

## FAULT DIAGNOSIS OF ROTATING MACHINES USING VIBRATION AND BEARING TEMPERATURE MEASUREMENTS

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### Summary

Acquisition and subsequent processing of vibration data for fault diagnosis of rotating machinery with multiple bearings, such as Turbo-generator (TG) sets, can be quite involved, as data are usually required in three mutually perpendicular directions for reliable diagnosis. Consequently, the task of diagnosing faults on such systems may be daunting for even an experienced analyst. Hence, the current study aims to develop a simplified fault diagnosis (FD) method that uses just a single vibration and a single temperature sensor on each bearing. Initial trials on an experimental rotating rig indicate that supplementing vibration data with temperature measurements gave improved FD when compared with FD using vibration data alone. Observations made from the initial trials are presented in this paper.

Keywords: Vibration Monitoring, Condition Monitoring, Rotating Machinery, Fault Diagnosis, Principal Component Analysis

### 1. Introduction

Acquisition and subsequent processing of vibration data for rotating machinery fault diagnosis can be quite intricate; as data are usually required in three mutually perpendicular directions for accurate fault diagnosis (British Standards Institution, 2009). To say the least, the processing of data acquired from complex systems such as turbo generating sets that consist of several stages of operations with multiple bearings is tedious, data intensive and consequently costly. Though traditional practice in vibration-based condition monitoring (VCM) is a mature technique for fault diagnosis of rotating machines, it is a relatively involved process that mandates judgment and expertise from a trained analyst. Additionally, the task of diagnosing faults on these systems may be daunting, if not impossible, for even an experienced analyst. Thus a more simple but robust technique is usually required and would be well appreciated by the relevant industries.

Recent studies (Elnady, et al, 2012; Elbhah and Sinha, 2013; Sinha and Elbhah, 2013) have suggested VCM methods that require significantly reduced number of vibration sensors. Elnady, et al (2012) proposed the use of the on-shaft vibration (OSV) measurement technique that requires special arrangement of the measurement instrumentation. Elbhah and Sinha (2013) and Sinha and Elbhah (2013) used just a single vibration sensor on each bearing by fusion of data in; the composite spectrum and higher order spectra respectively. However both methods were slightly computationally involved. The present study aims to keep both data acquisition and processing simple

and develop a diagnosis technique that uses fewer sensors while preserving moderate computational load. With the wide availability of temperature monitoring systems on rotating machines in industries and studies confirming the sensitivity of temperature to rotating machinery faults (Gaberson, 1996; Sabnavis, et al., 2004; Craig, et al, 2006; Nembhard, 2011; Yong-Wei and Jian-Gang, 2011), an opportunity exists to integrate temperature and vibration data for effective fault diagnosis. Hence, a simplified fault diagnosis (FD) method is proposed that uses just a single vibration and a single temperature sensor on each bearing. The temperature measurement is expected to compensate for the reduction in vibration sensors while replacing the need for advanced and complex signal processing of the vibration data in the fault diagnosis process.

The proposed vibration and the temperature measurements are made on an experimental rotating rig with two coupled rotors supported through 4 ball bearings (Nembhard, et al, 2013a). Different faults are simulated in the rig and both vibration and temperature measurements are collected and analysed in Section 2. Earlier studies used Principal Component Analysis (PCA) as a tool for the diagnosis in rotating machines (Li, et al, 2003; Liying, et al, 2012; Elnady, et al, 2012), so this method is applied in the present study. Results from analyses done are presented and discussed in this paper.

### 2. Experimental set up

Figure 1 shows a photograph of the experimental rig used for the experiment

(Nembhard, et al, 2013a). The set up consists of two 20 mm nominal diameter dissimilar length (100 mm and 50 mm) rigidly coupled rotors that are supported by four grease lubricated ball bearings. These are secured atop flexible steel pedestals that are bolted to a large lathe bed secured to the

concrete flooring. Machined sections accommodating balancing disks are mounted on each rotor. System drive is provided by a 0.75kW, 3 phase, 3000 rpm motor that is mated to the rotor-bearing system via a semi-flexible coupling. The main dimensions of the rig are provided in Figure 2.

