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Smart condition monitoring of worm gearbox

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ABSTRACT

Worm gearboxes are commonly used in many various fields of industrial applications such as escalators, presses, conveyors etc. However, heavy industries face important problems about this type of gears due to undetected failures. The vibration signal of a gearbox carries the signature of the fault. Hence, vibration measurement and graphical representation plays an important role for analysis physical conditions of gearboxes. Although there are many options for vibration measurement systems, cost effective and portable microcontrollers based monitoring system is a good option. In this study, smart monitoring system for worm gearboxes is investigated. Data acquisition system, various vibration analysis techniques, fault diagnosis and visualization are developed via Arm Cortex M4 microcontroller. It is shown that by analyzing the vibration signal using signal processing algorithms including time synchronous average (TSA), Fast Fourier Transform (FFT) and statistical metrics; early fault detection of the worm gearbox is possible. From the experimental results, the most suitable indicator for fault diagnosis of worm gearboxes is determined.

Keywords: Worm gear, Vibration, Smart monitoring I-INCE Classification of Subjects Number(s): 71.8, 72.2.1, 74.5, 74.8, 74.9

1. INTRODUCTION

Gearboxes are a crucial part of many industrial machines and systems. They help increase or decrease torque output and velocity of machine. They also adjust the direction of rotation. Worm gearboxes are used in case of a large reduction of speed between driving and driven shafts with a proportionate increase in the torque of the driven shaft. They have the advantage of taking up little space. Other advantages of worm gearboxes include the self-locking effect, low backlash, damage tolerance as well as quiet operation. However, they have some disadvantages. They generate high friction compared to the other gear types due to their sliding action which results in heat generation and hence lower efficiency (1). This type of gear can be found in most devices from home appliances to heavy machinery. For instance, worm drives are used in presses, rolling mills, conveyors, mining industry machines, escalators and also guitars etc. However, industrial companies face important problems about this type of gears due to undetected failures.

The worm gears consist of two components called worm screw and worm wheel. The worm wheel is similar to helical gear, with the only difference being that the top of the teeth curved inward to envelope the worm screw. As a result, the worm screw slides rather than rolls. Moreover, the surface of the worm wheel is generally softer than that of the worm screw (2). That's why; the worm wheel gear can be wear during the sliding process. Furthermore, worm gearbox failures tend to occur when a gear is working under high stress conditions, lack of lubrication, contaminated lubrication, long operation at high load, higher temperature, etc. If they aren't detected at early stage, there can be dramatic consequences such as pitting, wear, tooth breakage etc. Since most of the worm gearbox faults occur on the wheel gear, simulated pits were seeded on worm wheel gear tooth surfaces.

A large amount of research has been carried out into the fault diagnosis of gearboxes, but it is a fact

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that there is seldom published research for condition assessment of worm gears due to the challenges of analysis of worm gear vibration. Unlike the other type of gearboxes where defects cause periodic impacts around the gear mesh frequencies, such distinctive symptom is not obvious for worm gearbox because of sliding interactions between worm and wheel gears (3, 4, 5). Thus, the choice of the worm gear for this study is deliberate.

In literature review, Jamaludin et al. (6) summarized the limitations in applying vibration analysis to slow rotating machines. For slow speeds, the energy generated from the machines might have not showed as an obvious change in vibration. Thus, it causes undetectable failure using conventional vibration analysis. Peng Z. et al. (7) diagnosed faults in a worm gearbox using combined the oil and vibration analysis. The focus on the study was to develop an integrated approach to fault diagnosis using both wear debris analysis of gear oil and vibration analysis. By comparing the results of two techniques, more reliable assessment of the condition of worm gearboxes made. They concluded that oil analysis is a useful method for the detection of gear wear. It was shown on their study, for increasing wear, frequency spectrum has an offset from the baseline. This interpreted an indication of wear of the gears. Acoustic emission analysis for worm gear was implemented by Elforjani et al. (8). In that work, they investigated condition of worm gearbox under different shaft speeds and load conditions using acoustic emission and root mean square (R.M.S.) value of vibration signal. Flores et al. (9) developed a predictive maintenance system using motor current signature analysis (MCSA), to diagnose mechanical faults in a worm gear reducer of building elevator system. For safer people transportation, elevator failures must be detected as soon as possible. Their experimental study results showed that this technique can contribute to an effective preventive maintenance for safety transportation with elevators. Elasha et al. (1) studied about pitting detection in worm gearboxes with vibration analysis. They specified that parallel to wheel shaft axis is most sensitive direction of vibration measurement for fault diagnosis of worm gearbox. In this study, distinctive harmonics of worm shaft and gear mesh frequencies were observed in the frequency spectrum. It was interpreted the presence of pitting damage.

