Detection of Shaft Misalignment by Thermal Image Analysis of Coupling

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Abstract- Thermal imaging is considered an effective way for condition monitoring and fault diagnosis as thermograms present state and condition of a component under its operating temperature. The present work aims at analyses of different conditions of misalignment and recorded data for each fault in controlled conditions. The fault detection is achieved in two stages: image processing followed by image evaluation. In this work, image processing consists of application of gray scale image transformation to the original thermal image whereas image evaluation consists of selected region of interest for coupling, drive end bearing and non-drive end bearing and hence maximum temperature of the component is determined. Also, an attempt is made to provide a reliable choice between image processing and image evaluation method according to their need in particular fault detection method.

Keywords – Thermogram, Gray scale image transformation, Region of interest, Kurtosis, Coupling

I. INTRODUCTION

A rotary machine consists of driving as well as driven units which are connected together with the help of coupling. These couplings can be rigid, flexible or fluid type. In industries due to various reasons such as differential thermal expansion among the driving and driven components and errors arising from machine installation, improper foundation etc. the shafts of the driven and driving units may become misaligned. Misalignment in a motor drive system is a condition where the centerlines of coupled shafts do not coincide. Almost all misalignment conditions of motor drive systems in practice are a combination of parallel and angular misalignment [1] and [2]. This is one of the severe conditions that occur very frequently in motor drive systems and are most of the time responsible for drive failure [3]. Gibbons [4] derived the misalignment reaction forces generated in different couplings. Sekhar and Prabhu [5] numerically evaluated the vibration response of the rotor for the coupling misalignment. They suggested 2X vibration response as a characteristic signature of misaligned shaft. Misalignment in the machine results due to improper machine assembly and sometimes due to thermal distortion in bearing housing supports, arrives at abnormal rotating preload [6] and [7] and contributes 70% of rotating machine vibration problem [8]. Proper and accurate condition monitoring of such conditions has always been a challenge.

II. PROPOSED ALGORITHM

The thermogram is transformed to gray scale image and analyzed for temperature using statistical features.

A. Gray scale image transformation –

Gray scale image is also known as intensity, gray level, or gray scale image of which pixel value specifies intensity values and requires only 8 bit memory storage. In order to minimize the computational time and storage space image processing is often carried out by transforming color image to gray scale image [9, 10]. The purpose behind this conversion is to eliminate background and thereby, highlight temperature effect in the image. Conversion of color image to grayscale image is one of the image processing applications used in different fields effectively. A color image consists of primary color components such as red, green and blue. Each component requires 8 bit of memory storage therefore a color image requires 24 bit storage space [11]. In the present work the image conversion process has been performed using Matlab software.

B. Features based on histogram–

Histogram features, which are truly statistical features, are compact representation of image characteristics without requiring knowledge about them. Histogram features consist of mean, standard deviation, skewness, rms, entropy, and kurtosis. The first order histogram features can be calculated as follows:-

P (h) is first order histogram probability for an image I mathematically expressed as

$$P(h) = N(h) / M \quad (1)$$

where M is the number of pixels in the image I. The N (h) is the number of pixels at gray level h in the same window so that $0 \leq h \leq L-1$ where L being level.

The feature, mean is described as the average value of the pixels that gives some information about the general brightness of the image. L denotes total number of gray levels for the image range from 0 to 255. Standard deviation is the square root of the variance. It provides information about the spread of data. A high contrast image will have a high variance, vice versa. The root mean square abbreviated RMS or rms, also known as quadratic mean, is defined as the square root of the arithmetic mean of the squares of a set of numbers

$$RMS = \sqrt{\frac{(x_1^2 + x_2^2 + x_3^2 + \cdots + x_n^2)}{n}} \quad (2)$$

Skewness measures the asymmetry about the mean in the gray-level distribution. The skewness could also be measured by using the mean, mode, and the standard deviation where the mode is defined as the peak or highest value [9]. The skewness is expressed as

