RESEARCH INTO RELIABLE, INTELLIGENT AND COST EFFECTIVE USE OF ACCELEROMETERS FOR THE CONDITION MONITORING OF ROTATING MACHINES

Rmdan Shnibha
Harouge Oil Operations- Libya
Ghanant Al_Arif
24 December Street
Telephone: (218) 911700535
rshnibh@yahoo.com

Abstract: This paper presents fundamental work being carried out on designing and building an intelligent monitoring system based on vibration measurements

The vibration sensor, e.g. the accelerometer, is the main element in the condition monitoring system and all the signal processing and decision-making depend upon its performance. Unfortunately, the high cost of accelerometers limits their usage, especially, when simple electronic circuitry interfacing is essential and the bulky and costly additional charge amplifiers are unsuitable, particularly in smart and wireless vibration measurement systems.

MEMS-based accelerometers offer an alternative solution owing to their low cost and small size. However, MEMS accelerometers are delicate and cannot stand harsh industrial environments, although no thorough investigation into their performance within such an environment has been carried out.

In this paper, three newly-developed MEMS accelerometers, from different manufacturers, were packaged in-house and their performances were examined and compared with a well-known piezoelectric accelerometer.

A 1.1 kW three phase induction motor test rig was purposely designed and built for this research to undertake vibration measurements and condition monitoring testing. MEMS accelerometers performance testing was carried out under different motor speeds and load conditions. Two types of common faults were also introduced, namely, phase imbalance, an electrical fault, and misalignment for the mechanical type of fault.

It was concluded that the performance of one of the MEMS accelerometers was improved by the packaging strategy; reasonable and comparable results were achieved.

Keywords: intelligent, condition monitoring, MEMS, induction motor

Introduction:

Condition monitoring and condition-based maintenance aim at increasing machine availability, performance, reducing consequential damage, increasing machine life, reducing spare parts inventories and reducing break-down maintenance.
A general condition system is depicted in figure 1. The key part of this model is sensing through the use of sensors that measure key attributes of machine, information-processing (monitoring, collection, and displaying) through the use of an embedded computer. The signal condition takes the transducer signal and modifies it to a desired magnitude; decision –making and action-taking are done by humans.
With an intelligent condition monitoring system, pre-warnings can identify the nature of the problem and inform maintenance personnel. A controlled or planned shutdown of the process reduces further potential problems and damage, resulting in reduced production loss and repair cost while time needed to repair and restart the process is reduced.

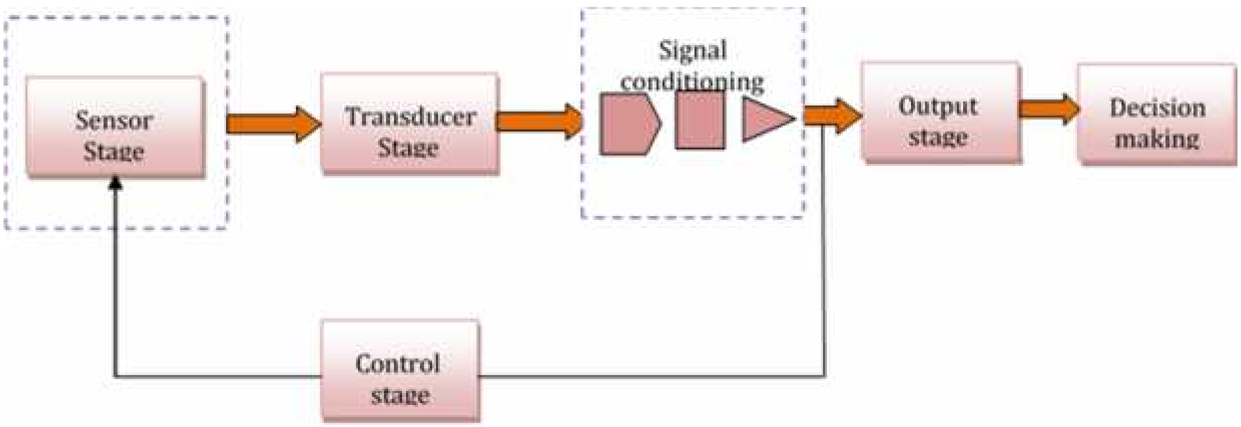

Figure 1 General condition monitoring.