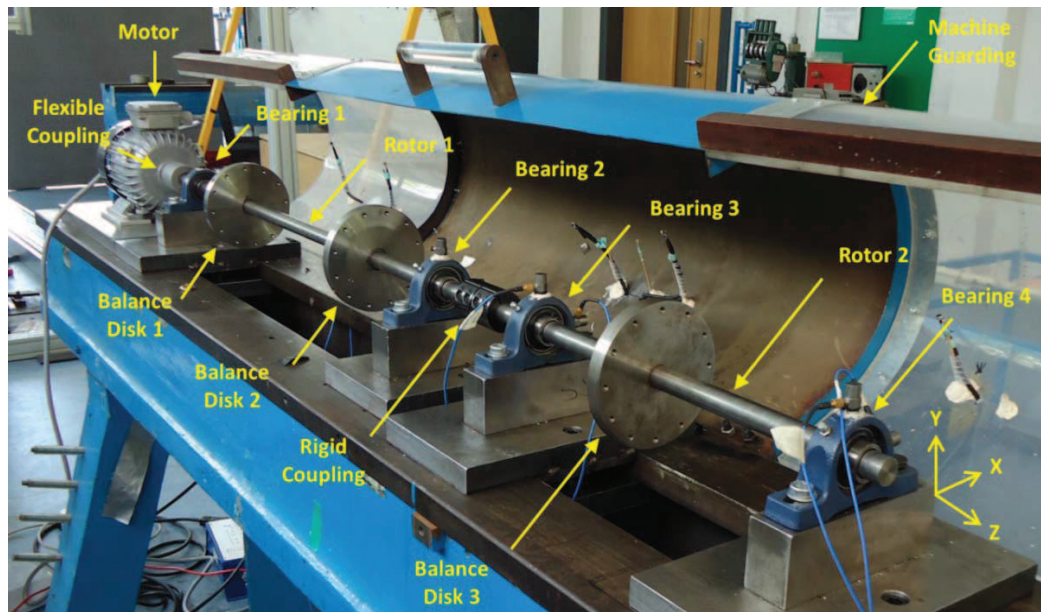
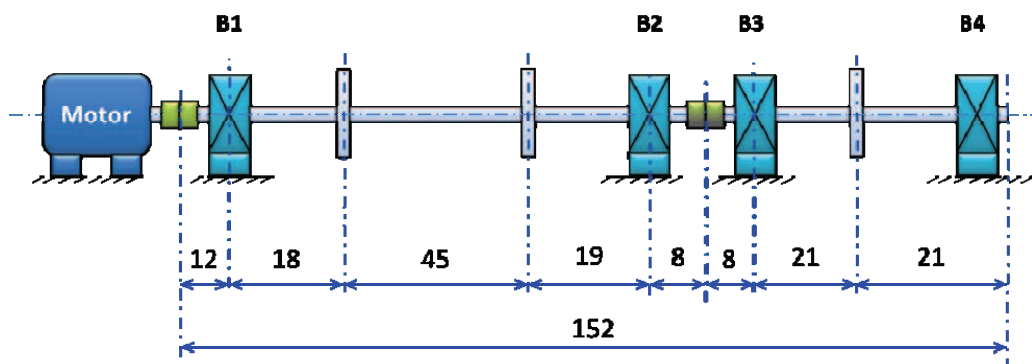


Figure 1. Experimental rig mechanical layout



Note: All dimensions shown in cm

Figure 2. Schematic of experimental rig with dimensions

The instrumentation and software schematic for the set-up is depicted schematically in Figure 3 (Nembhard, et al, 2013a). Rig speed is varied with a speed controller that is operated from a personal computer. The dynamic response of the system is then measured with 100 mV/g accelerometers. Each bearing location has two accelerometers that are mounted with adhesive in mutually perpendicular directions. The vibration data are transmitted through two four channel signal conditioners to a 16 Bit Analogue to Digital (A/D)

Data Acquisition System. Data logging software then stores the digitized vibration data on the personal computer. To measure the thermal response of the system, K-type thermocouples are attached between the bearing casing and outside of the outer race of each bearing. This mounting position was used to get the most immediate and accurate temperature measurements possible. All four temperature readings were captured with an eight channel data logger and saved to the personal computer for later analysis.