Data acquisition and fault diagnosis system generally adopts PC as acquisition and processing platform. The main contribution of this paper is development of a gearbox fault diagnosis and vibration data acquisition system based on the ARM microcontroller technology. Data acquisition, signal processing, analysis, and visualization of decision are integrated in one system. In present work, analog vibration signal is acquired from the worm gearbox and converted into analog voltage signal by means of accelerometer sensor. This voltage is normally in mV, which has to be isolated and amplified before inputting to the analog to digital converter unit. The signal conditioning unit isolates and amplifies the mV signal output from accelerometer sensor. This sensor output voltage signal has both positive and negative voltages. It changes with direction of acceleration. Thus, to measure this voltage, external bipolar analog to digital converter (ADC) has to be used. The vibration signal is then converted from continuous time analog signal to discrete time digital signal by ADC for subsequent signal processing. STM32F429ZI series high performance ARM Cortex 32 bit RISC core microcontroller is used here for implementation advanced signal analysis methods, such Time Synchronous Average (TSA), statistical indexes, Fast Fourier Transformation (FFT). After the signal analysis is completed, the chosen characteristics of measured signal are compared with the reference healthy model of worm gearbox. Conclusion of fault diagnosis is displayed by TFT screen and stored in USB memory stick.

2. CONDITION MONITORING TECHNIQUES

Condition monitoring is the process of determining the condition of machinery while in operation. Vibration monitoring, temperature monitoring, lubricant analysis, acoustic emission, infrared thermography, ultrasound testing, motor current signature analysis, etc. are the main technologies for machinery condition monitoring (10). For smart monitoring of gearboxes, analysis of vibration signals is appropriate technique, because for any change in the gearbox condition, there will be most likely an effect in vibration signal. That means defects on a gear will change the amplitude and phase of the gear's vibrations signal (11).

The condition monitoring of complex systems requires crucial algorithms and intensive calculations. Therefore, most of research about monitoring was conducted by using PCs, data acquisition cards, signal condition kits and other helpful devices. Vibration signal acquisition by using PC requires expert knowledge, manual operation and complex and expensive data transmission equipments. In traditional data acquisition systems, the data measured from acquisition card are generally send into the computer, and specific software analyzes the data. But, over the past few years there has been major technological developments related to digital system. Therefore, for effective and continuous monitoring, smart monitoring technologies start to be used. These technologies have some advantages such as portability, easy to relocate, reduction in system size, quick start up, wireless communication, on-line monitoring, simplicity, etc. Comparison of different systems for condition monitoring can be seen in Table 1.

Table 1 – Comparison of vibration monitoring devices

Features	Smart monitoring	Standard monitoring
Cost	Low < 100$	High > 500$
Hardware	One embedded system	More electronic devices
Software	Complex algorithms difficult to apply	More easy
Advantage	Portable	More applicable

In smart condition monitoring systems for vibration analysis, researchers benefit from high speed microcontrollers. But, this type of solution requires adapting complex signal processing algorithms to the limited computing resources of microcontroller. For this purpose, up to date, they have used DSP, microcontrollers, embedded systems, FPGA, etc. Zhang et al. (12) studied in condition monitoring of CNC milling machine tool subject. Their aims were to enhance the quality, productivity of machined products and reduce the machining cost by detecting tool failures. For this purpose, they used signal conditioning circuit, microcontroller board and PC. The tool vibration signals came from three axes accelerometers were amplified by signal conditioning unit, and then was measured by data acquisition board. This data was sent from board to PC because of decision making and visualization of conclusion. Betta et al. (13) designed a DSP based measurement system for vibration analysis on rotating machines. In their study, vibration signals were acquired on line and processed to monitor condition of the machine status via two parallel DSP. Both time domain and frequency domain methods were used to analyze vibration signals. Their study also includes pattern matching diagnostic procedure, which detects failures by comparing healthy and faulty rotating machine.

3. STRUCTURE OF THE PROPOSED DATA ACQUISITION SYSTEM

3.1 Hardware system development

Smart condition monitoring system in this experimental research includes acceleration sensor, amplifiers, speed measurement module, analog digital converter, data acquisition, signal processing unit, visualization and storage device. The hardware parts of this vibration monitoring system are represented in Figure 1.