$$S = \frac{1}{\sigma_g^3} \sum_{h=0}^{L-1} (h - \bar{h})^3 P(h) \quad (3)$$

Kurtosis is a measure of whether the data are heavy-tailed or light-tailed relative to a normal distribution. That is, data sets with high kurtosis tend to have heavy tails, or outliers. It is given by the ratio of the fourth central moment and the square of the variance [9]

$$K = \sum_{h=0}^{L-1} \frac{(h-\mu)^4}{\sigma^4} \quad (4)$$

Energy is a measure that tells us something about how the gray levels are distributed. The energy measure has a maximum value of 1 for an image with a constant value, and it gets increasingly smaller as the pixel values are distributed across more gray-level values. Entropy on the other hand is a measure that provides information that how many bits are needed to code the image data.

III. EXPERIMENT AND RESULT

To diagnose the fault a series of experiments were carried out using rotor-bearing test rig which consists of a motor, two deep groove ball bearing, bearing housing, shaft, rotor disc, flexible coupling, PC for saving data, thermal camera and a variable frequency drive in order to drive motor at different speeds. The thermal camera is the key device and some of its parameters require to be set due to their importance for data acquisition, especially for thermal image data. The most important parameter is emissivity and the other parameters are relative humidity, scale temperature, focal length of camera, and distance. All of these parameters are chosen according to the experimental condition. In this study, all parameters were maintained constant. In the experimental setup the shaft was supported by the two identical deep groove ball bearings (Manufacturer: NBC, Bearing number: 6204-ZZ) fitted in split type Plummer block. A three phase alternating current motor of 0.5 HP capacity (Manufacturer: Rotomotive, speed 2810 RPM) was used to drive the shaft connected through the flexible coupling and a balanced rotor disc mounted at the center of the shaft with provision for attachment of the unbalance load. In order to get speed variation a drive (Manufacturer: Danfoss) was connected to the motor that controls the RPM of motor ranges from 300 to 1600 through the frequency variation. The speed of the shaft was measured using an proximity switch with digital display. The experiment for each condition was carried out by driving motor upto 1456 RPM using variable frequency drive. This speed was maintained for 50 minutes to reach the machine to stable condition. A schematic diagram of the set up on which experiments were conducted is shown in Fig.1.

