level was much lower below 40-mil misalignment. The rubber coupling displayed similar low vibration characteristics up to 60-mil misalignment. But the steel coupling, very stiff, showed high levels of vibration even below 20 mils misalignment. No significant difference was observed between parallel and combination of parallel and angular misalignment. The study did not include pure angular misalignment.

5. Discussion

The results clearly indicate a significant variation in vibration spectra as a function of operating conditions. Both amplitude of the dominating peak and its location along the frequency axis changes in a complex manner. The data indicate that it is not possible to conclude that the cause of real world machinery malfunction is shaft misalignment just by looking at a single vibration spectrum at an operating condition. A careful examination is essential to differentiate misalignment from other sources of vibration. Some experimentation and cross correlation analysis along with a rotor dynamics model may be necessary to fully diagnose a problem.

Since misalignment vibration seems to be a strong function of coupling type (stiffness) and rotational speed, a detailed rotor dynamics model is needed to develop a predictive model for misalignment vibration spectra. The misalignment phenomenon is non-linear and much more complex.

The results of this study confer with common sense that when two misaligned shafts are joined together by a coupling, the machine structure is subjected to deformation (strain). The deformation will be different at each angle of rotation depending upon the amount and type of misalignment. The corresponding stress will depend upon the stiffness of the machine structure. The spatial Fourier transform of the angular deformation (or stress) curve will contain several terms. Now when the machine starts turning, the angularly varying stress will produce vibration at each of the Fourier components, assuming a linear relationship. The problem is complicated further due to the inherent non-linearities of a machine.
The frequencies of peak vibration amplitude, MFS locations and directions were inconsistent even with speed and coupling held constant. Increased speed also caused increased peak vibration with frequency shifts that did not correlate with the speed.

As another general rule, peak vibrations in the misaligned machine were in the axial direction. An exception to this rule was also seen.

For predictive maintenance applications where the goal is machinery health monitoring, it is sufficient to realize that the problem is complex. One can routinely trend the vibration spectra until it becomes severe. But for root cause analysis, one must exercise caution and perform a detailed analysis. Obviously, the rules provided in training courses and wall charts are doubtful at best.

The changes that occurred with shifts of speed and misalignment clearly show the truth behind misalignment vibration spectra. There is no evidence of a signature typical of misalignment.

6. Conclusions

- Simple vibration spectral analysis for a given operating condition does not provide a good, reliable tool for detecting machinery misalignment
- A proper analysis of the shaft misalignment induced vibration is rather complex. It may require modeling machinery non-linear dynamics.
- Misalignment vibration is a strong function of machine speed and coupling stiffness.
- Softer coupling seems to be more forgiving and tend to produce less vibration than a stiffer coupling.
- The rules provided in training courses and wall charts are doubtful at best.
- More work is needed to develop simple rules, if possible, for diagnosing machinery shaft misalignment.