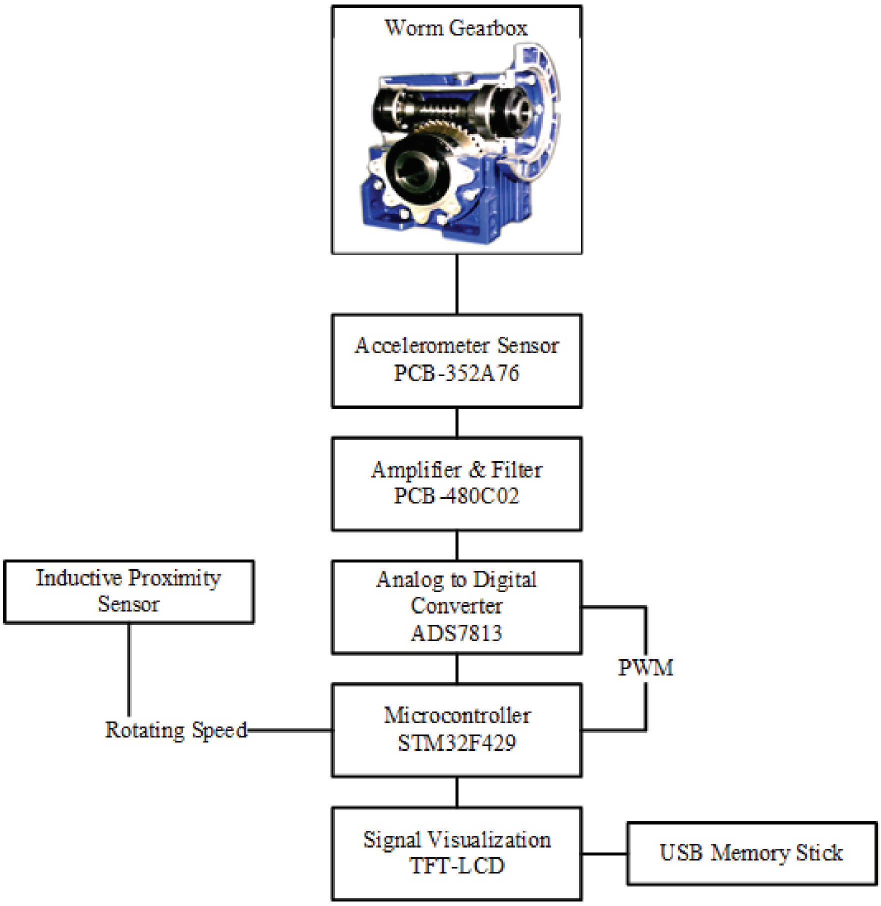

Figure 1 – The hardware parts of vibration monitoring system

Effective vibration analysis first begins with acquiring an accurate signal from vibration sensors such as accelerometer. According to requirement, suitable sensors are chosen to acquire vibration signal. Piezoelectric or MEMS acceleration sensors are used in order to measure vibration. These sensors convert vibrations into analog voltage signals. Vibration signals were picked up in intersection area of worm and wheel gear through x axis by means of accelerometer sensor. Placement of acceleration sensor on worm gearbox is shown in Figure 2. Sensor output voltage, sensitivity, bias level and frequency bandwidth have to be specified according to system necessity. In this study, PCB Piezotronics brand 352A76 series accelerometer sensor whose sensitivity is 9.77 $mV/m/s^2$ and frequency bandwidth range 5-10000 Hz is preferred.

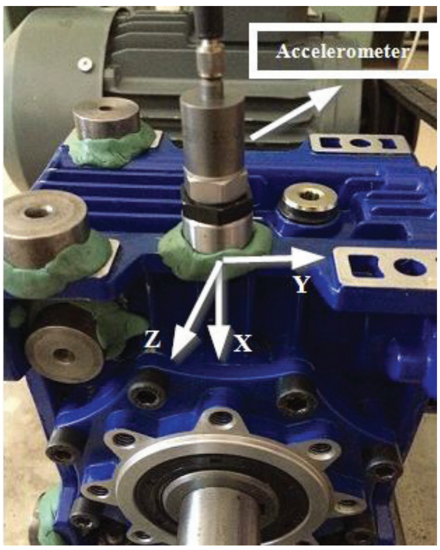

Figure 2 – Placement of acceleration sensor on worm gearbox

Electronic components (capacitors, resistors, amplifiers) were built to amplify sensor output voltages and filter noise in order to capture the real vibration signal. These products provide conditioning of vibration sensor signals for transmission to data acquisition system. Charge converters and amplifiers convert high impedance signals to low impedance voltage signals. Signal conditioners can have AC or DC coupling and provide additional conditioning including gain, filtering and integration. For this purpose, PCB Piezotronics brand 480C02 series signal conditioner is chosen. This model with its 27 volts supply will allow the positive side of the signal to go to +14 volts. The negative side of the signal is capable of -8 volts.