As shown in figure 1 the precision selection and location of sensors is very important and the decision analysis depends upon their performances.
Typically, a smart sensor contains physical transducers, a network interface, a processor and memory core that can all be fabricated on a single die. The physical transducers can be made very small because silicon micromachining technology used to make integrated circuits is now being used to create micro-electro-mechanical systems (MEMS) that can become an integral part of a smart sensor. Thus, MEMS technologies and smart sensors are now acknowledged as a major focus of the current sensor development.
Vibration measurement is at the heart of the monitoring of rotating machines. Vibration monitoring is non-invasive but uses a number of specialised sensors, broad bandwidth and complex analysis. The precise selection and location of sensors is very important and the decision analysis depends on their performance.
Unfortunately, the high cost of the vibration sensor (e.g. the accelerometer) limits their usage, especially, when simple electronic circuitry interfacing is essential and the bulky and costly additional charge amplifiers are unsuitable. Consequently, smart and wireless

vibration measurement systems combined with specialist software and a (well paid) engineer analysing the data are required.

However, microelectromechanical system MEMS-based accelerometers offer an alternative solution owing to their low cost and small size, mobility and flexibility. They can be integrated with smart sensors to enable signal processing and self- diagnosis capabilities.

This has led to a new area of research within the field, allowing cheap sensor devices to be created which will enable the industry to move towards condition-based maintenance rather than periodic or breakdown based maintenance. This will reduce maintenance costs and avoid accidental shut-downs of critical plants. According to Maruthi et al [1], vibration analysis using a MEMS accelerometer is less expensive compared to conventional sensors (US $ 250 to US $ 25).

However, at present, the use of the MEMS accelerometers for machine condition monitoring is still limited to the testing stage in the laboratory experiments; Sabin [2] has used the MEMS accelerometer together with a conventional accelerometer for measuring the vibration of a pump during its normal operation. He found that the frequency content from both sensors was in good agreement. However, no rigorous investigation has been conducted to compare the performance of these MEMS accelerometers which are used to detect induction motor faults. Albarbar et al [3] performed a study which proved that MEMS accelerometers are of sufficient quality to be utilized for machinery health and condition monitoring purposes. He carried out a test performance of a MEMS accelerometer for different excitations and compared it with a piezoelectric accelerometer. He found that the MEMS accelerometer had good agreement with the piezoelectric accelerometer in his experiment [4]. Colin et al [5] performed a study which showed that an array of low cost MEMS transducers can determine results comparable with those obtained using high performance transducers by testing a composite vertical stabilizer (tail plane).

Induction motors are among the most important electromechanical systems, which are widely used in almost every industry. Induction motor faults such as winding faults, unbalanced stators and rotors, broken rotor bars, eccentricity and bearing faults have been studied. Several studies have shown that 30%-40% of induction motor failures are due to stator winding breakdown. Slow fluctuations in the supply voltage or even imbalance between the phases can cause operational problems such as overheating which leads to winding insulation over-stress. As a rule of thumb, for every 3.5% voltage unbalance per phase, the winding temperature increases by 25% in the phase with the highest current. Transient voltage conditions result in reduced winding life [6]. Shaft misalignment is a prevalent fault associated with rotating machines, and it occurs when the shaft of the driven machine and the shaft of the driver machine do not rotate on a common axis. Shaft misalignment is a measure of how far apart the two centrelines are from each other.

In this study, three newly developed MEMS accelerometers, from different manufacturers, were packaged in house and their performances were examined and compared with a well-known piezoelectric accelerometer. Two test rigs were conducted for sensors performance: the first was a shaker test, and the second one was the actual experiment.

This paper is organized as follows. In the second section MEMS accelerometers are presented. The proposed signal processing technique is introduced in section 3. Section 4 describes the test rig, the instrumentations and data collection. A discussion of the results and conclusions are presented in Sections 5 and 6 respectively.

2. MEMS Accelerometer

The EMS accelerometers, which include both the signal conditioning circuitry and the sensor, are fabricated together on a single monolithic chip. The output signals are analogue voltage that are proportional to acceleration. It uses sensing change in capacitance as shown in figure 2. The deflection of the internal mass changes the capacitance between the finger and the adjacent cantilever beams. The sensor has an electronic device which will convert the capacitance change due to acceleration into a voltage.

