OBSERVATIONS ON DYNAMIC RESPONSES OF MISALIGNMENTS

Mohsen Nakhaeinejad **Suri Ganeriwala**

SpectraQuest Inc., 8201 Hermitage Rd, Richmond, VA 23228
Tel: (804)261-3300 www.spectraquest.com

Abstract

Experiments investigated dynamic effects of angular and parallel misalignments in rotating machinery on machine behavior. Different levels of angular and parallel misalignments were applied to the SpectraQuest Machinery Fault Simulator™ (MFS) rigid, rubber and helical beam couplings. For each case, shaft speed, motor and bearings vibrations, and bearing forces were measured. Forces and vibration signals were studied in time and frequency domain. Results indicate strong effect of coupling stiffness on vibrations and forces. Severe parallel and angular misalignments can generate low frequency modulations in vibration signals. Also, axial forces due to misalignment were observed in angular and parallel misalignments.

Keywords: Misalignment, Rotating Machinery, Fault Diagnostics, Vibrations

INTRODUCTION

Misalignment in rotating machinery is one of the most common faults causing other faults and machine failure. It causes over 70% of rotating machinery vibration problems [1]. A misaligned rotor generates bearing forces and excessive vibrations making diagnostic process more difficult. A perfect alignment can never be achieved practically and misalignment is always present. Also, many factors such as thermal growth, uneven applied loads, inappropriate foundations, etc., can disturb the alignment. Vibration spectrum analysis has been a common tool for misalignment detections for a while. In-depth study of dynamic forces and vibrations is helpful for understanding and diagnosing of misalignments. There have been many research on analytical study of misalignments considering vibration and dynamic forces [2-5]. However, there have been relatively limited experimental studies [6-8] in full-monitoring of misaligned rotors. This study was aimed to investigate experimentally effects of misalignment type and levels, and coupling materials on machine response.

The SpectraQuest's Machinery Fault Simulator™ (MFS) (Fig. 1), a comprehensive test-bed for in-depth studies of the most common machinery faults, was used for experiments. Three different couplings were used, angular and parallel misalignments in different levels were introduced, the machine was fully monitored through sixteen channels of speed, vibrations and forces during each experiment, and collected data were analyzed in time- and frequency domains.

EXPERIMENTS

The SpectraQuest's Machinery Fault Simulator™ (MFS) was used for misalignment experiments. MFS is a comprehensive test-bed for rotating machinery experiments and for in-depth studies of the most common machinery faults including misalignments. MFS consists of an induction motor coupled to the main shaft supported by two rolling element bearings.

