Optimising Sensor Location for an Enhanced Gearbox Condition Monitoring System

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Abstract. Sensors location plays an important role in designing an effective condition monitoring system. Stability and reliability of information captured entirely depends on sensor location. The aim of this research is to investigate the relationship between sensor location and detecting the fault in a gearbox system. This paper proposes a methodology for locating indirect monitoring sensors such as acoustic emission and vibration on a gearbox system to obtain high quality information regarding the behaviour of machine conditions. Experimental work is designed to evaluate the optimum sensors’ position for detecting faults in the gearbox system. The gearbox is operated under healthy and unhealthy conditions with varying levels of effective speed and load using full factorial experimental design method. The spectral kurtosis has been implemented as a sensory feature by computing the kurtosis for a range of frequency components in a time frequency diagram. The results from this study have shown that the implemented approach is a suitable method for providing a better understanding of acoustic emission and vibration signals to improve the reliability and the capability of condition monitoring system.

Keywords: condition motioning, acoustic emission, vibration, optimising sensor location, gearbox

1. Introduction

Gearbox systems play an essential part to many machineries such as production machines and power plants and they take a key function in many industrial applications. A gearbox system normally contains many components and subassemblies such as: gears, bearings and shafts which should work together smoothly and effectively [1]. In some cases gearboxes are exposed to a variety of undesirable parameters including an improper installation, lack of lubrication and material fatigue. These parameters could lead to progressive deteriorations of the health condition of rotating machines, causing an unexpected machine down time that may lead to substantial economic losses [2]. The industrial community usually requires effective and reliable sensing tools to monitor the health condition of the machinery and to capture structural defects at their initial stage. Accelerometers and Acoustic Emission (AE) sensors have been applied in many different applications monitoring of machineries [3]. However, indirect and signals-based sensing is influenced by noise from the
surrounding environment. The negative impact of signal measurement can be substantial at the incipient stage of a fault when the intensity of the associated vibration is often overwhelmed with the background noise. For example the vibration signal of the monitored inner components are influenced by the noise of motors and shafts, which could lead to collecting unreliable data. In order to enhance the quality of sensing information, a high signal-to-noise ratio needs to be maintained. This can be attained by either selectively adjusting the sensor characteristics such as bandwidth and sensitivity; or by optimising the placement of the monitoring sensors. Taking such measures will ensure a comprehensive coverage of the signal features with a minimal structural repercussion [4].

The area of sensor positioning has been investigated over the past years. Cotae [5] and [6] proposed sensors positioning method to reduce the traces of the covariance matrix which associated with the structural parameters estimation. Tongpadungrod et al. [7] used Principal Component Analysis (PCA) to evaluate the optimum location for sensors. Papadimitriou et al. [8] proposed utilising information entropy method which is a measure of uncertainties in the model parameters for determining the optimal sensor configuration. Cyrille [9] proposed new method, called the effective independence, which orders multiple nominee sensor locations based upon their contribution using Fisher information matrix. Hongxia and Xiuye [10] proposed the optimum sensor positioning of gearbox layout using particle swarm optimization (PSO) algorithm to solve the fitness problems based on the gearbox finite element model. However, research on sensors optimal placement on gearbox is still relatively new. Al-Habaibeh [11] established a new method named Initial Optimisation Procedure (IOP) for optimising sensors position in order to enhance the condition mentoring system for cutting machine. In this paper, the IOP method will be adjusted and applied for gearbox optimum sensors positioning to improve loose bearing detection. The paper will also investigate the relationship between vibration and acoustic emission sensors sensitivity to the fault.

This paper is organised as follows; the background introduction is given in Section 1. In Section 2, the principles of vibration and acoustic emission are explored. In Section 3, sensor optimisation procedure which used to enhance the information quality received from gearbox is explained. Section 4 presents experimental setup and apparatus that are used in this research. Result discussion is given in Section 5. Conclusions are drawn in Section 6.