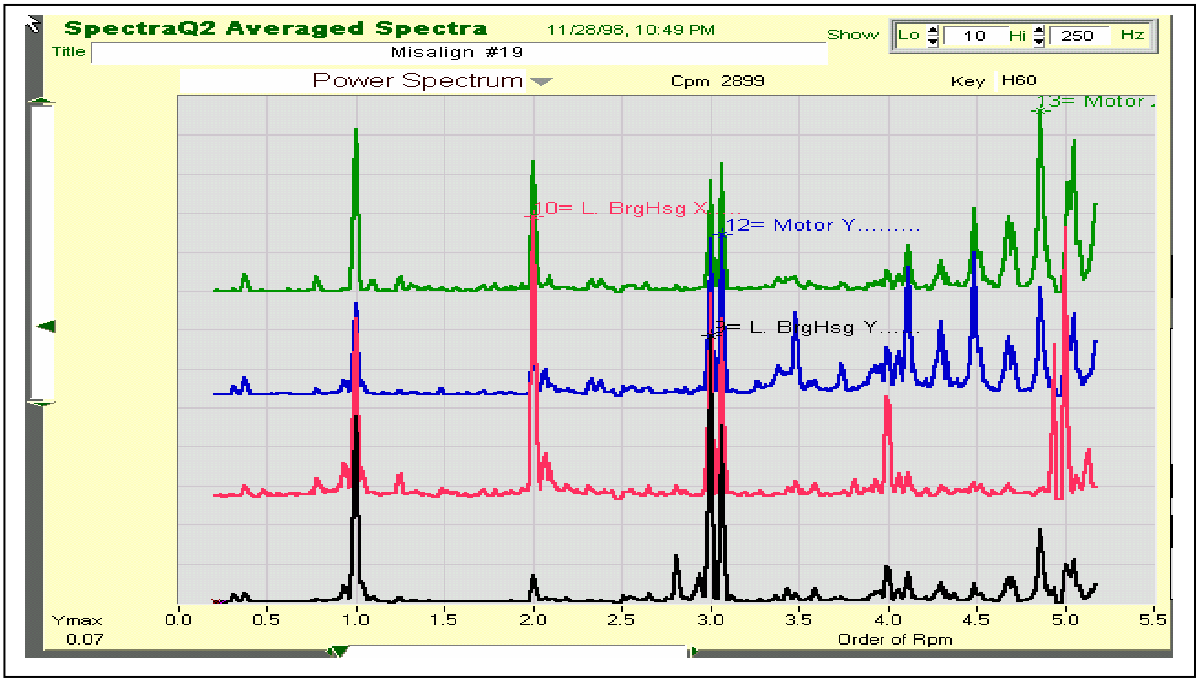
7. References

1. J. Piotrowski, *Shaft Alignment Handbook*, Marcel Dekker, Inc, New York, 2nd. Ed., 1995.

Table 1

MFS Locations Monitored				
Location	***Channel Number***	***Channel Legend***	***Coord-inate***	***Direction***
Right Bearing Housing	1	Hor R. BrgHsg	Y	Horizontal
	2	Vert.R. BrgHsg	Z	Vertical
Gear Box	3	Hor. G. Box	Y	Horizontal
	4	Vert.G. Box	Z	Vertical
	5	Axial G. Box	X	Axial
Base Plate	6	Vert.Base	Z	Vertical
	7	Hor. Base	Y	Horizontal
Reciprocating Mechanism	8	Axial Recip	X	Axial
Left Bearing Housing	9	Hor L. BrgHsg	Y	Horizontal
	10	Axial L. BrgHsg	X	Axial
	11	Vert.L. BrgHsg	Z	Vertical
Motor	12	Hor.Motor	Y	Horizontal
	13	Vert.Motor	Z	Vertical
	14	Axial Motor	X	Axial

Figure 1. A snap shot of Spectra Quest's Machinery Fault Simulator used in the study.