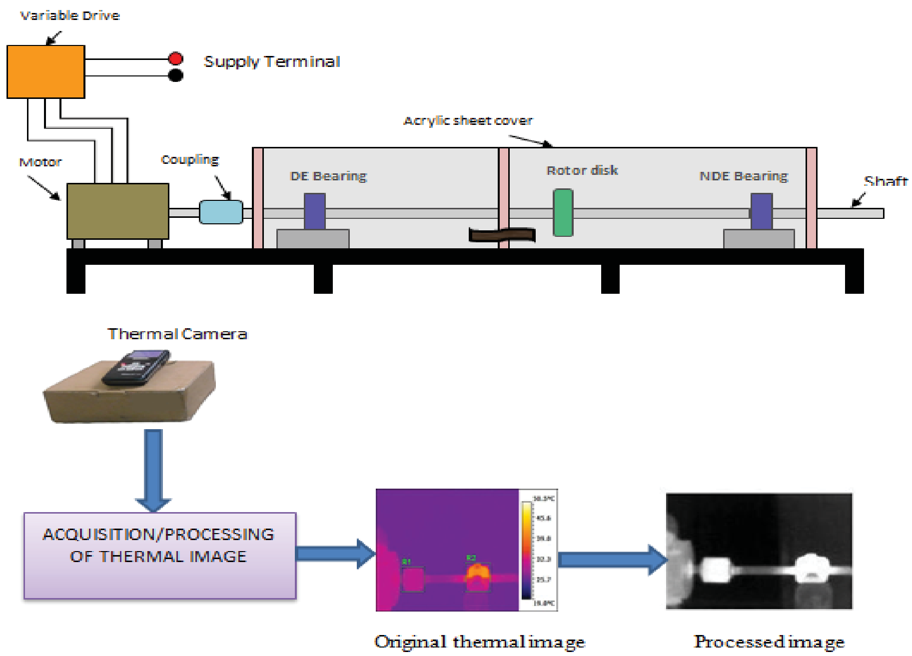

Figure 1. Schematic diagram of experimental setup

Surface temperature of components in setup is a function of various parameters including: machine part motion, misalignment, unbalance and environmental conditions etc. The various machine parts have relative motion with each other and pave way for increase in temperature. If there is any abnormality inside machine, then the friction of these parts will further change the machine component temperature. It is very difficult to control these parameters intentionally. But the environmental conditions were room temperature, humidity and radiations can be controlled. Hence attention is required for considering these parameters. In this experiment, controlled environment (constant room temperature) was maintained. For attaining the stability of machine it was run for 50 minutes in a controlled environment before acquiring thermal images. After running for that period of time the temperature of various parts the of set up attains steady state. The subject should be in front of the camera and there should be no other heat source in the camera view because that may change the temperature scale range of a thermal camera. A typical thermal image of coupling and drive end bearing is shown in Fig.2. Thermal image of non-drive end bearing is shown in Fig.3.

In the process of image evaluation for shaft misalignment, region of interest is selected to determine the maximum temperature of components. Table 1 shows the value of maximum temperature for different misalignment conditions. Similarly, the variation of maximum value of temperature for different conditions of misalignment for coupling, drive end bearing and non-drive end bearing can be shown using scatter plot. Fig. 4, 5 and 6 show the variation of temperature and misalignment for selected regions of components in the original thermal image.

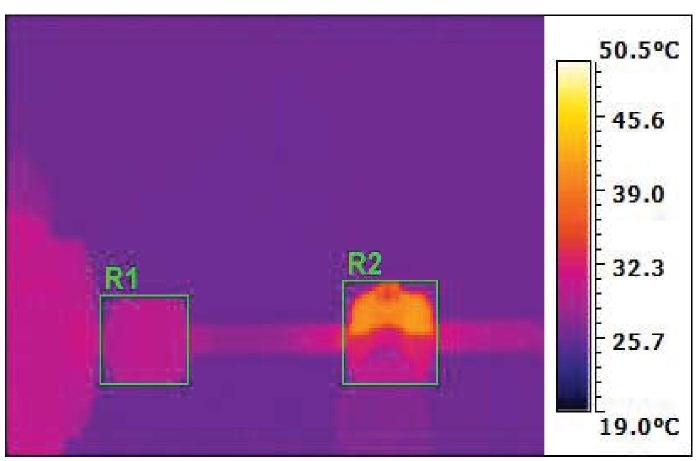

Figure 2. Thermal image of coupling and drive end bearing with selected regions R1 and R2 respectively

Likewise the process is repeated for different conditions of misalignment. The maximum temperature values are recorded for each case. Fig. 3 shows the selected region of non-drive end bearing in the image.

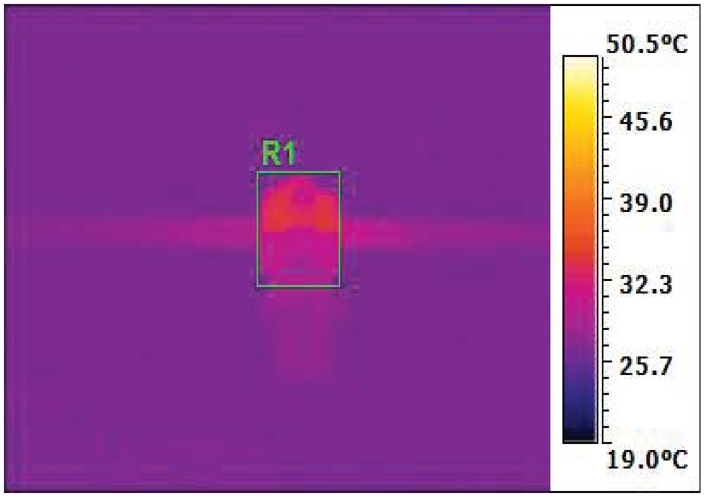

Figure 3. Thermal image of non-drive end bearing with selected region R1

Table 1. Maximum temperature values for different misalignment conditions

Coupling		Drive End Bearing		Non-drive End bearing	
Misalignment (mm)	Temperature (°C)	Misalignment (mm)	Temperature (°C)	Misalignment (mm)	Temperature (°C)
0	33.1	0	36.8	0	43.8
4	38.1	4	37.3	4	48.4
8	38.4	8	39.3	8	48.7
12	38.7	12	41.7	12	49.8
16	42.1	16	44.5	16	51.8