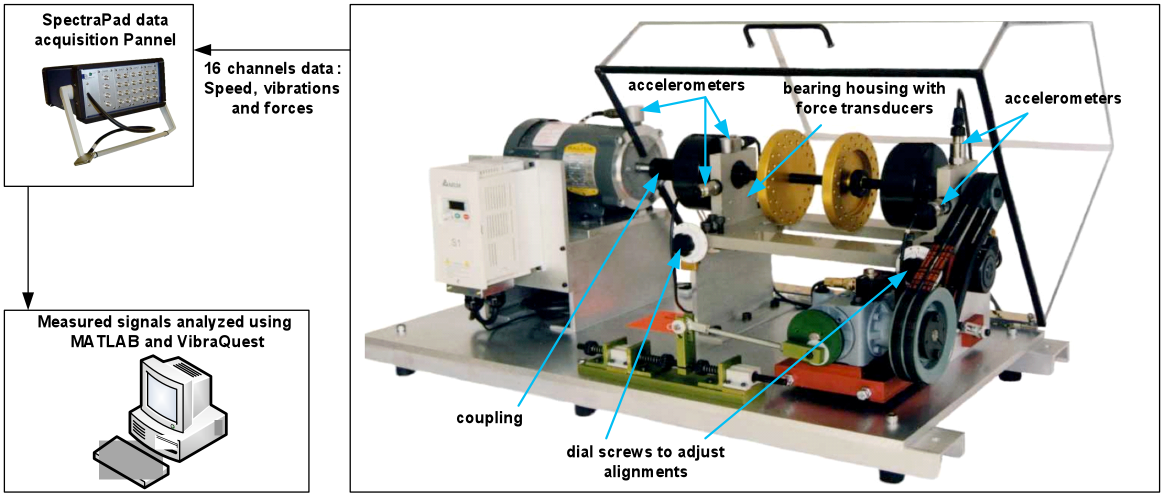


Fig. 1 SpectraQuest's Machinery Fault Simulator (MFS) and SpectraPad data acquisition board were used for misalignment experiments.

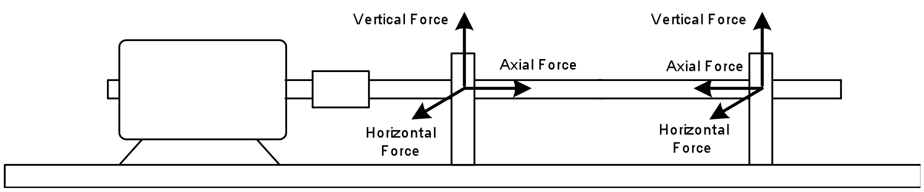


Fig. 2 Force transducers coordinates for the left and right bearing housings

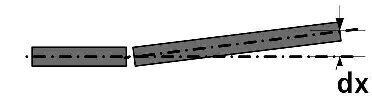
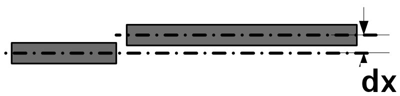
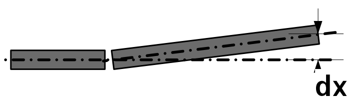
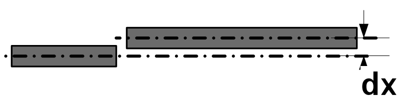
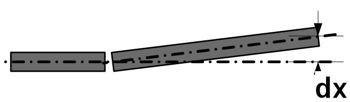
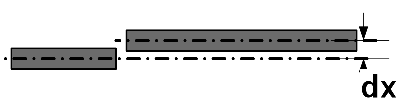
Vibrations of the motor, inboard bearing and outboard bearings were measured in three directions with accelerometers. Bearing housings with built-in force transducers measured vertical, horizontal and axial forces on each bearing. Tachometer detected the light reflected off the shaft and the actual speed was determined from spectra. Sixteen channels of data were acquired and recorded simultaneously using the SpectraPad DAQ board at 5120 Hz sampling rate for 10 seconds.

Table 1 Specifications of the MFS machine used for experiments [9]

induction motor: Marathon, 1HP	CAT No - D 393
shaft diameter	0.625 (inch)
shaft length	21 (inch)
shaft overhung from outboard bearing	2.4 (inch)
rotor bearings span	14.1 (inch)
rolling element bearings, 9 balls	MB ER-10K

Experiments were designed to study the effect of coupling stiffness, level and type of misalignment on vibrations and dynamic forces. For each coupling, angular and parallel misalignments were introduced in three levels using dial screws on the left and right ends of the base plate and 16 channels signals were measured for the shaft speed of 50 Hz (Table 2).