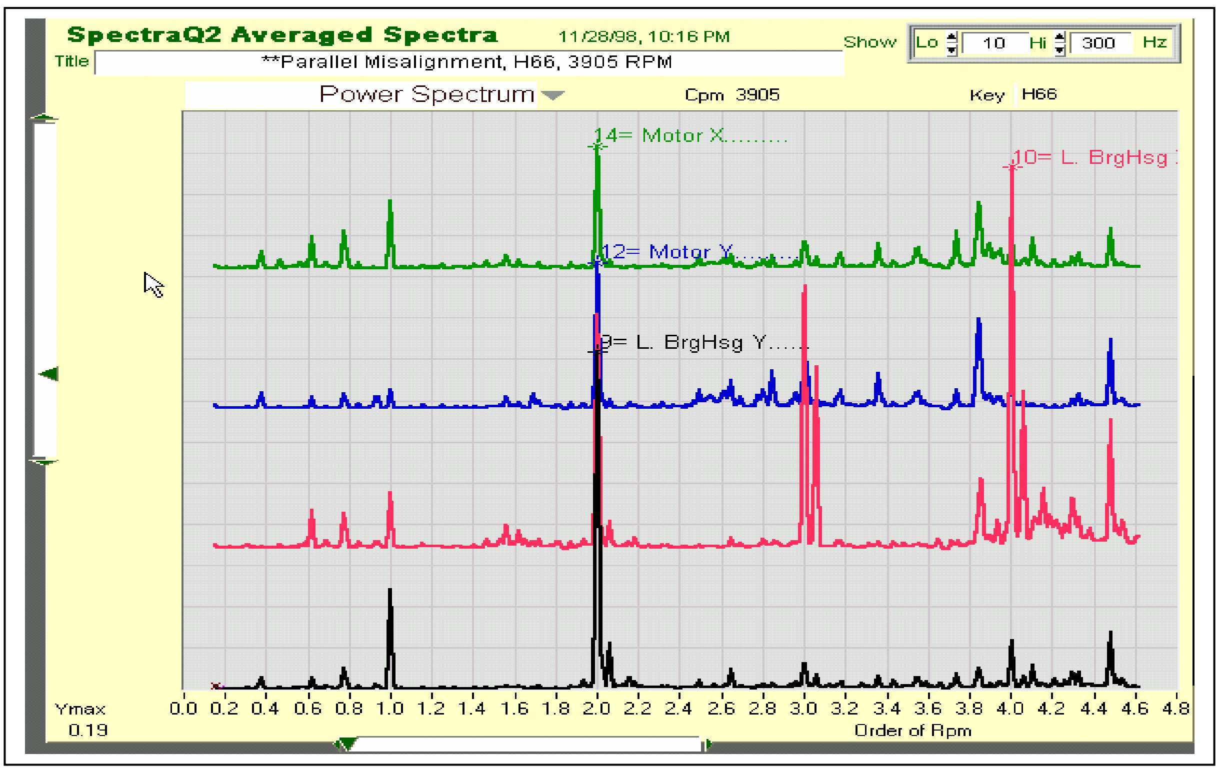
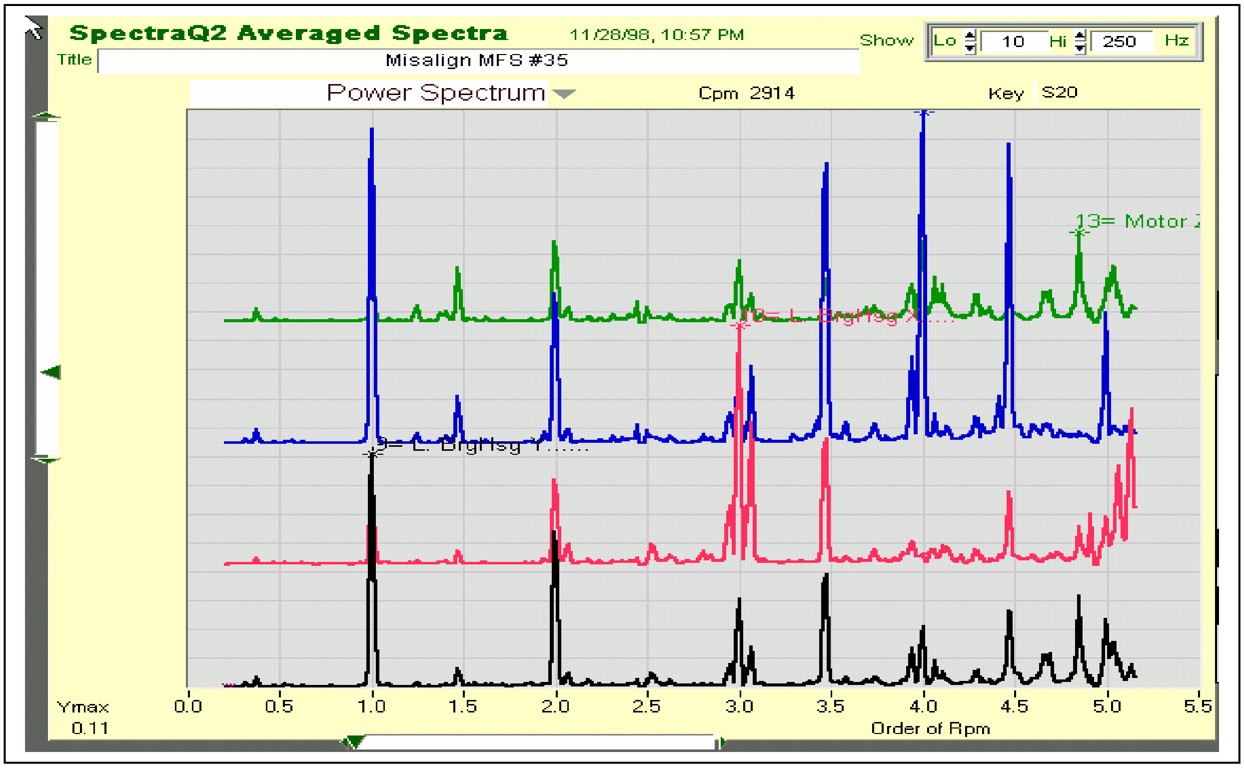


Figure 2. Comparisons of Vibration Spectra of the Left Bearing Housing and the Motor in vertical and axial directions of the Misaligned MFS with Helical Coupling at Two Different Speeds. The graphs illustrate the effect of speed on the spectra. At higher speed amplitude increases and the peak shows at 2X. The frequency scale is displayed as Order of RPM. Graphs are shifted vertically to clarify the differences. The vertical scale is 0.2 G's per block.