Since there are many kinds of working conditions in different speed situations, the fault model of worm gear is also different. According to rotating speed, distinctive frequencies of gear can change. In order to realize the fault diagnosis of different conditions, it is necessary that the rotation speed of gear should be known. The velocity of worm gear shaft was measured by an inductive proximity sensor. This sensor is a non-contact device capable of high-resolution measurement of change in the position of worm wheel shaft.

In order to manipulate the data using a microprocessor, analog signals have to converted into discrete digital numbers. For this purpose; Texas Instruments brand ADS7813 series featuring SAR, low power, 16 bit resolution, 40 kHz maximum sampling frequency, SPI communication, ±10V input range bipolar analog digital converter was chosen. Although microcontrollers have analog to digital converter unit, an external ADC is necessary because microcontroller internal ADC operates only in range from 0 to 5 input volts.

Microcontroller based data acquisition device was selected as analysis, diagnosis and visualization hub. STM32F429 Discovery board with STM32F429ZIT6 high performance ARM Cortex M4 core microcontroller featuring 2 Mbytes of Flash Memory, 256 Kbytes of RAM, 32 bit, frequency up to 180 MHz is chosen for digital signal processing. Microcontroller is suitable for DSP instructions. Discovery board has also 2.4´ TFT LCD on board which is useful for graphical user interface and visualization of gear condition. USB memory stick was also used in order to store collected data and diagnostic results.

3.2 Software system development

The software implemented in this work can be divided into two main categories, data acquisition and signal processing.

3.2.1 Data Acquisition

Digitization is necessary for transferring of the signal to the microcontroller. The data acquisition was done with an external ADC which accepts analog signals as input. According to Nyquist sampling theorem, sampling frequency was taken as 2000 Hz since the significant frequency components of vibration waveform are below 1000 Hz. Analog to digital signal conversion starts with every falling edge on the ADS7813 conversion input. ADC conversion trigger signal was generated by the Pulse Width Modulation (PWM) output of microcontroller every 0.5 ms. After each conversion finished, reading conversion result was done with SPI communication between ADC7813 and STM32F4 microcontroller board.

3.2.2 Signal Processing

In the early stages of failures, low amplitude vibration signal will be masked by other sources. However, detection of these faults is critical at this stage. As a result, more effective signal processing methods such as time domain analysis, frequency domain analysis and time-frequency domain analysis are required in order to get more reliable gearbox condition monitoring. Suitable algorithms for microcontroller implemented in this study, are illustrated in Figure 3.