Table 2 Misalignment experiment design

Type of Coupling	Type of Misalignment	dx (mil)	Signals Measured
Beam Coupling		0 15 30 45	1) Tachometer 2) Acc motor vertical 3) Acc motor horizontal 4) Acc motor axial 5) Acc left bearing vertical 6) Acc left bearing horizontal 7) Acc left bearing axial 8) Acc right bearing vertical 9) Acc right bearing horizontal 10) Acc right bearing axial 11) Force left bearing vertical 12) Force left bearing horizontal 13) Force left bearing axial 14) Force right bearing vertical 15) Force right bearing horizontal 16) Force right bearing axial
		15 30 45	
Rigid Coupling		0 15 30 45	
		15 30 45	
Rubber Coupling		0 15 30 45	
		15 30 45	

RESULTS AND DISCUSSIONS

For each experiment defined in Table 2, tachometer signal, vibrations and dynamic forces were measured. Figures 3 and 4 show effects of misalignment types and levels on machine vibrations. Figure 3 plots time-domain vibration signals of the right bearing housing in three directions for different levels of angular misalignments. The rotor was coupled to the motor by a helical beam coupling. The top plots (a-c) are vibrations of the healthy machine with aligned rotor. In this paper, 'low', 'medium', and 'high' misalignments represent misalignments dx of 15, 30 and 45 mils respectively. The horizontal vibration (Fig. 3.b) is more dominant than vertical and axial vibrations. As shown in Fig. 3.k,m , angular misalignments can generate horizontal and vertical vibrations modulated by the low frequencies (1-2 Hz). However, the modulation is not appeared in the medium angular misalignments (Figs. 3.g-j). Time domain axial vibrations are not affected much by misalignments.

Figure 4 plots outboard bearing time-domain vibrations in three directions for different levels of parallel misalignments. Parallel misalignments (Fig. 4) generate more vibrations than angular misalignment (Fig. 3). Figures 4.g-m highlights severe vibrations modulated in low frequencies (1-2 Hz) for parallel misalignments. Also, for the severe parallel misalignment, slight axial vibrations with modulations are observed (Fig. 4.m).

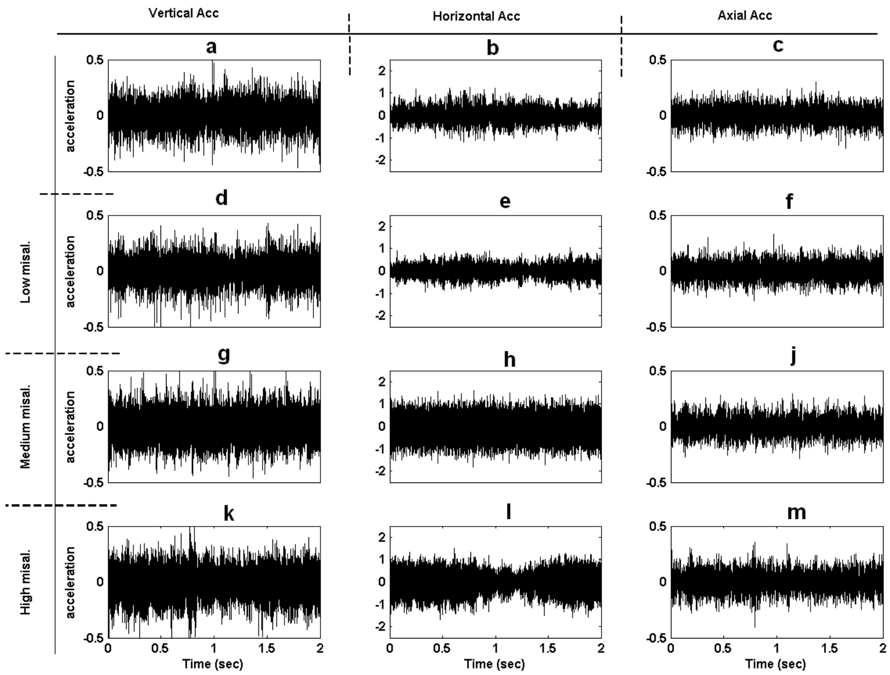


Fig. 3 Vibrations of the outboard bearing housing for different levels of angular misalignments. (shaft speed f=50Hz, helical beam coupling)