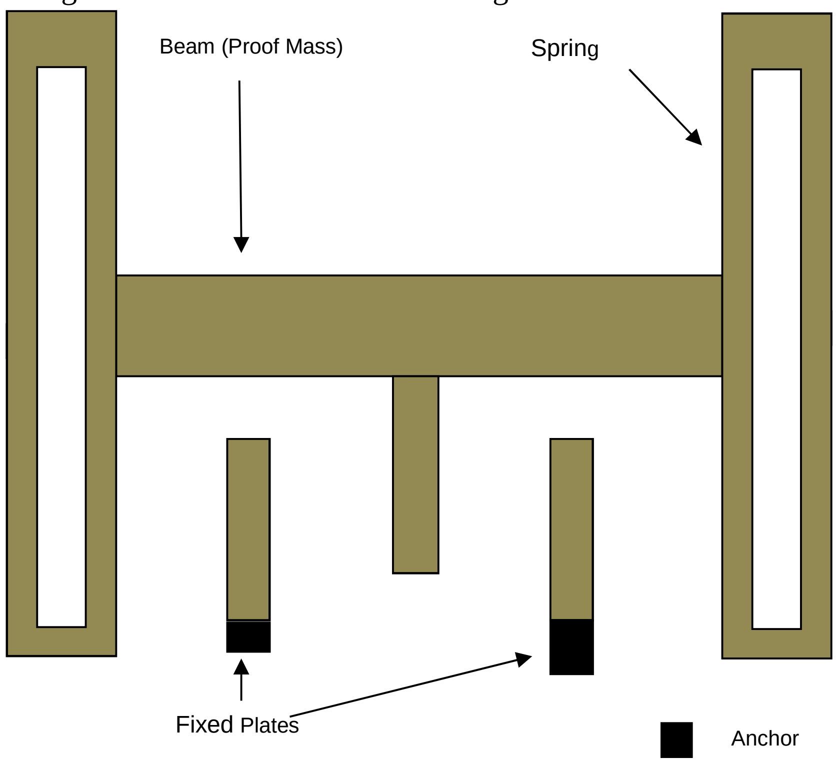

Figure 2 Capacitive MEMS accelerometer

The choice of accelerometers depends on several factors and some of them are listed below:
Static characteristics of sensors

- Input range : interval between the maximum and minimum of input
- Output range : interval between the maximum and minimum of output
- Span : the interval of output range of a measurement system Span= Omax -omin
- Zero: the system output corresponding to a zero input.
- Resolution: is the smallest detectable incremental change of input that can be detected in output signal.
- Sensitivity: is the rate of change in output corresponding to the rate of change in input.
- Repeatability: inability of a sensor to represent the same value under identical conditions.

- Deadband: range of input in which the output remains at zero.
- Hysteresis: the delay phenomenon in output due to energy dissipation.

Dynamic characteristics of sensors

A measure of a sensor's capability of the following rapid change in input:

- Delay (response time)
- Rise time
- Overshoot
- Settling time

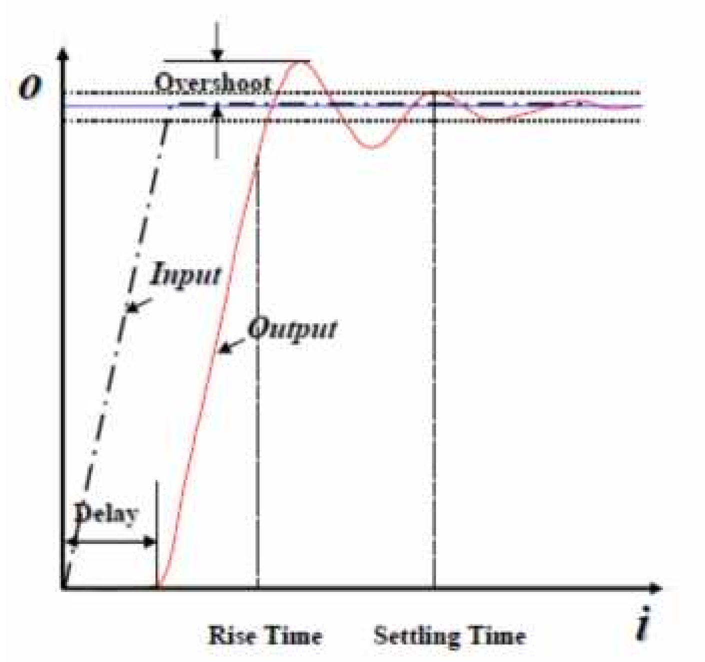

Figure 3 dynamic characteristics of sensor

There are more factors to consider when choosing the sensor such as cost, size, weight, linearity, and environment (temperature, shock, vibration, etc.).