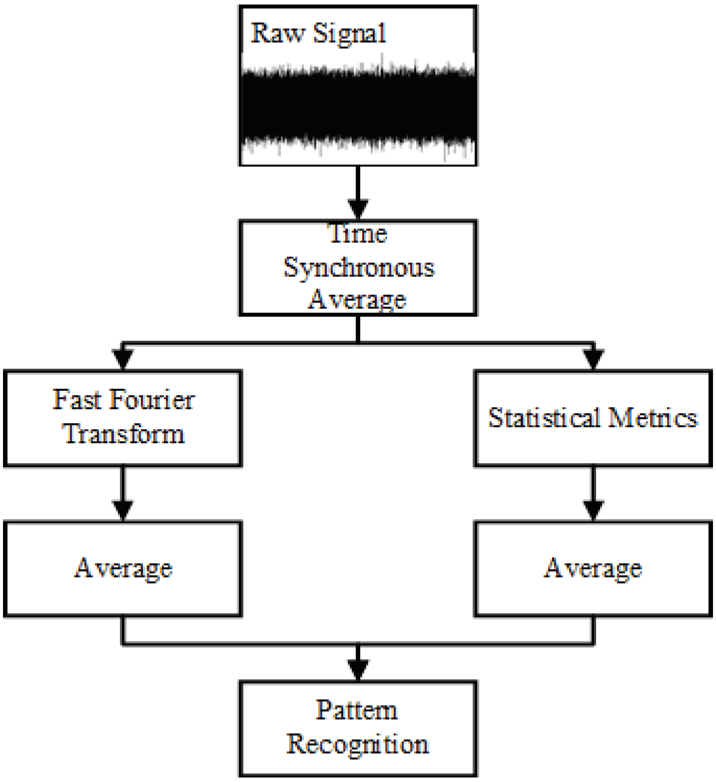

Figure 3 – Signal processing flow chart

Time synchronous average (TSA) is the method used in order to eliminate effects of signal components that are not synchronous with the shaft rotation. TSA allows the removal of noise from a vibration signal. The TSA method was well suited for worm gearbox analysis. The signal coming from accelerometers is averaged in time, employing periodicity with wheel shaft rotating speed; thus significantly improving the signal to noise ratio (14). Acquired averaged waveform is one shaft cycle in duration. The noise will be reduced by a factor of $1/\sqrt{n}$, where n is the number of averages. A simplified block diagram of TSA is shown in Figure 4.

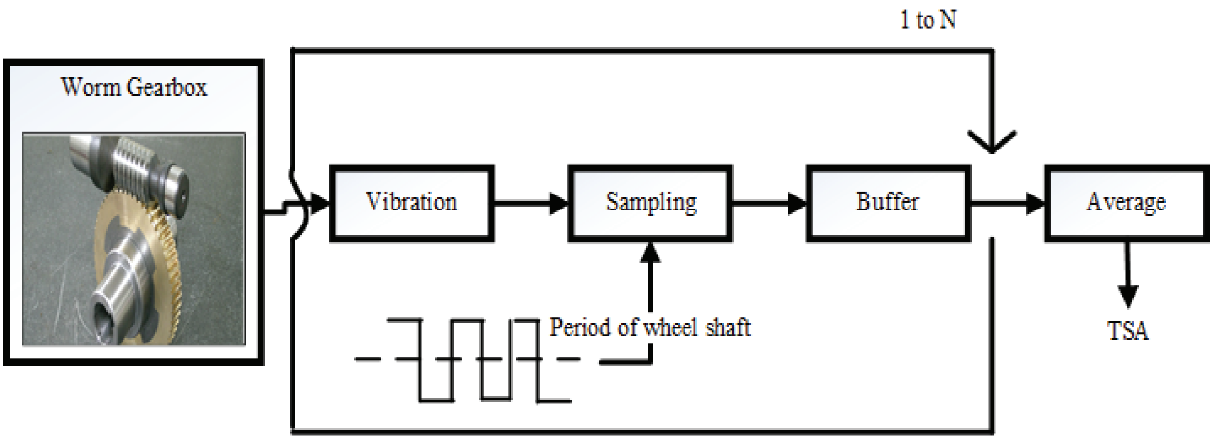

Figure 4 – A simplified block diagram of TSA

Time domain analysis of vibration signals is one of the simplest fault detection approaches. It can give qualitative information about the machine condition. Time-domain analysis uses the amplitude and temporal information from gear vibration time signal in order to detect faults. An example of vibration signal measured with data acquisition system visualized in time domain on TFT screen is shown in Figure 5(a). Use of the time waveform enables detection of changes in the vibration signal caused by faults, but it is difficult to diagnose the source of faults by using time domain analysis. Analysis of the time-domain signal uses statistical parameters, as seen in Table 2.

Table 2 – Statistical metrics

Methods	Formula	Description
Arithmetic mean	$= \dfrac{\sum_{i=1}^{N} x_i}{N}$	measures central value of signal.
Root mean square	$= \sqrt{\dfrac{1}{N}\sum_{i=1}^{N} x_i^2}$	measures the magnitude of signal.
Skewness	$= \dfrac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^3}{\left[\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}\right]^3}$	measures the asymmetry of the signal about its mean value.
Kurtosis	$= \dfrac{N\sum_{i=1}^{N}(x_i - \bar{x})^4}{\left[\sum_{i=1}^{N}(x_i - \bar{x})^2\right]^2}$	measures the smoothness and heaviness of tail in signal.

Spectral analysis of the vibration signal in the frequency-domain is the most common method used for detection and diagnosis of gear failure. In this technique, time domain vibration signal is transformed into the frequency domain by using FFT algorithm. In frequency domain of vibration data, the most important frequencies are the tooth meshing frequency, their harmonics and sidebands. For worm gearboxes, the behavior of worm shaft frequency and their harmonics can be strong predictor of the presence of faults (1). An example of vibration signal measured with data acquisition system visualized in frequency domain on TFT screen is shown in Figure 5(b).