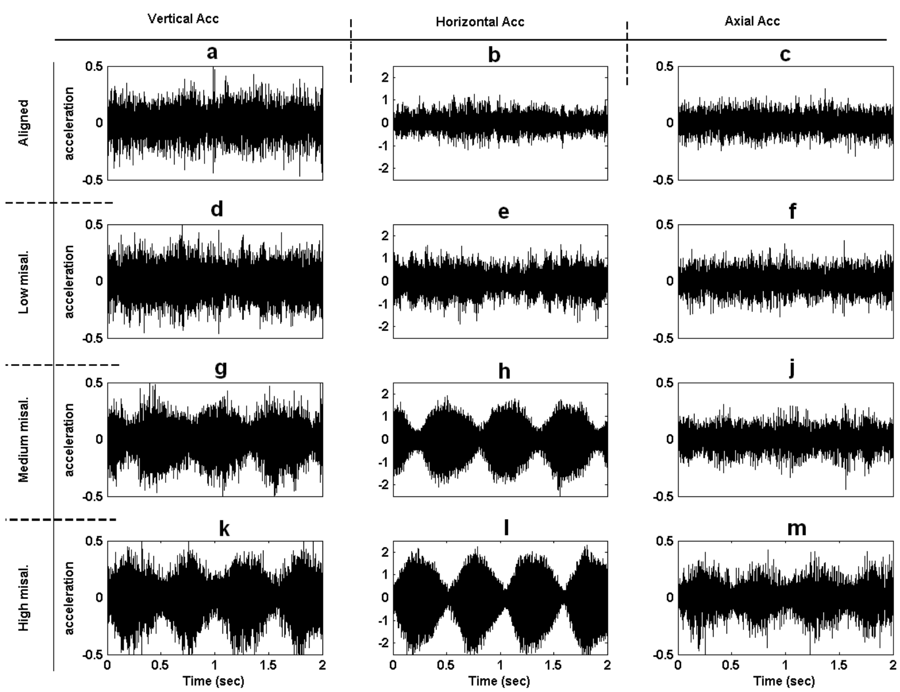


Fig. 4 Vibrations of the outboard bearing housing for different levels of parallel misalignments. (shaft speed f=50Hz, helical beam coupling)

The power spectra of the outboard bearing horizontal vibrations for different levels of angular and parallel misalignments are shown in Fig. 5. Shaft speed frequency 1X=50 Hz is clearly visible in the baseline spectra (Fig. 5.a) with faint higher harmonics representing possible little rotor imbalance or misalignment. Introducing angular misalignment, 3X and 5X harmonics are excited. The parallel misalignment excites 3X and 6X but not much 5X. For both angular and parallel misalignment, 2X harmonics are excited slightly but the 1X is not affected. Power spectrum of vibration signals picked from different locations and directions of the machine revealed different harmonics. This irregular pattern might be due to different dynamic force patterns at different locations. Therefore, a unique vibration spectrum pattern cannot be generalized for all locations of the machine. But, in presence of misalignment, low frequency modulations appeared as sidebands around 3X and 5X harmonics were observed for all cases.

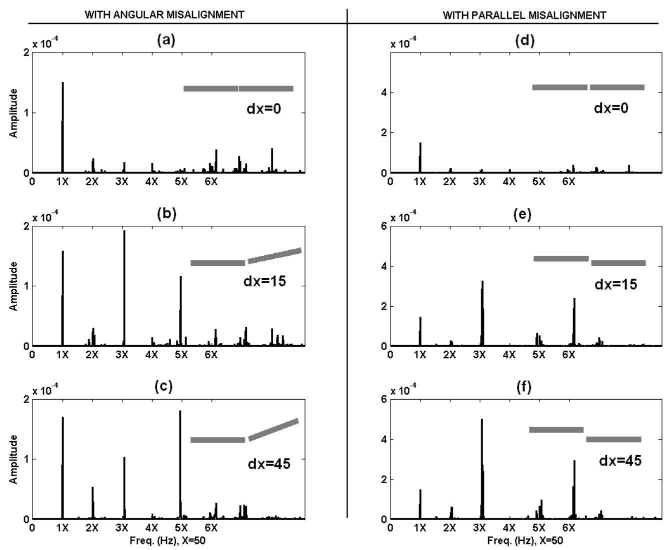


Fig. 5 Power spectrum of outboard bearing horizontal vibrations for angular (left) and parallel (right) misalignments. a,d: aligned; b,e: low misalignment; c,f: severe misalignment (f=50Hz, helical beam coupling)