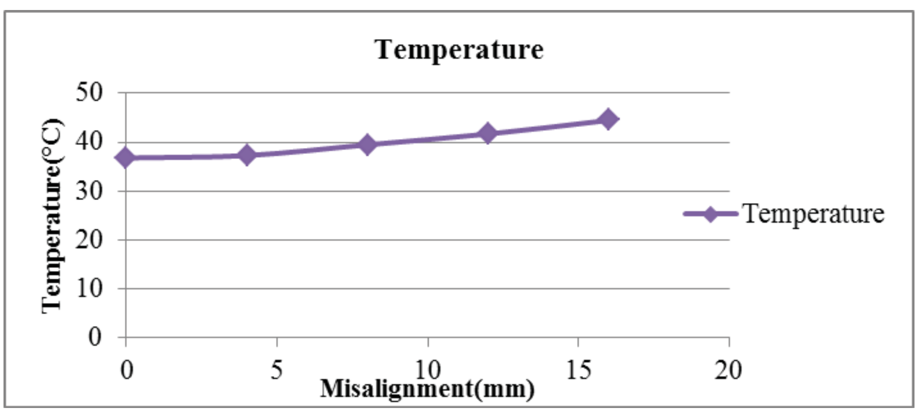

Figure 4. Temperature variation for drive end bearing

Fig. 4 represents temperature rise for drive end bearing at different misalignment conditions. It can be noticed that as the value of misalignment increases there is equivalent temperature rise of component. This temperature rise is due to increase in magnitude of unbalance forces and moments at bearing ends.

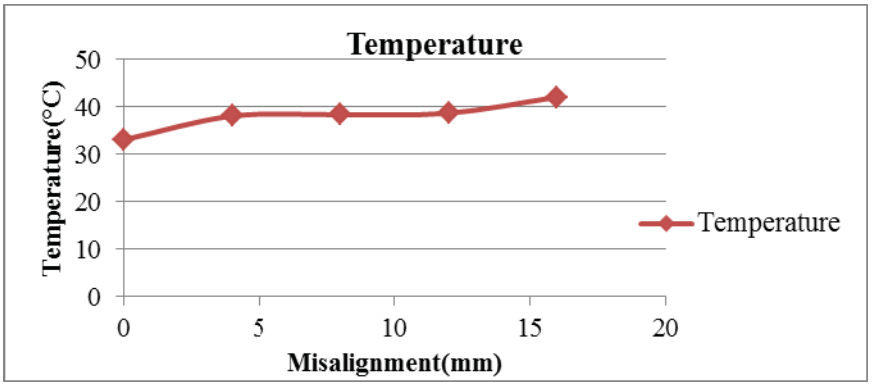

Figure 5. Temperature variation for Coupling

Fig. 5 shows temperature variation for coupling in the system for different values of misalignment. Coupling helps in connecting driving shaft with driven shaft. If there is any deviation in centerline of shafts it results in increase in temperature of coupling. Above figure clearly shows that the misalignment value reflects with corresponding increase in temperature.