It is very important to know that the distinctive frequencies related to rotating components in gear transmission systems will vary according to the rotational speed of gear. Therefore, before the implementation of FFT, rotating speed of worm wheel gear was measured. Moreover, random noise influence can cause some peak on FFT. To minimize faults of FFT, it is common to look at several sections of the time waveform, calculate several FFT and display averaged result.

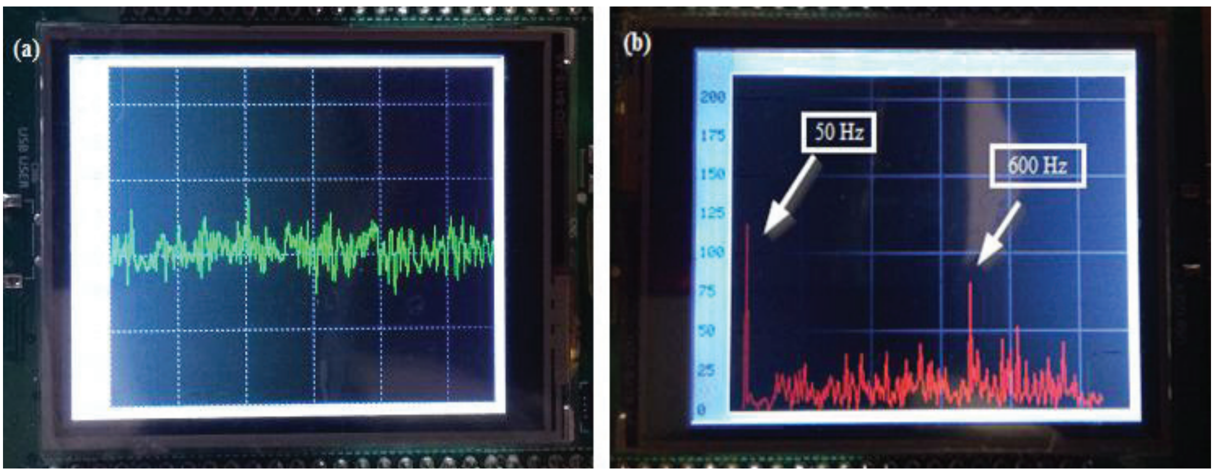

Figure 5 – Vibration signal in (a) Time and (b) frequency domain on TFT screen

4. EXPERIMENTAL SETUP

The experimental system consists of an AC motor (2.2 kW, 3012 rpm, 3 faze), a worm gearbox and an electromagnetic brake (max 65 Nm). Worm gearbox's gear ratio is 1:15. Worm gear used in the reducer is made by 8620 case hardening steel (21NiCrMo2) and hardened to the value of 58-60HRC. Wheel gear is a mono-block body made of CuSn12 bronze alloy. Experimental test rig and operation conditions can be shown in Figure 6.