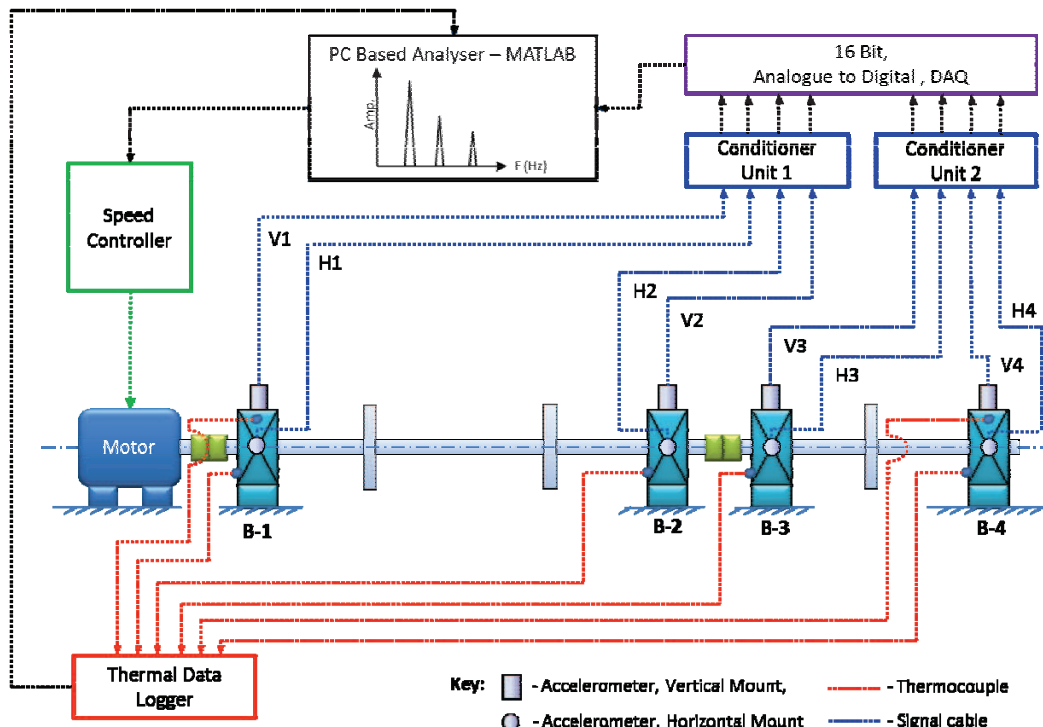


Figure 3. Schematic of software and instrumentation

### 3. Experiments

On starting system from rest, bearing temperatures were recorded for a period of ten minutes at 5 second intervals. Vibration data, at a sampling frequency of 10 kHz, was collected at the ten minute point for a total sample time of one minute. After each experiment the system was allowed to cool to ambient temperature before configuring the rig for a different scenario. Experiments were performed at 2400 rpm (40 Hz). Data for the healthy machine condition was first collected in order to establish baseline conditions for the rig. Data were then collected for three fault conditions; cracked rotor, rotor rub and coupling misalignment. The cracked rotor condition was simulated with the crack in three different positions. In each case a “breathing crack” (Sabnavis et al, 2004),

with a depth of 20% shaft diameter was created (see Figures 4(a),(b)).

Rub was simulated by a Perspex apparatus consisting of a base bolted to the lathe bed (at 115 mm from bearing 4) and a stand with a 22 mm diameter hole drilled parallel to the axial centre line of the shaft. The shaft passes through the hole and rub its inner bore (see Figure 5). Misalignment was the final scenario tested in order to minimise the effect of any residual misalignment that could be retained in the system after testing. A steel shim was installed under Bearing 3 housing to induce angular misalignment in the y-z plane across the rigid coupling located between Bearing 2 and Bearing 3 (see Figure 6). Further details of experiments done are given by Nembhard, et al (2013b). Table 1 summarizes the experiments and data collection procedure employed.