2. Vibration and acoustic emission characteristics
Significant research work has been documented in literature where vibrations and AE with advanced signal processing techniques are investigated to monitor and predict the health of rotating machinery. The interest for applications using AE for condition monitoring systems has grown significantly over the past decade. Even though, vibration monitoring has dominated successfully for several decades in many industrial applications. AE technology provides some attractive advantages over vibration. Firstly, AE does not have specific direction; in some cases one AE sensor is sufficient to perform the task. In contrast, vibration monitoring requires information from three sensors from three different axes. Usually, positioning of sensors is essential to obtain reliable information related to the conditions of the machine. Secondly, AE is highly sensitive and offers opportunities for identifying defects at an earlier stage when compared to other condition monitoring techniques. As AE mainly detects high frequency elastic wave, it is not affected by structural resonances and mechanical background noise with low frequencies. Resources for AE in rotating machines usually come from many different defects such as initial crack, pitting and bearing damage. These defects generate abnormal sound that propagate on the surface of material and cause a displacement of these waves which can be measured with an AE sensor [12].

3. Determining sensor location methodology
Sensors technologies have received great attention within the industrial community and they are key component in any condition monitoring system. Sensors could be categorised in two groups: fixed-position and free position or indirect sensors. Fixed-position sensors which are located in predefined
position on the machine according to the manufacturer instruction or their functionality. These sensors are usually mounted directly to mechanical component or installed close to certain place to measure the physical quantity, for example speed and torque sensors. While, free-position or indirect sensors do not have specific locations on machine and they could be installed at any location on the machine. Also, there is no specific industrial methodology to determine the optimum location and position in certain location on a gearbox system or its components.

In this study, a new application of the IOP algorithm is presented for locating free-position indirect sensors, such as vibration and acoustic emission, for gearbox system to preform high quality of information regarding the characteristic of the gearbox tool. Data sensory were captured using full factorial method with three factors which are: 3 levels for speed and torque and 2 levels of gearbox condition. Nine from eighteen experiments of loose bearing condition used to determine most suitable location for locating the vibration and acoustic emission sensors. To analyse the collected data, the proposed initial step is to obtain a representative characteristics by using suitable signal processing methods such as Fast Fourier Transform (FFT). The second step is to extract the optimum frequency value using Spectral Kurtosis (SK) method to obtain useful feature representing the nature of the fault. The final step involves clustering to determine the optimum location of sensors and understand sensors behaviour in terms of characteristic and response to fault.

3.1. **Scheme of optimum sensor location**

The IOP procedure is used to establish optimum sensors location for the condition monitoring system. As shown in Figure 1, it consists of three main steps: the first step named an Extreme Value of Parameters Test (EVPT), which is used to comprehend the behaviour of the required signals in order to identify the parameters that approximately provide the upper and lower signal level. The second step called the Sensor Positioning Optimisation (SPO), which is used to change the sensor position to an ideal place where the sensor is most sensitive to the gearbox condition to determine the best position for the sensors. The final step is called Signal Condition Adjustment (SCA), which is used to adjust the signal conditioning system gains and ranges to guarantee high amplification of the signals without reaching saturation point which would guarantee a high quality of signal. The following sections will explain the methodology in detail.

3.1.1. **The Extreme Value of Parameters Test (EVPT)**

Eighteen experiments were conducted with varying speed and load from low to high. It was found that, in order to be able to select a suitable initial positioning for the sensors and initial readings, it is important to use machine parameters that are known from practical experience to produce the maximum and minimum absolute levels of machine signals. Experiments with highest vibration are normally generated by the maximum speed, whilst minimum speed generates low vibration. Therefore, by using this experiment, with minimum value of speed, it is possible to ensure that the sensor can sense the abnormal machine condition. The
maximum values are used to make sure no saturation level is reached. In order to understand the behaviour of the monitoring signals and find the parameters which give the extreme values, i.e. maximum and minimum voltage levels, Extreme Value Parameters Test (EVPT) procedure is found helpful in adjusting the monitoring systems [11]. The procedure of Extreme Value Parameters Test (EVPT) requires a number of experiments with variety of input factors to find the parameters which give the absolute maximum and minimum values of voltage in order to adjust signal conditioning and identifying sensors location. The EVPT procedure has been found useful in this paper for the initial adjustment of the system and the sensory position.