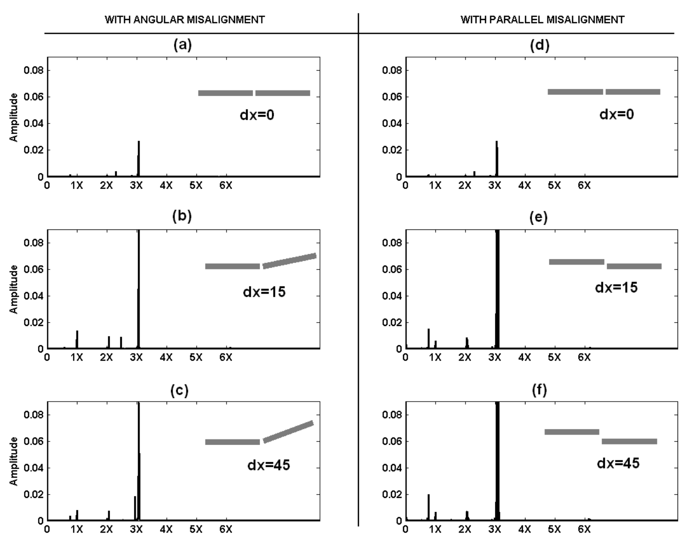


Fig. 6 Power spectrum of outboard bearing axial force signals for angular (left) and parallel (right) misalignments. a,d: aligned; b,e: low misalignment; c,f: severe misalignment (f=50Hz, helical beam coupling)

The axial dynamic force measured from the outboard bearing housing for angular and horizontal misalignments are transformed to frequency domain and power spectra of the axial force signals are presented in Fig. 6. Aligned rotor, low and severe misalignments are compared. For both angular and parallel misalignments, the 3X frequencies are excited by introducing the fault. The axial force is seen to be more sensitive to parallel misalignment than angular one. The baseline spectra (Figs. 6.a,d) has little 3X information showing little rotor misalignment. Since rotor imbalance generates lateral force and vibrations, the vertical and horizontal signals are contaminated by imbalance faults. But, the axial force signals especially in axial direction have misalignment information with little imbalance information. Therefore, axial vibration and force signals can be used to detect and separate misalignment from imbalance faults. However, axial force spectrum as seen in Fig. 6 does not have enough information to isolate angular and parallel misalignments. Time domain analysis was used for this purpose, which will be presented.