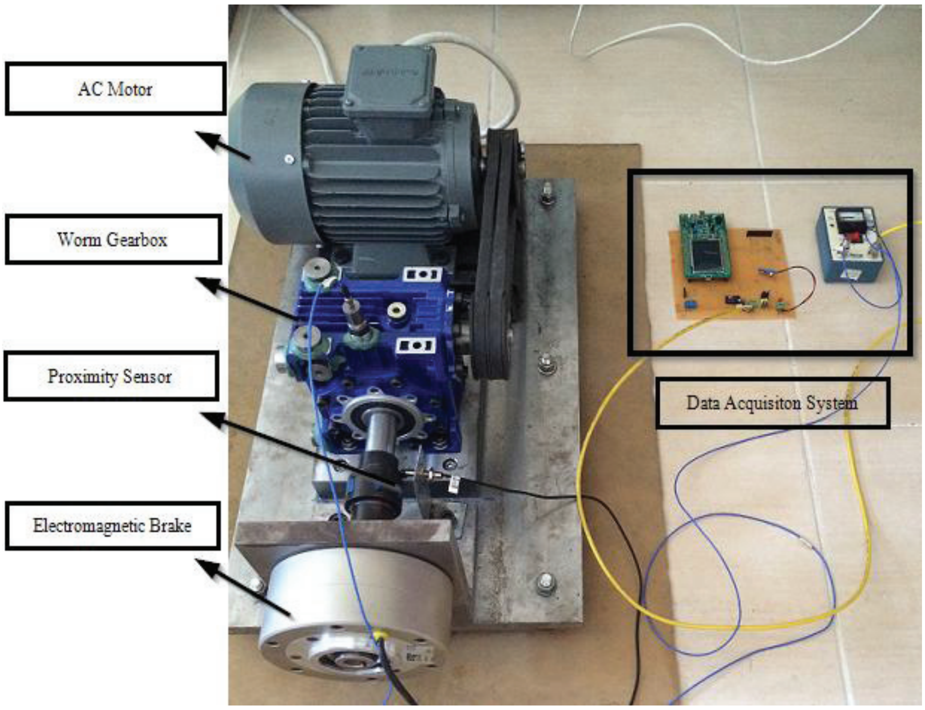

Figure 6 – Experimental test rig

5. FAULT DETECTION

In the experiment, specified gear load was applied to worm gearbox by the electromagnetic brake. During an overloading condition, some teeth on a gear may be subjected to a higher load than the capacity of the gear. In such cases, a pitting fault may occur in time on the wheel tooth surface. Healthy form of wheel gear of the worm gearbox is shown in Figure 7(a). In order to simulate the deterioration due to the excessive load condition, seven artificial surface pits were introduced on three of the wheel gear teeth, as shown in Figure 7(b). The number of simulated pits was increased on the neighboring tooth surfaces in order to represent development of the pitting fault, as illustrated in Figure 7(c). The diameter and depth of pits are approximately 2mm and 1mm, respectively.

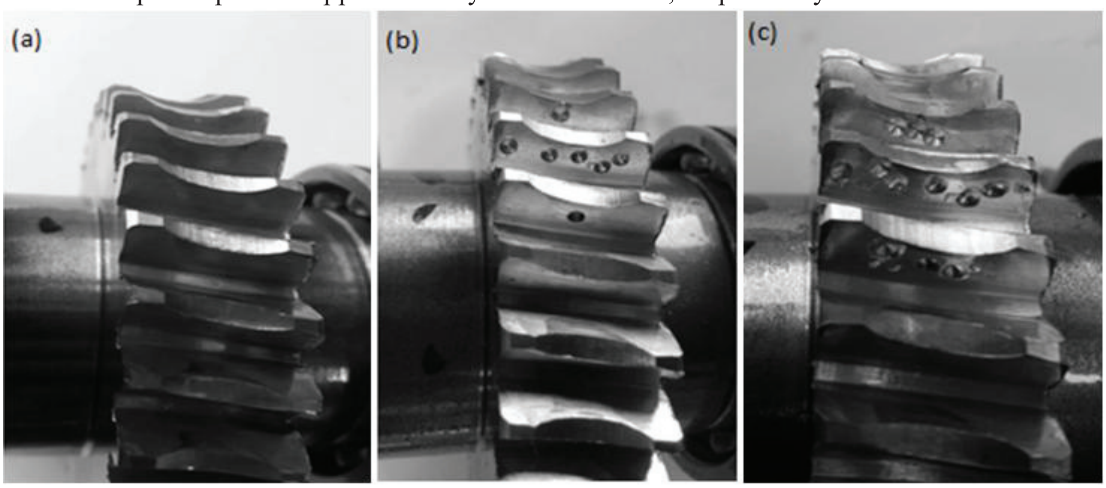

Figure 7 – Pitting stages used in the experiments; (a) No Fault, (b) Faulty 1, (c) Faulty 2

For the experiment, worm gear input shaft angular velocity was set at 3000 rpm (50 Hz). The vibration data was captured for 30 seconds with 2 KHz sampling frequency. The results of statistical metrics are shown in Figure 9. Although mean, kurtosis and skewness results are meaningless, effects of increasing the number of pits can be seen in RMS results. It is observed that the RMS value increases as the number of pits increases.