3.1 Induction motor (Experimental) test rig.

The schematic diagram for the test rig and instrumentations is shown in Figure 4. It comprises a 1.1kW variable speed induction motor, a DC Generator and a resistor bank to act as a load and to dissipate the electrical energy. The instrumentation consists of a conventional accelerometer and three MEMS accelerometers. Conventional accelerometer sensitivity is 100mV/g. The output of the piezoelectric accelerometer is filtered and amplified via a charge amplifier. The technical specifications of the piezoelectric accelerometer and the MEMS accelerometers are briefly listed in Table 1. The model numbers and the manufacturers' names of the MEMS accelerometers used in the experiments were deliberately not mentioned, as the intention was to share experiences among several engineers and researchers involved in the area of vibration sensing and condition monitoring. The MEMS accelerometers were packaged to make them more robust for industrial use. The accelerometers' power supplies were stabilized to 5 volts using a solid state voltage regulator to prevent the power supply from affecting the sensitivity. The measured data were then transferred to the computer using 24-bit resolution data acquisition. The sampling frequency was set to 50k Hz.

The developed LabVIEW based system allows the user to monitor and store machine variables, and subsequently a MatLab code was used for further signal processing.

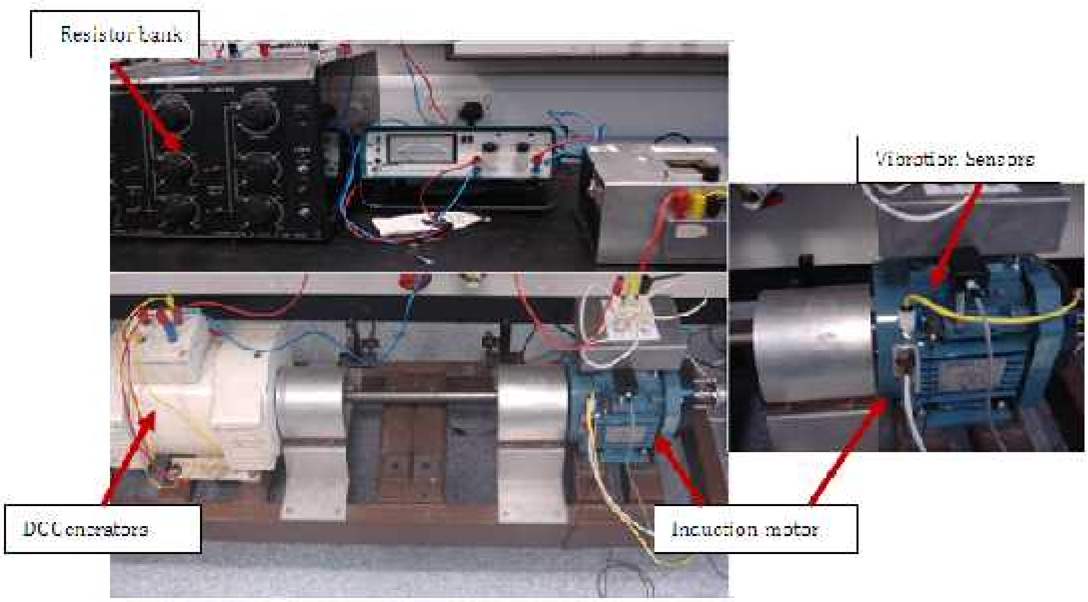

Figure 4 Schematic diagram of induction motor test rig

Table 1 Technical specifications of accelerometers.

	Piezoelectric	MEMS 1	MEMS 2	MEMS 3
Price £	315	15	32	22
Mass	27 g	<1.0 grams	<1.0 grams	<1.0 grams
Sensitivity	100mv/g for Vs=5V	250 mV/g for Vs=5 V	250 mV/g for Vs=5 V	120 mV/g for Vs=5 V
Resolution	3mg	2mg	2mg	2 mg
Frequency response 3dB	2kHz	10 kHz	32 kHz	18 kHz
Temperature range	-40C to 200C	-40 C to + 85 C	-40 C to + 125 C	-55C to 125C

3.2. Shaker Test of MEMS sensors

The test rig was built as shown in figure 5 to test the performance of the MEMS accelerometers. The test rig contains a shaker, function generator, amplifier, data acquisition and computer. A number of test experiments conducted when the shaker was excited by sine wave at different frequencies and with different amplitude levels and responses were simultaneously measured from all accelerometers.

The time domain and frequency domain of measured signals are shown in figures 7 to 10, where the exciting frequency was set at 55 Hz and 95 Hz and at different amplitudes, 0.2 & 0.7 g.

It can be clearly shown that all the responses of the MEMS 2 are in good agreement with the Piezoelectric accelerometer.