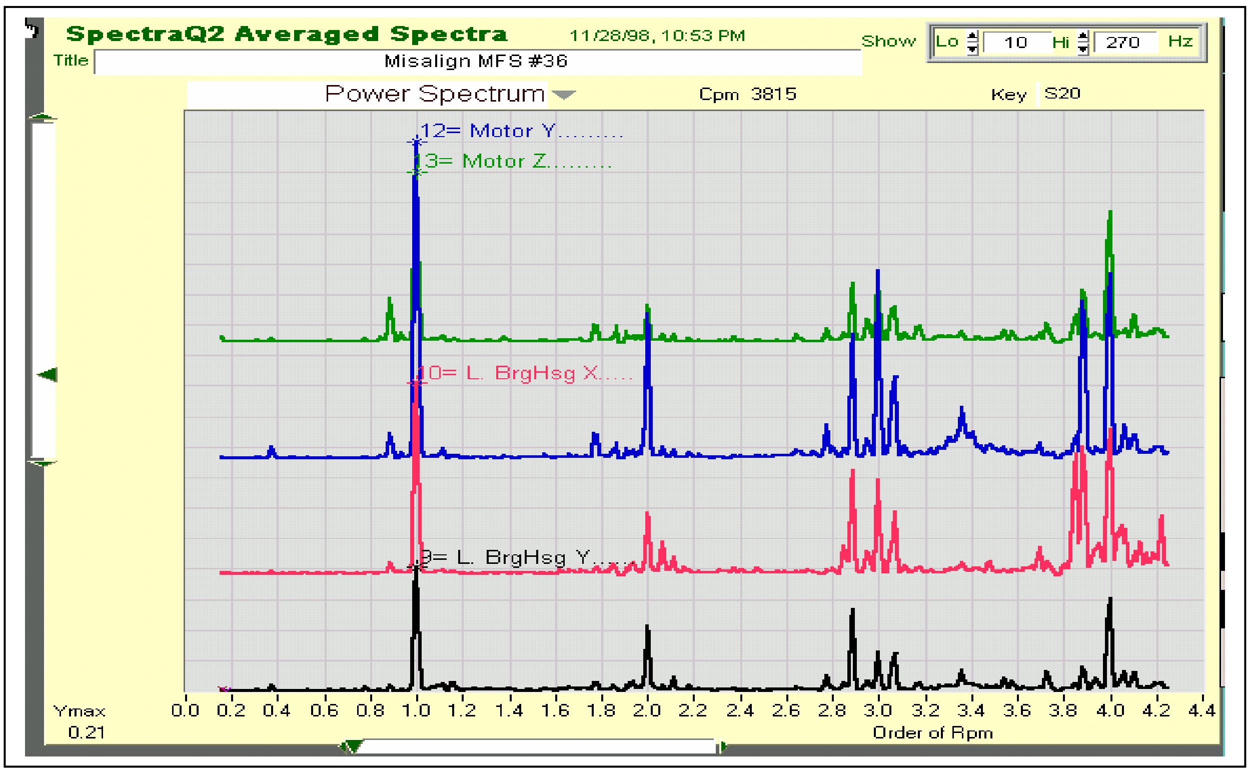
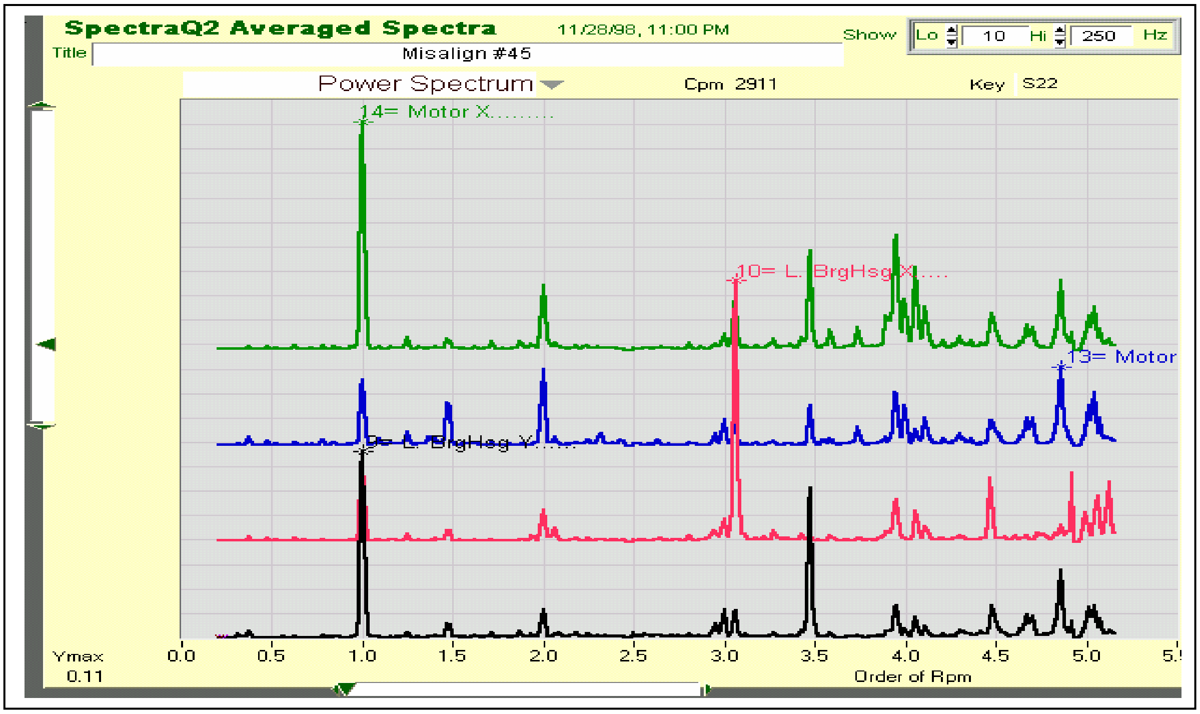