3.1.2. Sensor position optimization. Identifying the parameters which generate the highest and lowest voltage values, it is possible to reach for a better position for the sensors using the minimum level signal. Following the placement of the sensor in the new position, a new test is implemented using the minimum level machine parameters and the place which offers the highest signal levels, and best frequency sensitivity is selected to be the optimum position for the sensors under the position optimisation process. Then, the Sensor Conditioning Adjustment (SCA) step is performed to guarantee suitable magnification of signals without saturation.

3.1.3. Sensor conditioning adjustment. Sensor conditioning is conducted individually for each group of sensors which have the same extreme value parameters. As shown in Figure 2 the procedure begins by operating the machine with the parameters that give absolute minimum level signals. The gain/range of the sensors output value is adjusted to have an absolute output voltage around 30% of the upper/lower limits. Then the loose bearing test which provides the high level signal is conducted to ensure that the absolute voltage is between 60% to 70% of its corresponding limit. If the output voltage is greater than 70% then that could be a risk of access the saturation status during some normal conditions, therefore the gain/range of the sensors have to be attuned to a suitable magnification values.

**Figure 2.** Sensor conditioning adjustment procedure.
4. Experimental setup and apparatus
A schematic diagram of the test rig is shown in Figure 3. The test rig consists of a gearbox which has two types of bevel gears and the driven gear and shaft. The axes of the gears and shaft are supported by two ball bearings. All components are immersed in an oil basin in order to ensure proper lubrication. Ac motor drives the gearbox which in turn power the generator via shafts and couplings. Input and output speed and torque signals are measured with rotary transducers attached to the motor/generator shafts. The vibration signals are recorded by three accelerometers mounted at three different locations in the gearbox case. AE sensor is mounted on the case shell of the gearbox in order to measure sound signal that emitted from gearbox components. Output signals of the sensors are sent to a data acquisition card (National Instrument USB DAQ6259) which is connected to a computer. The system under monitoring is the gearbox, which is part of the driving system used in agitators of chemical system which has been provided by Chemineer Ltd.

![Figure 3. Schematic diagram of the mechanical system.](image)

4.1. Full-factorial design of the experiments
The Design Of Experiment (DOE) method is used to examine and analyse the quality of products based on some essential design of parameters and levels during the manufacturing process. This analysis explores the influence of factors on overall system performance and the interdependency between factors and levels. The DOE method is widely applied in various industries and academic applications. The full-factorial design requires a high number experiments or calculations. But it provides high precision results on the relationships between factors without losing information. The first step for the DOE is to determine the number of factors and the levels which need to be investigated. To explore the main interaction and effects of factors and obtain the maximum power density output, this study uses the full factorial method to deal with the test matrix of two factors of three-levels and one factor of two levels. Table 1 lists the design factors and levels considered. The model includes three factors, including speed, load and gearbox condition (healthy and loose bearing condition) resulting in 18 sets of experiments.
| No. of Experiments | Levels | Gearbox Condition | Values |
|--------------------|--------|-------------------|--------|
|                    | Speed  | Load              | Speed (rpm) | Load (Nm) |
| 1                  | 1      | 1                 | 100       |
| 2                  | 2      | 1                 | 500       | 3        |
| 3                  | 3      | 1                 | 900       |
| 4                  | 1      | 2                 | 100       |
| 5                  | 2      | 2                 | 500       | 9        |
| 6                  | 3      | 2                 | 900       |
| 7                  | 1      | 3                 | 100       |
| 8                  | 2      | 3                 | 500       | 15       |
| 9                  | 3      | 3                 | 900       |
| 10                 | 1      | 1                 | 100       |
| 11                 | 2      | 1                 | 500       | 3        |
| 12                 | 3      | 1                 | 900       |
| 13                 | 1      | 2                 | 100       |
| 14                 | 2      | 2                 | 500       | 9        |
| 15                 | 3      | 2                 | 900       |
| 16                 | 1      | 3                 | 100       |
| 17                 | 2      | 3                 | 500       | 15       |
| 18                 | 3      | 3                 | 900       |