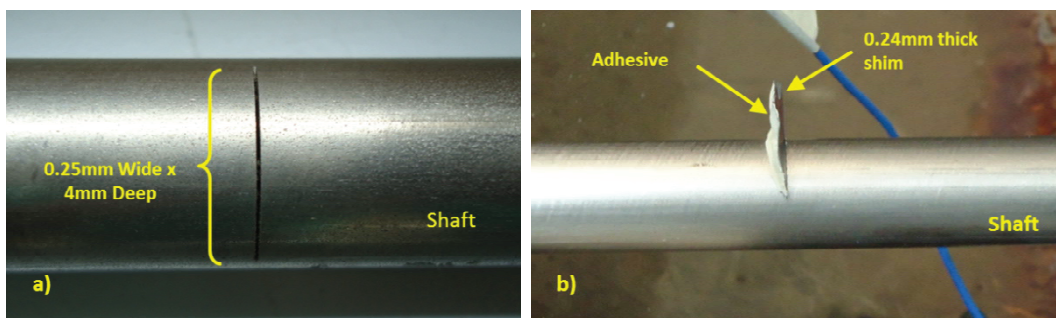


Figure 4. Details of apparatus used for rub simulation

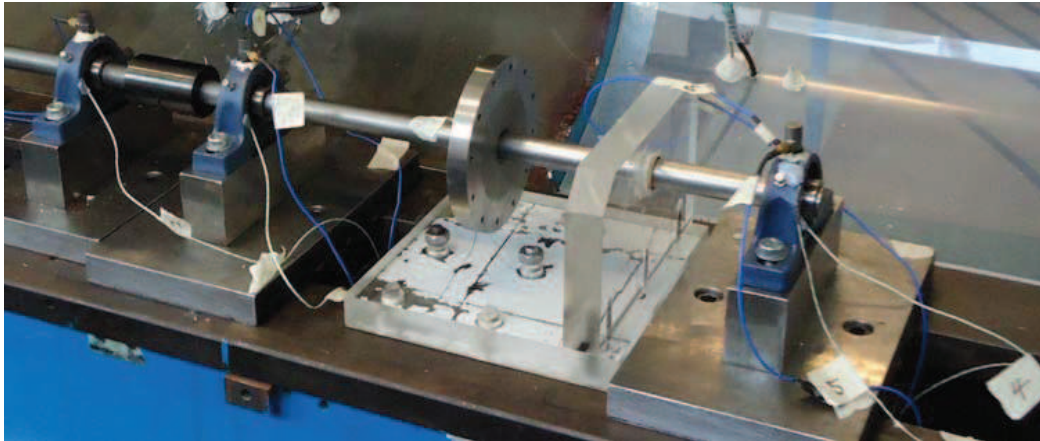


Figure 5. Close up of apparatus used for rub simulation between bearing 3 and bearing 4