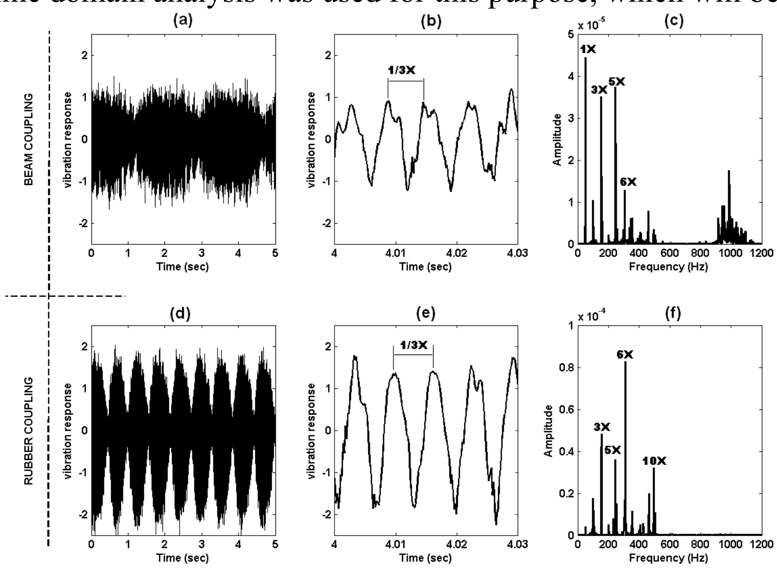


Fig. 7 Bearing horizontal vibrations in presence of angular misalignments (dx=45 mils) for helical beam and rubber couplings. a) time-domain vibrations with beam coupling for 5 sec b) magnified time-domain vibrations with beam coupling for 0.03 sec c) vibration spectrum of misaligned rotor with beam coupling d) time-domain vibrations with rubber coupling for 5 sec e) magnified time-domain vibrations with rubber coupling for 0.03 sec f) vibration spectrum of misaligned rotor with rubber coupling. (f = 50 Hz)

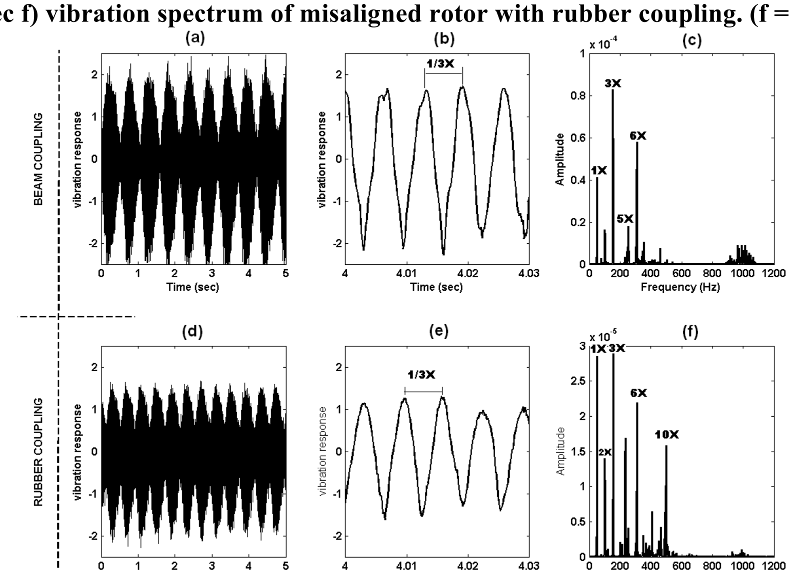


Fig. 8 Bearing horizontal vibrations in presence of parallel misalignments (dx=45 mils) for helical beam and rubber couplings. a) time-domain vibrations with beam coupling for 5 sec b) magnified time-domain vibrations with beam coupling for 0.03 sec c) vibration spectrum of misaligned rotor with beam coupling d) time-domain vibrations with rubber coupling for 5 sec e) magnified time-domain vibrations with rubber coupling for 0.03 sec f) vibration spectrum of misaligned rotor with rubber coupling. (f = 50 Hz)

Figures 7 and 8 show effects of couplings on bearing vibrations in presence of angular and parallel misalignments. The rubber coupling is more flexible in bending and torsion. Figure 7 illustrates vibration signals for angular misalignment in time- and frequency- domains for helical beam and rubber couplings. The time-domain plot for beam coupling reveals the modulation frequency of 0.54 Hz (Fig. 7.a) and the main frequency of 3X (Fig. 7.b). These frequencies are observed in the spectrum (Fig. 7.c) as sidebands and the 3X harmonics respectively. Also, other harmonics such as 1X, 5X and 6X are observed. For the rubber coupling, the time-domain vibrations (Fig. 7.e) show the main 3X frequency but the modulation frequency is changed to 1.7 Hz (Fig. 7.d). The vibrations spectrum for rubber coupling (Fig. 7.f) contains higher harmonics as well. The main difference between two couplings is the modulation frequency. Also, high frequencies (20X) are excited in the beam coupling signals (Fig. 7.c), which is not significant for the rubber coupling.