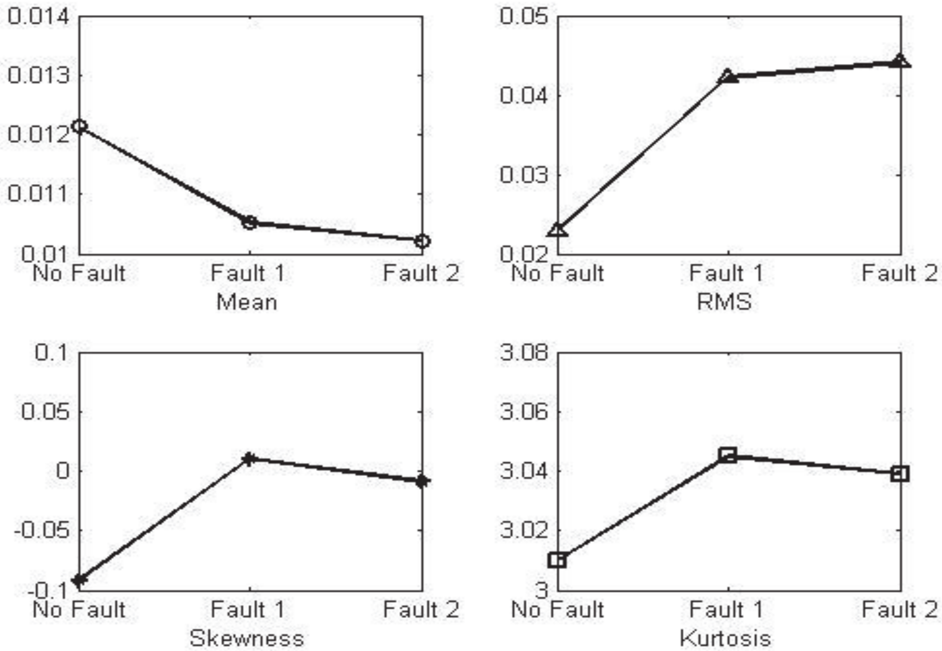

Figure 9 – The results of statistical metrics

The results of frequency domain analysis are shown in Figure 10. The worm shaft frequency and its harmonics can be seen in Fault1 and Fault 2 cases. Such phenomenon is known to be associated with gear pitting (15). Elasha et al. also reported similar results in their study (1).

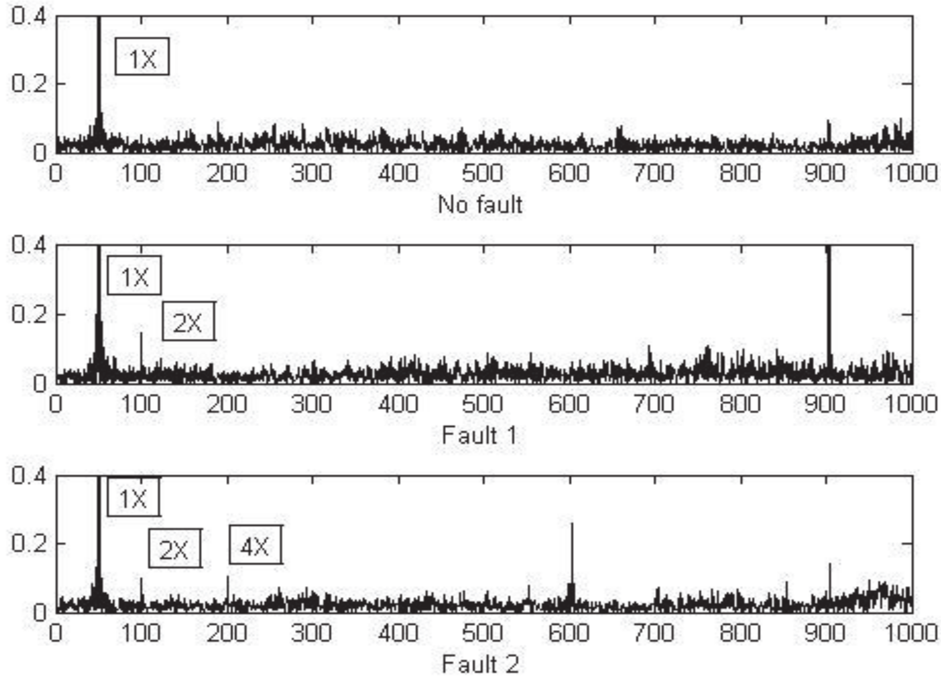

Figure 10 – Frequency domain for three conditions

In addition, the frequency component at 900 Hz is related to the one of the fundamental frequencies of the test rig, which was found from impact response. It is seen that, the amplitude of frequency response at this frequency increases due to existence of pitting failure, as shown in Figure 10.

6. CONCLUSION

In this study, embedded system based architecture for vibration analysis is described. Smart monitoring systems, on-line fault diagnosis hardware architecture, signal conditioning, data acquisition and signal processing algorithms were explained. The experiments were conducted under increasing number of simulated pits. According to our results, RMS value of vibration signal and worm shaft frequency harmonics are indicators of wheel gear pitting faults of worm gearbox. Smart condition monitoring system has proved that the developed system can accurately realize the worm gearbox fault diagnosis, without using PC-based analysis and processing procedures.

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