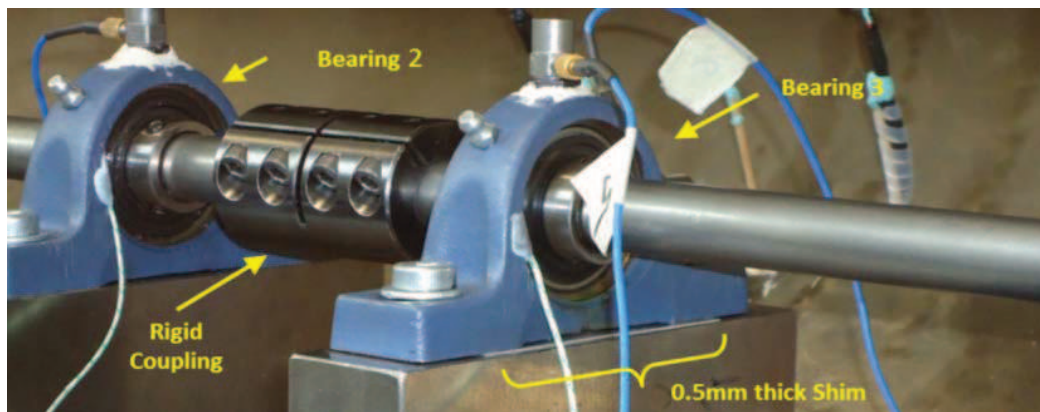


Figure 6. Details of Misalignment simulation at Bearing 3.

Table 1. Summary of experimental procedure used. One fault scenario was simulated at a time

No	Code*	Scenario Name
1	Healthy	Healthy
2	Cr Nr1	Crack near Bearing 1
3	Cr Nr2	Crack near Bearing 2
4	Cr Nr3	Crack near Bearing 3
5	Mlign	Misalignment
6	Rb Nr4	Rub near Bearing 4

\*Same nomenclature is used in figures throughout rest of paper

#### 4. Data Analysis

For each machine condition, the acceleration spectrum was generated from data measured in the horizontal radial direction between 5 Hz and 1 kHz. Each spectrum was analysed to gain insight into to the condition.

Principal Component Analysis (Jolliffe, 2002) was then performed; first with vibration data only and then with vibration and temperature data. Firstly, for each machine condition, the measured vibration data was segmented into 20 observations. Each observation was used to compute one time domain feature (root mean square [rms]) and three

frequency domain features (amplitudes of 1x, 2x and 3x harmonic components). Each bearing location was treated as a separate set of features. Hence a total of 16 features (4 bearings x 4 features) were computed. These were used to populate a feature matrix,  $X_v$ , for loading to the PCA algorithm. Each scenario simulated was treated as a different set of observations; hence matrix  $X_v$  would have 16 rows (features) and 120 columns (6 scenario x 20 observations). Before computing of Principal Components (PCs), each element in  $X_v$  was converted to zero mean and unit variance (Jolliffe, 2002; Elnady, et al, 2012).

Temperature measurements were processed to add to this vibration data. Since temperatures were recorded during machine run up it was necessary to extrapolate it to obtain steady state bearing temperatures and for this a simple thermodynamic model of the bearing plus curve fitting process were used. Assuming the majority of heat loss from a bearing was via conduction to the steel pedestals, which could have acted as a large heat sink, the bearing temperature change values would be as shown in Equation (1).

$$\Delta T = (T_{max} - T_o)e^{-At} \quad (1)$$

(where  $\Delta T$  is temperature increase,  $T_{max}$  is steady state temperature,  $T_o$  is ambient temperature,  $A$  is an arbitrary variable and  $t$  is time).

Unknown variables in the equation for each condition were adjusted until the model (dashed lines) matched the warm up curves (solid lines) as shown in Figure 7(a). These variables were then used to generate full steady state curves (as shown in Figure 7(b)) for each fault condition. Full interrogation of the acceleration spectra was also done to ascertain if any bearing fault was present; as this would have affected the temperature measurements. The steady state temperatures calculated for each bearing were included as an additional feature, which resulted in a 20 x 120 feature matrix,  $X_{t+v}$ . The process of normalizing elements in  $X_{t+v}$  was repeated and PCs were calculated.

## 5. Results and Discussion

### 5.1 Spectral Analysis of vibration data only

Figure 8 shows the typical amplitude spectra at Bearing 2 for all conditions tested. It can be seen that the method did give an indication of the presence of fault conditions, as there were noticeable increases in the 1x component for all fault conditions relative to the healthy spectrum. However, fault diagnosis was not possible as different faults generated similar spectral features. In an attempt to improve the diagnosis, the amplitudes of the 4x, 3x and 2x harmonic components for each bearing location at all conditions tested was normalized with their respective 1x component. These were used to generate plots of the normalized 3x harmonic component against the normalized 2x harmonic component and the normalized 4x harmonic component against the normalized 2x harmonic component, as shown in Figures 9(a) and 9(b) respectively. The main objective of normalizing with the 1x component is to remove the effects of unbalance which would be present across the spectrum. Consequently this would leave the spectral features present fully representative of the condition present on the rig. It was expected that different faults would form clusters in each plots, however, the results obtained did not show any useful discriminative feature. As expected, it seems the simple spectrum is not adequate for the diagnosis of these simulated faults without phase information (Sinha, 2002; Sinou, 2009).