Figure 3. Comparisons of Vibration Spectra of the Left Bearing Housing and the Motor in vertical and axial directions of the Misaligned MFS with the Steel Coupling at Two Different Speeds and 20 mils misalignment. The graphs illustrate the strong effect of speed on the spectra and its amplitude. At higher speed note the higher peak at 2X than 1X. Also, note modulation at the higher harmonics. The frequency scale is displayed as Order of RPM. Graphs are shifted vertically to clarify the differences. The vertical scale is 0.2 G's per



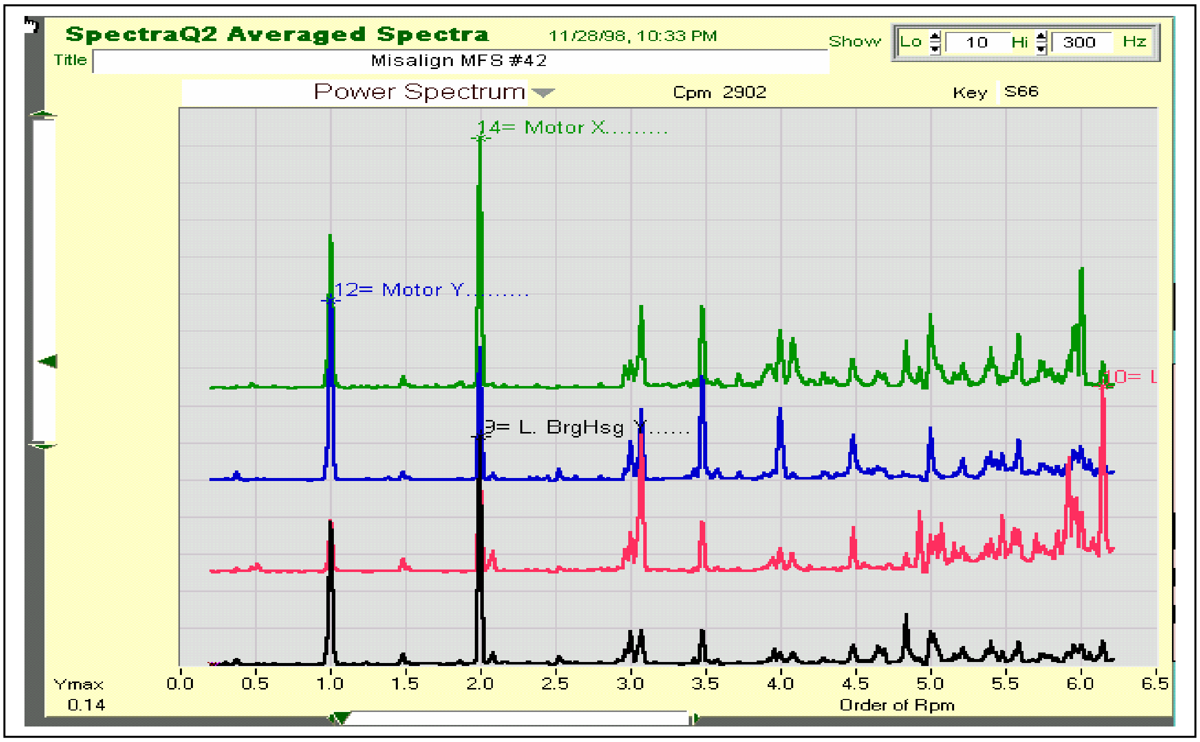
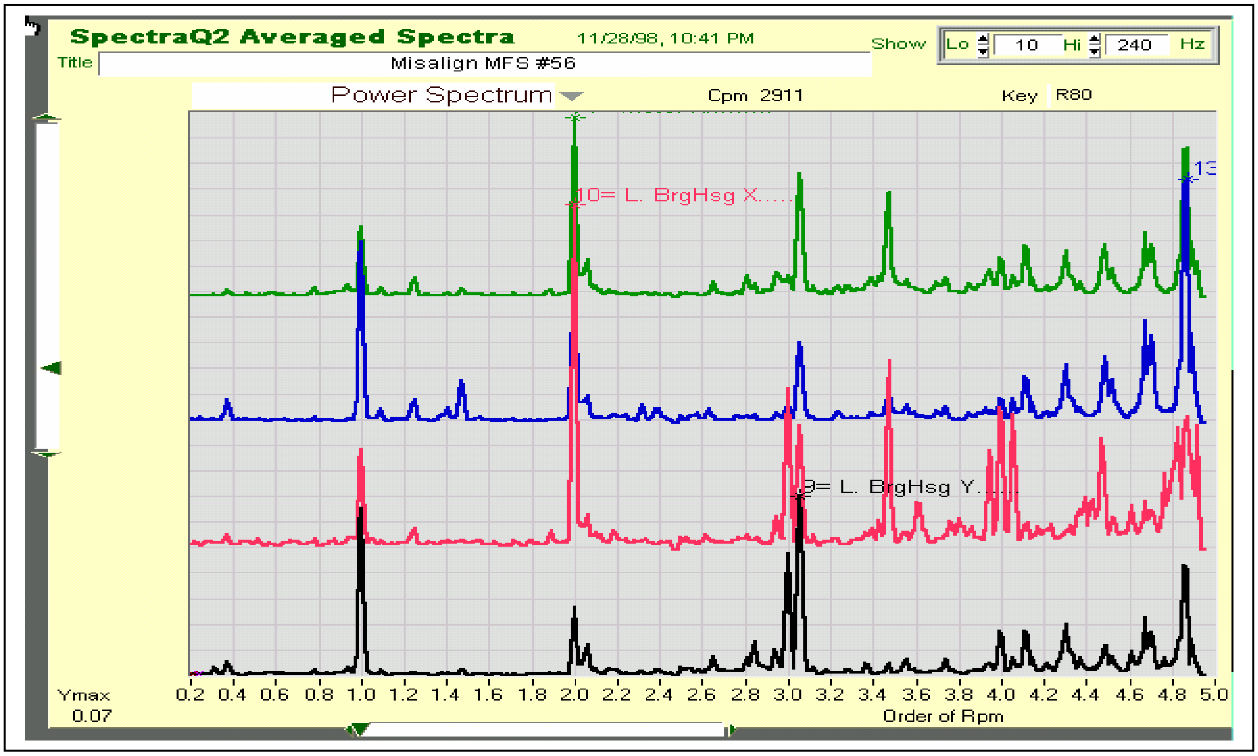