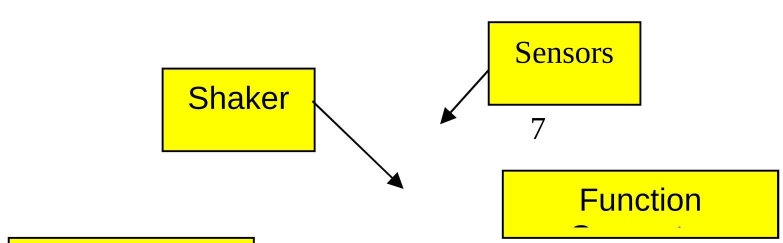

Figure 5 test rig for performance mems sensor

3.3 Packaged unit

The MEMS accelerometers were packaged as shown in figure 6 in the laboratory to assess whether MEMS accelerometers can stand harsh industrial environments are easy to use, easy to connect to machines, easy to power and can be easily protected. The package unit is cheaper compared with using a conventional sensor.

Figure 6 Packaged unit of MEMs sensors

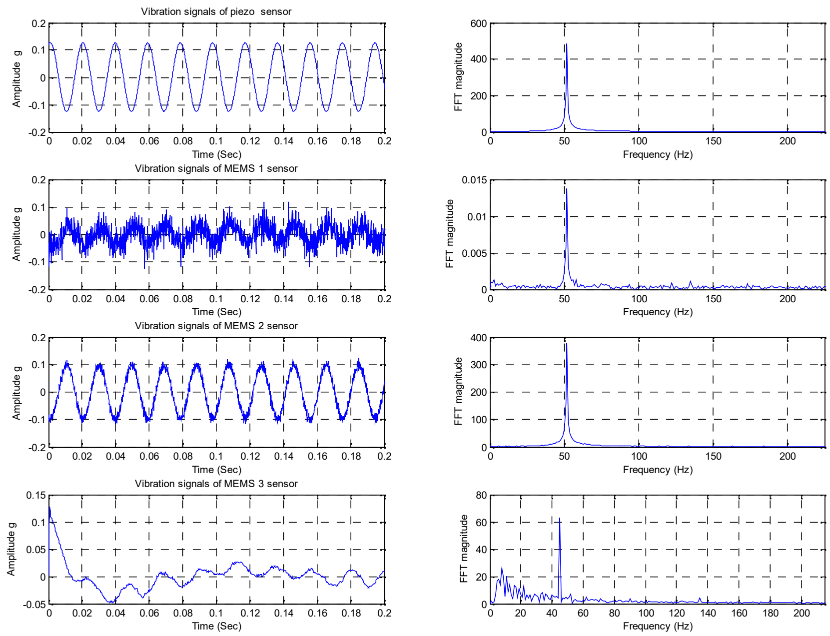

Figure 7 Measured acceleration responses by the MEMS accelerometers and the piezoelectric accelerometer at 55Hz for the excitation amplitude 0.2g

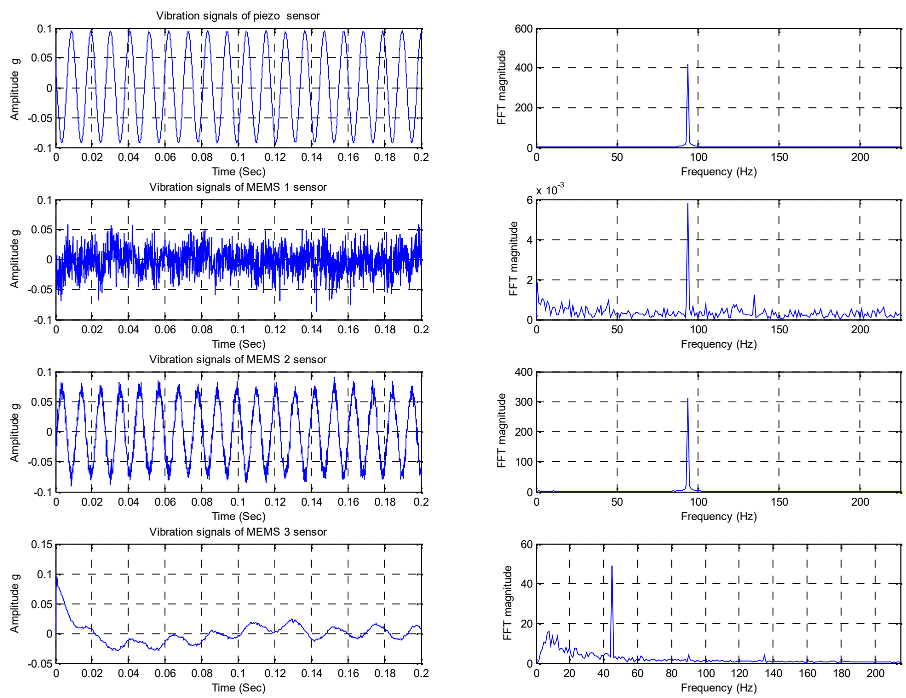

Figure 8 Measured acceleration responses by the MEMS accelerometers and the piezoelectric accelerometer at 95Hz for the excitation amplitude 0.2g