Figure 8 illustrates vibration signals for the parallel misalignment in time- and frequency-domains for helical beam and rubber couplings. Again, 3 X frequencies are observed as main frequencies in both beam (Fig. 8.b) and rubber couplings (Fig. 8.e). The modulations for beam and rubber couplings are changed to 1.9 Hz and 2.4 Hz respectively (Fig. 8.a,d), which is higher than what observed for angular misalignment. Helical beam signals reveal high frequencies around 20X (Fig. 8.c), which are not significant in rubber coupling. The spectrum patterns observed in parallel misalignment for both beam and rubber couplings are almost overlay the patterns observed in angular misalignments. For the beam coupling, machine vibration is more sensitive to parallel misalignment (Fig. 8.a) than angular one (Fig. 7.a). With the rubber coupling, angular misalignment vibration levels are almost the same as parallel misalignment vibration levels (Fig. 7.d and 8.d).

Misalignments in rotating machinery generate dynamic forces at rotor supports causing vibrations and damage to the bearings. Each bearing support was monitored for dynamic forces in three directions. Figures 9 and 10 illustrate bearing forces for angular and parallel misalignments respectively. For each case, inboard bearing forces in three directions are plotted at the left and outboard bearing forced at the right. Each graph plots mean values of normalized forces vs. severity of the misalignment for three different couplings. Also, force variations for each data point are shown as error bars on the graph.

Since misalignments were introduced horizontally, vertical forces are not changed much as seen in Figs. 9.a,d and 10.a,d. As observed in Figs. 9 and 10, the rotor with rigid coupling is more sensitive to misalignments and force variations, shown as error bars, are observed to be higher than force variations for other couplings even when machine is almost aligned. This situation can cause severe bearing dynamic forces and faults. However, axial force variations for the helical beam coupling are higher than rigid coupling since beam coupling are more flexible axially. With angular misalignments, horizontal forces in both inboard and outboard bearings are increased for all three couplings as shown in Figs. 9.b,e. With parallel misalignments, inboard bearing horizontal forces are much higher than outboard bearing forces (Figs. 10.b,e). This change is much more significant for the rigid coupling. The variations of vertical and horizontal forces for all cases are not much affected by the severity of misalignments. However, axial force variations are higher when more severe misalignments are introduced. Also, axial forces due to misalignments in outboard bearings are much higher than inboard bearings.