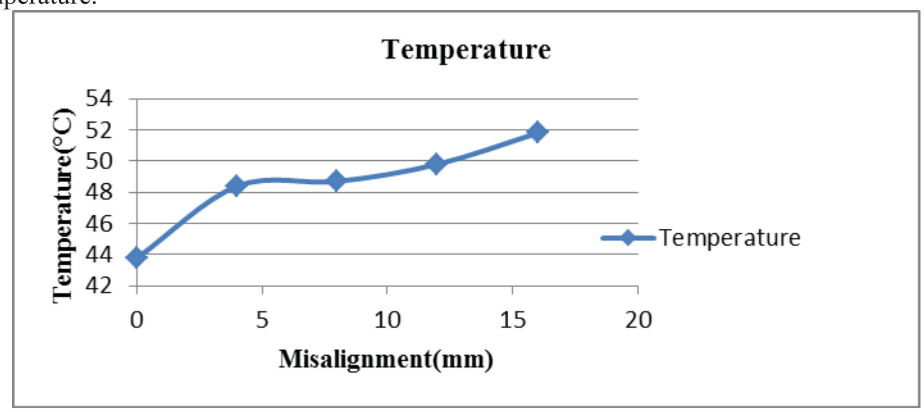

Figure 6. Temperature variation for Non-drive End Bearing

From Fig.6 it is clear that higher degree of misalignment shows corresponding increase of temperature in the system. Since magnitude of unbalance forces and moment increases at the bearing ends and this gives rise to frictional heat generation results in increase in temperature. From Table 1 it is found that in non-drive end bearing temperature rise for different misalignment values is more than the coupling and drive end bearing. Therefore the inference may be drawn that effect of misalignment is more at non-drive end bearing. In addition to image evaluation image processing may be an alternative way to fault separation method wherein image features are used. Fig.7 shows original thermal image for coupling and drive end bearing. Gray scale transformed image is shown in Fig. 8. Features of original thermogram showing coupling and drive and bearing and its gray scale image is shown in Fig. 9 and Fig. 10 respectively.