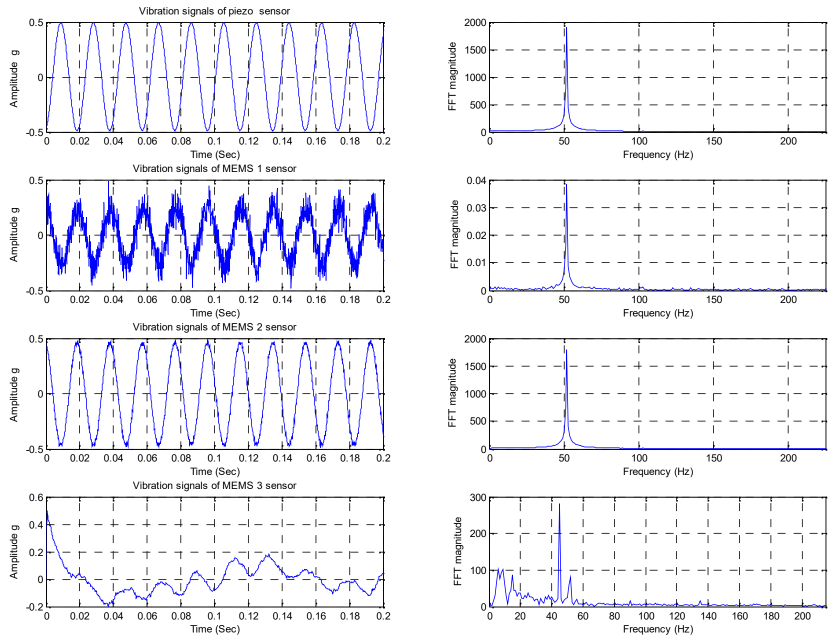

Figure 9 Measured acceleration responses by the MEMS accelerometers and the piezoelectric accelerometer at 55Hz for the excitation amplitude 0.7g

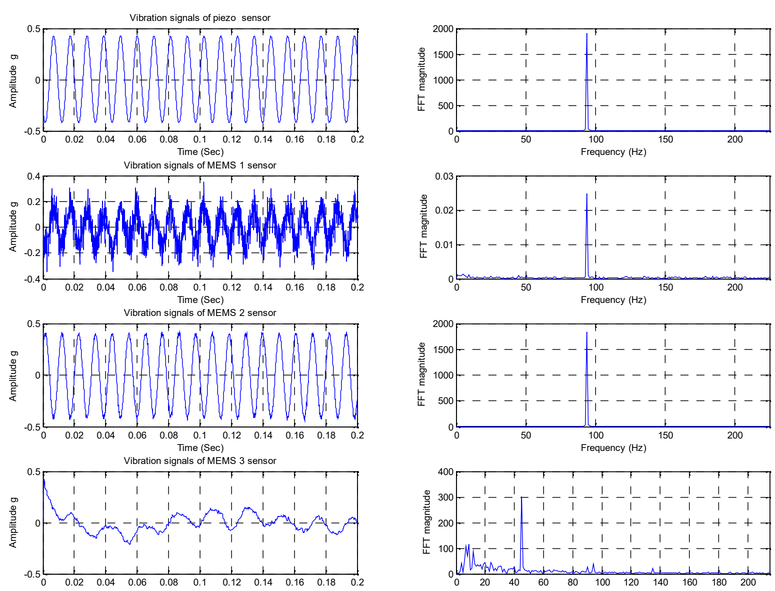

Figure 10 Measured acceleration responses by the MEMS accelerometers and the piezoelectric accelerometer at 95Hz for the excitation amplitude 0.7g

4. Experimental Result

The motor was tested at 1500 rpm and 100% load in a healthy condition and then under four different phase imbalance voltages of 5, 10, 15, 20 and 25 V; these represented 2%, 4%, 6%, 8% and 10% respectively, of the main nominal voltage level. And mechanical faults (1mm and 2mm misalignment)

A number of statistical methods were applied to the measured vibration signal (see Figures 11 and 12). The applied statistical signal processing includes RMS, STD and Kurtosis. No sufficient and reliable condition-related information can be observed. Further information about statistical signal processing including RMS, STD and Kurtosis can be found in various papers [7].