4.2. Signal processing and features selection
Sensory data captured from machines are usually affected by high level of noise and some random characteristic. Therefore, signal analysis is required to simplify and extract the meaningful information for maintenance and decision-making process. Filtering and amplifying signals are often used to minimise noise and to improve signal-to-noise ratio. Time domain and frequency domain methods, such as Fast Fourier Transform (FFT) are used to analyse the behaviour and the pattern of measured signals. In this study the FFT spectrum is applied to select optimum features of the unhealthy status of the gearbox with high precision. Condition monitoring systems considerably rely on data analysis and features selection. Feature selection can considerably improve the accuracy of results for classification model. Kurtosis is used to extract reliable information from the spectrum of healthy and faulty data, which is used as feature to be fed into classification model for fault detection. In this paper, spectral kurtosis is implemented for classification in order to determine the most suitable location of sensors.

5. Results and discussion
Optimum sensor position procedure is applied on the gearbox system with loose bearing defect to identify sensitive sensor location to the fault. Three possible sensor locations are investigated using AE and vibration sensors. Three sets of experiments are conducted, each set of experiments are based on changing speed and load as mentioned in Table 1 using full factorial method. Loose bearing condition has been investigated to identify the most suitable place for sensors with high sensitivity to the fault. Figure 4 shows three possible positions indicated as P1, P2, and P3.
Figure 4. Three positions of Acoustic emission and vibration sensors were tested.

Spectral Kurtosis (SK) features are extracted from the power spectrum to represent each experimental condition. Figure 5 shows the spectral kurtosis for vibration signals based on three acceleration sensors in three different locations (P1, P2 and P3). The x-axis represents variation of speed and torque based on full factorial method as shown in Table 1. The curves in figure 5 represent spectral kurtosis of vibration features under loose bearing conditions. Based on the spectral kurtosis of the vibration signals in positions P1, P2, and P3, it can be noticed that the curves are very close to each other particularly positions P1 and P2. Therefore, it can be concluded that SK features of the vibration signals are not influenced by changing the sensor’s position.

Figure 5. Spectral kurtosis features of vibration sensor using loose bearing data for three positions.

Data sets are captured and analysed using FFT and SK methods to select the useful information representing every position separately. Three curves in Figure 6 represent the locations in gearbox for sensor positions P1, P2 and P3 respectively. It can be observed that P2 and P3 locations are less
sensitive in comparison to location P1. It could be argued that P1 position is the most sensitive location since it gives highest amplitude reading for all combinations of speed and load.

![Figure 6](image1.png)

**Figure 6.** Spectral kurtosis features of Acoustic Emission sensor using loose bearing data for three positions.

Figure 7 shows the spectral kurtosis for acoustic emission signals. The data can be easily separated (linearly). Therefore, it can be seen clearly that the features of spectral kurtosis of AE signals are sufficient features to determine the sensitive sensor location for gearbox of unhealthy condition. This tool is used to display the data sets into three groups related to sensor locations. It provides a better understanding of these data sets in terms of the sensitive location for the sensors. Also according to EVPT procedure it can be stated that P1 position is the most suitable location for the sensor; because SK Features of acoustic emission give the highest levels compared with other locations P2 and P3.

![Figure 7](image2.png)

**Figure 7.** Clustering for optimum position of Acoustic Emission sensor.
6. Conclusion
A new application of the Initial Optimisation Procedure is investigated for the positioning of sensors and signal conditioning adjustment in gearbox system using vibration and acoustic emission sensors. The procedure is found to be experimentally useful for identifying the optimum position for monitoring the gearbox system with most appropriate signal conditioning. It has been found that the suggested procedure can indicate the most sensitive position for the sensors among the initially selected ones to ensure high quality of signals and reliable condition monitoring system.

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