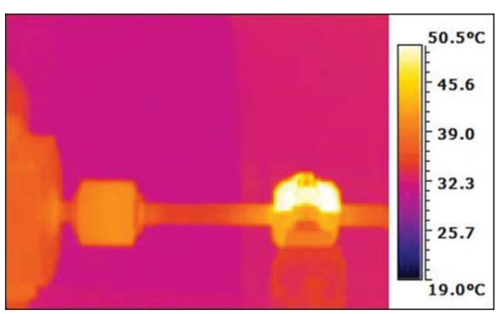

Figure 7. Original thermal image for coupling and drive end bearing

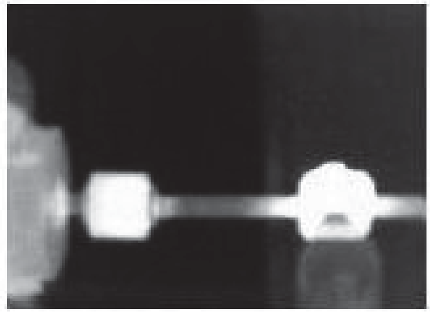

Figure 8. Gray scale image for coupling and drive end bearing

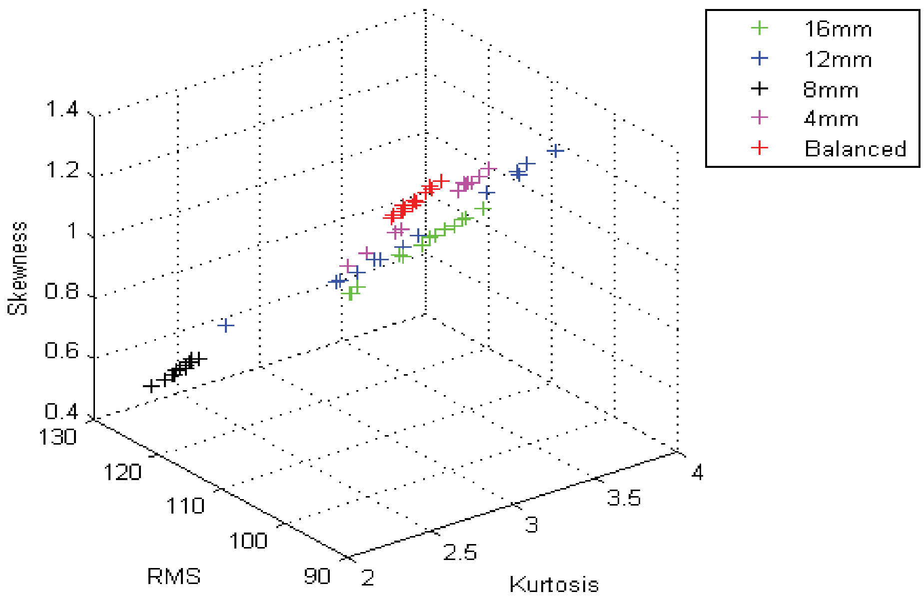

Figure 9. Original image features for coupling and drive end bearing

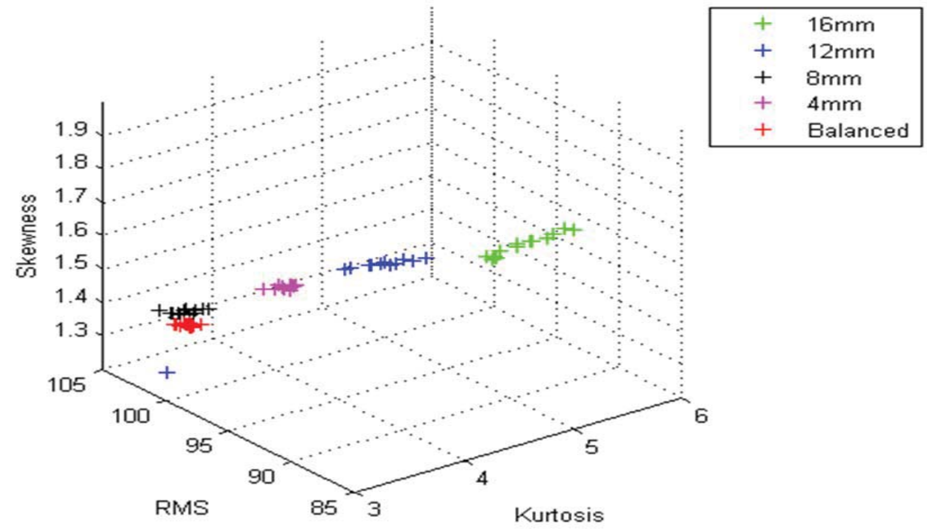

Figure 10. Gray scale image features for coupling and drive end bearing

Image features such as kurtosis, mean, standard deviation, rms, entropy and skewness were calculated for different misalignment conditions. To separate the fault these features were plotted on 3-D scatter plots in Fig. 9 and Fig. 10. The respective figure shows the cluster formation for original image features and the clusters for different misalignment condition overlap with each other. After applying gray scale image transformation these were plotted and shown in Fig.10 wherein features cluster for different faults are separable and clear and therefore it appears to be an effective way of fault separation.

IV. CONCLUSION

In this paper, a fault separation method using thermal images consisting of gray scale image transformation has been presented to separate between normal and different misalignment conditions of machine. The thermal images captured from machine conditions are preprocessed using gray scale image transformation to reduce data computation. Due to this transformation some image information gets lost but higher feature cluster separability is obtained. This may be seen from Fig.9 for coupling and drive end bearing. Also image evaluation may be successfully applied to differentiate between normal and misalignment conditions of a machine. From there lies case in Table 1 temperature values of coupling, drive end bearing and non-drive end bearing it is obvious that temperature as the condition changes from normal state to misalignment state in machine. As compare to ambient temperature which is 30.4°C the rise in temperature for coupling is 2.8°C, 7.8°C, 8°C, 8.3°C and 11.8°C for different misalignment conditions of 0mm, 4mm, 8mm, 12mm and 16 mm respectively. Similarly for drive end bearing values of temperature rise are 6.4°C, 6.9°C, 8.9°C, 11.3°C and 14.5°C respectively. Whereas for non-drive end bearing these values are 13.4°C, 18°C, 18.3°C, 19.4°C and 21.4°C for corresponding misalignment condition of 0mm, 4mm, 8mm, 12mm and 16mm respectively. Also the variation of temperature for different conditions of misalignment has been shown in Fig.4, 5 and 6. From these figures and above data for temperature rise, the inference is drawn that as misalignment in the system develops and increases the temperature of components increases. As misalignment increases the magnitude of unbalance forces and moments at bearing ends, and the frictional heat generation increases. Also, it has been observed that temperature rise for non-drive end bearing is more than that for coupling and drive end bearing.

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