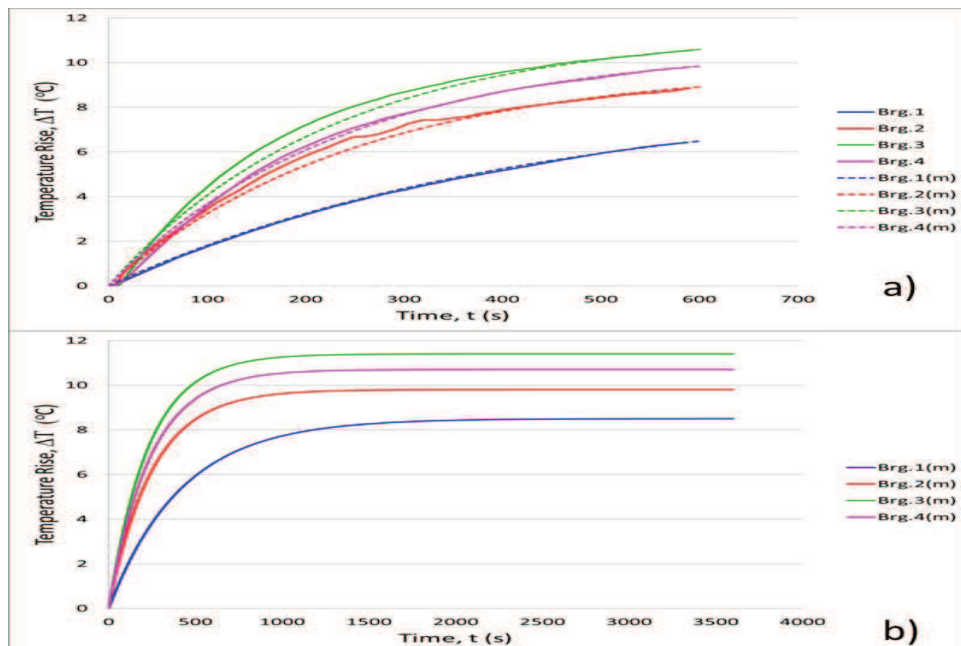


Figure 7. Sample showing progression of temperature trends in curve fitting process: a) transient curve fitting and b) generation of steady state curves

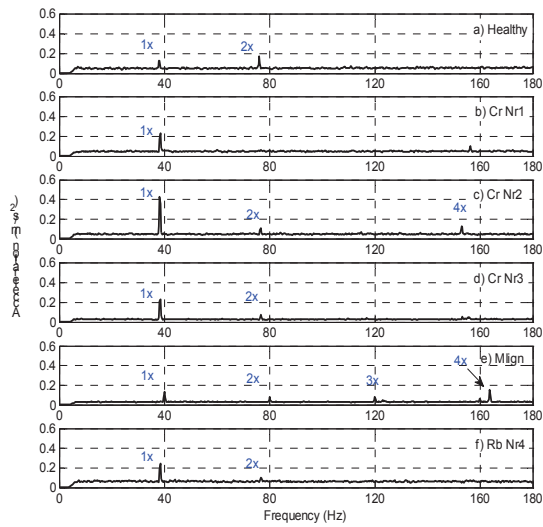


Figure 8. Typical amplitude spectra at Bearing 2 for all conditions tested.