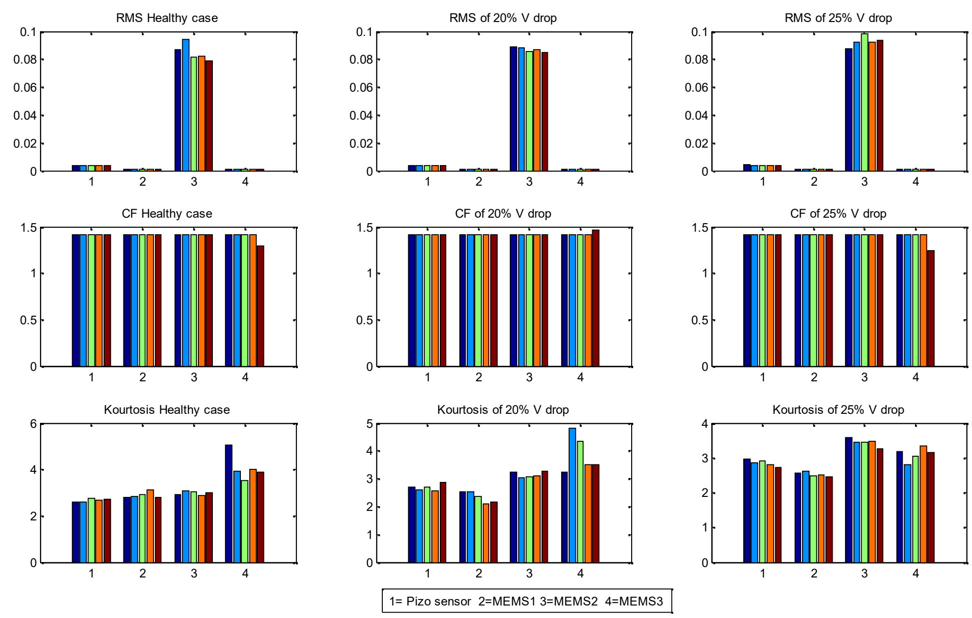

Figure 11 Time domain parameters: the motor at full load is equipped with various conditions (healthy, 20% & 25% V drop at 1500 rpm speed)

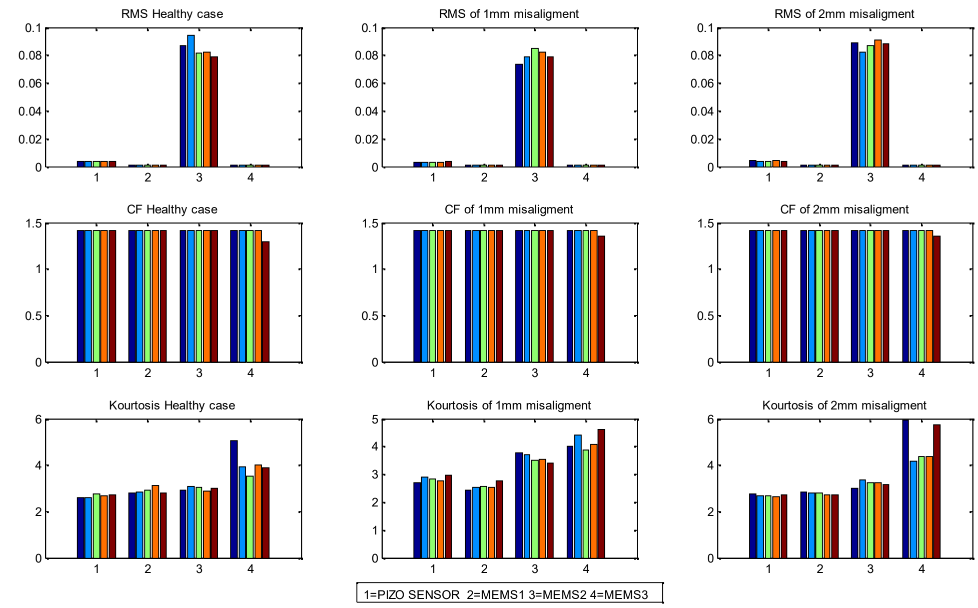

Figure 12 Time domain parameters. The motor at full load is equipped with various conditions (healthy, 1mm & 2mm misalignment at 1500 rpm speed)

The measured signals were transformed into the frequency domain, where the frequencies of their main components were identified. In Figure 13 (vibration) the first frequency component is at 25 Hz, rotor rotation speed; the second is at 50 Hz, due to the power supply or the second harmonic of rotor running speed; the third is at 100Hz, which could be the second harmonic of power supply frequency or fourth harmonic of the rotor frequency. There was a slight increase in the amplitudes of these components.