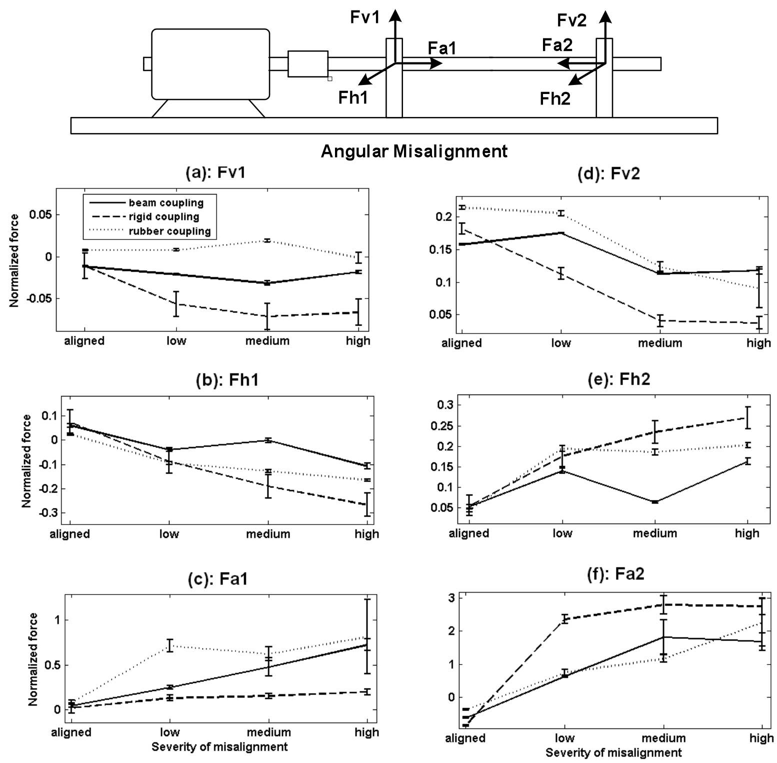


Fig. 9 Dynamic forces generated by angular misalignments for different shaft couplings.

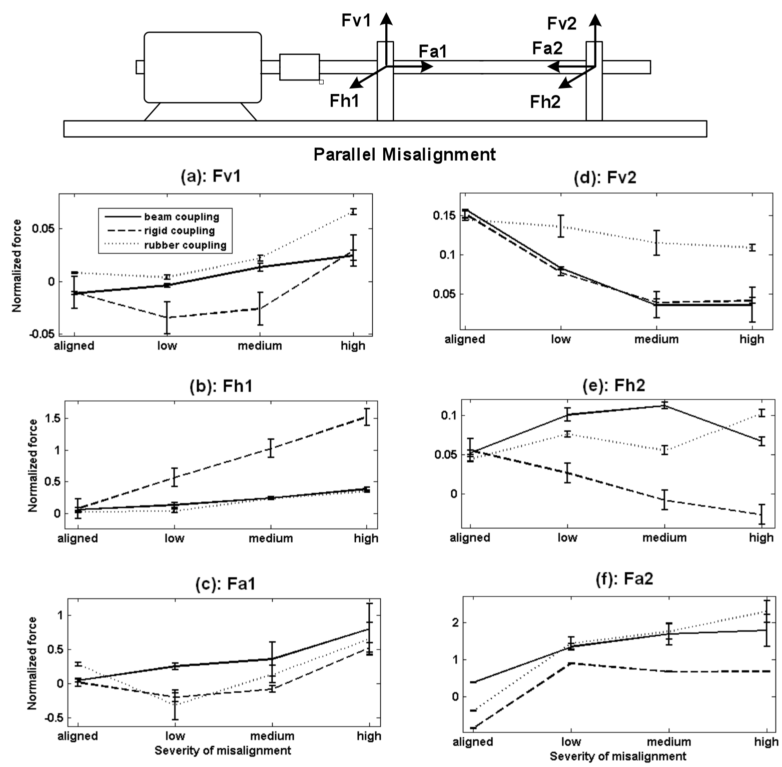


Fig. 9 Dynamic forces generated by parallel misalignments for different shaft couplings.

CONCLUSIONS

Misalignments in rotating machinery can generate bearing forces and excessive vibrations causing machine faults. Time-domain analysis of vibrations and forces is a useful tool for misalignment diagnosis. Misalignments in rotating machinery can excite vibration harmonics from 2X to 10X harmonics depending on the signal pickup locations and directions. Time-domain vibrations reveal 3X frequencies carried by low frequency modulations (0.5-3 Hz).

Bearing housing forces are very sensitive to the type and level of misalignments. Also, stiffness and structural design of the coupling can change the forces and vibrations significantly. Results suggested vibrations and forces of a machine with rigid coupling to be more sensitive to the parallel misalignments than angular misalignments. Regarding the axial forces, higher forces with more variations can be generated in a misaligned rotor coupled with a helical beam coupling than rigid coupling. Investigating axial forces in frequency-domain reveals significant 3X and 5X harmonics for angular and 3X and 6X harmonics for parallel misalignments.

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