Figure 4. Comparisons of Vibration Spectra of the Left Bearing Housing and the Motor in vertical and axial directions of the Misaligned MFS with Steel Coupling at Two Different levels of Misalignment. The graphs illustrate that the vibration spectra and its amplitude increase with an increase in the amount of misalignment. Note the high frequency vibration for the motor sensor. The source is not clear. The frequency scale is displayed as Order of RPM. Graphs are shifted vertically to clarify the differences. The vertical scale is 0.2 G's per block.



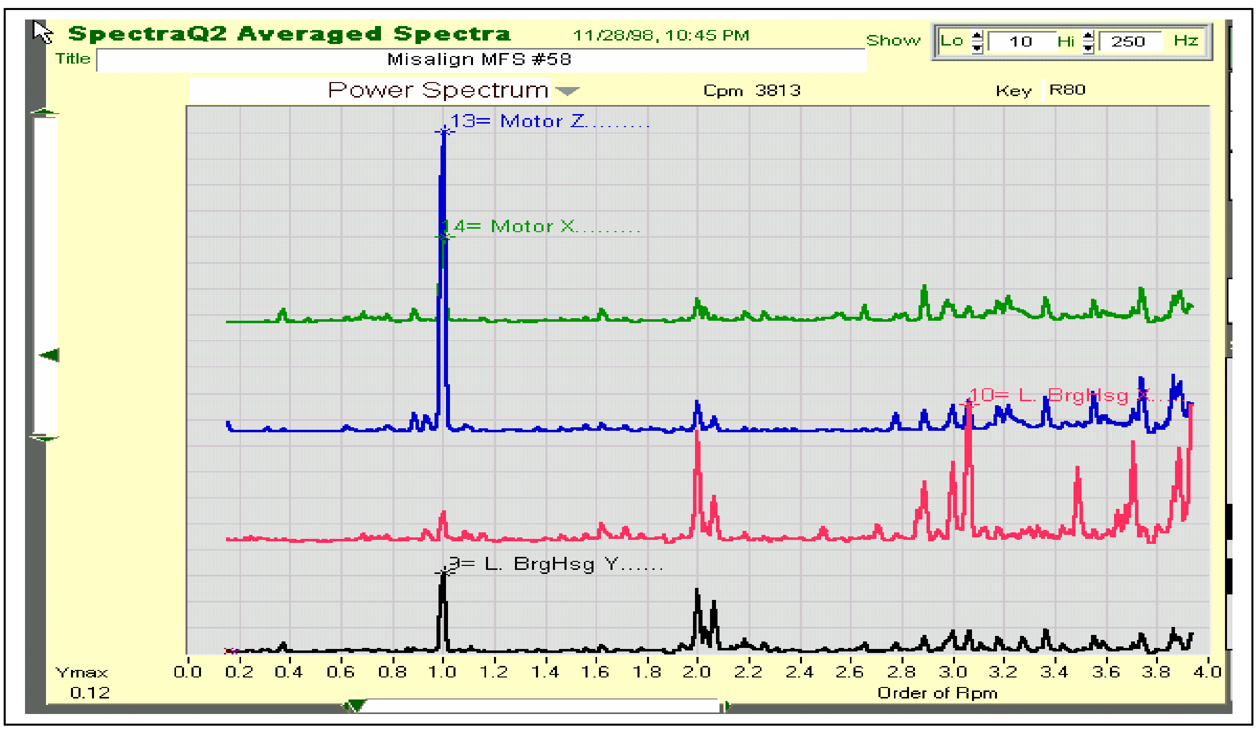


Figure 5. Comparisons of Vibration Spectra of the Left Bearing Housing and the Motor in vertical and axial directions of the Misaligned MFS with the Rubber Coupling at Two Different Speeds and 80 mils misalignment. The graphs illustrate relatively small effect of speed. At higher speed note the higher peak at 1X and at the 2X at lower speed. Also, note modulation at the higher harmonics. The frequency scale is displayed as Order of RPM. Graphs are shifted vertically to clarify the differences. The vertical scale is 0.2