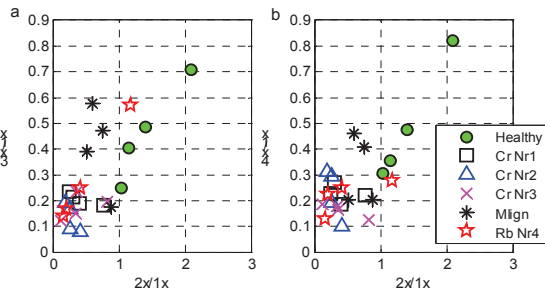


Figure 9. Comparison of spectral features for all conditions tested at 40 Hz: Healthy, Crack near Bearing 1, Crack near Bearing 2, Crack near Bearing 3, Misalignment and Rub near Bearing 4.

**5.2 Fault Classification with vibration data only**

Figure 10 shows a two dimensional (2D) PC plot which correlates the 2nd PC (PC2) against the 1st PC (PC1). Healthy condition did not occupy a defined space as there was some overlap with it and the Rub near bearing 4 data points. It was also observed that there was overlap between Misalignment and Crack near bearing 1 and 3 data. This is analogous to results obtained in the spectrum analysis (see Figure 8) where it was not possible to distinguish cracked rotor from misalignment. It therefore appears that PCA with vibration data alone is no more useful than spectrum analysis in this case.

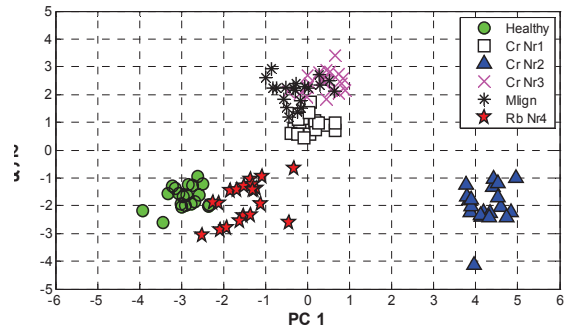


Figure 10. Fault Classification by PCA without Temperature - 40 Hz

**5.3 Fault Classification with vibration and temperature data**

Figure 11 shows the 2D PC plot that was produced. It can be seen that the addition of temperature fully separates healthy from all faulty data. The overlap between Misalignment and Crack near bearing 1 and 3 that was noticed in PCA with vibration data only (in Figure 10) does not exist in this plot. It was interesting to note that the Crack near bearing 2 condition was mostly unperturbed by the addition of temperature. Notwithstanding, the addition of temperature puts each fault condition in a clearly defined region, which may be useful for fault diagnosis. Additionally, when compared to the simple spectrum in Figure 8(c); where Crack near bearing 2 was observed to be the most severe fault (possessing the largest 1x component and with noticeable increase in 2x harmonic component with respect to the healthy spectrum), a similar observation is made here, as the said condition has the greatest separation from the healthy case. Therefore, in addition to fault classification, it seems this method may be able to provide useful information on fault severity. Further experimentation would be required to verify this.

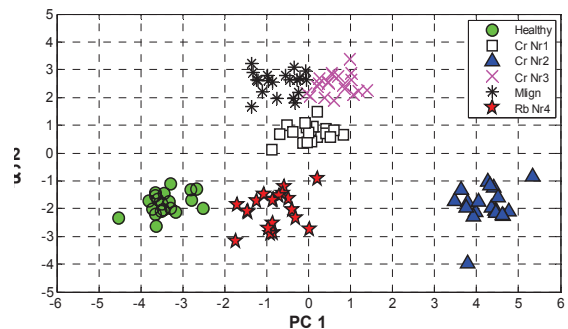


Figure 11. Feature classification by PCA, with Temperature - 40 Hz.

**Conclusion**

A fault diagnosis technique for rotating machinery, rotor-related faults is proposed using a single vibration sensor together with a simple temperature sensor on each bearing. Initial trials show that supplementing vibration data with

temperature measurements gives better separation of healthy and faulty data, allowing clearer diagnosis of faults when compared with vibration data alone. The proposed method also seems to be simple and non-intrusive and thus have the potential for future application. However further experimentation on different rigs with different faults is required to fully explore the potential and validate the usefulness of the method.

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