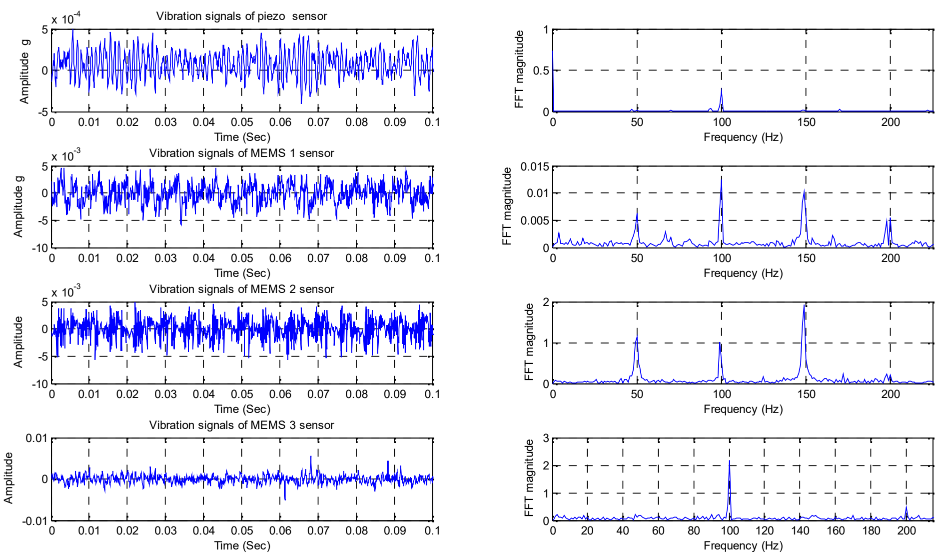

Figure 13 Time and Power spectra of the signal of the piezoelectric accelerometer and MEMS accelerometer. The motor is at full load and 1500 rpm speed

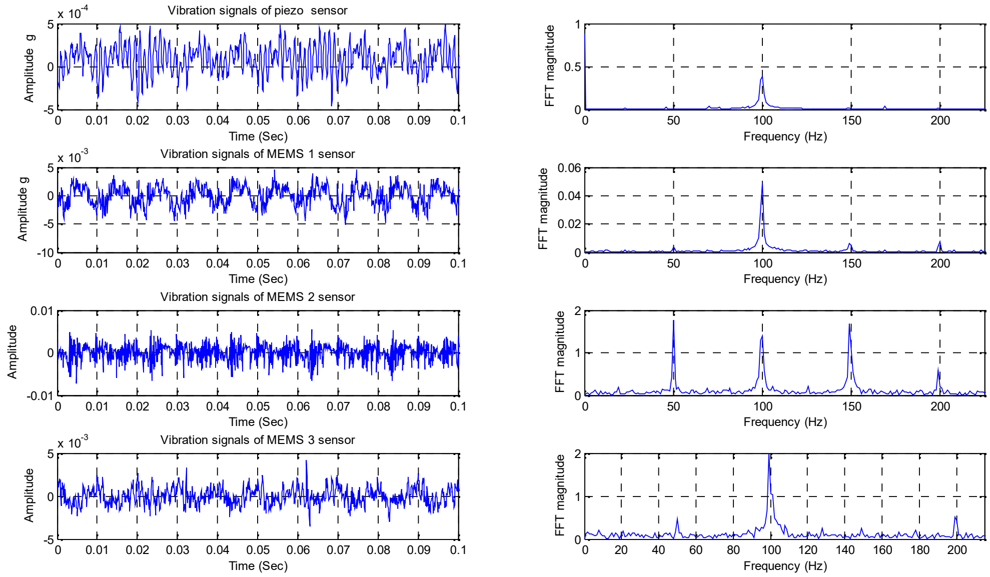

Figure 14 Time and Power spectra of the signal of the piezoelectric accelerometer and MEMS accelerometers. The motor at full load is equipped with 20% voltage drop at 1500 rpm speed.

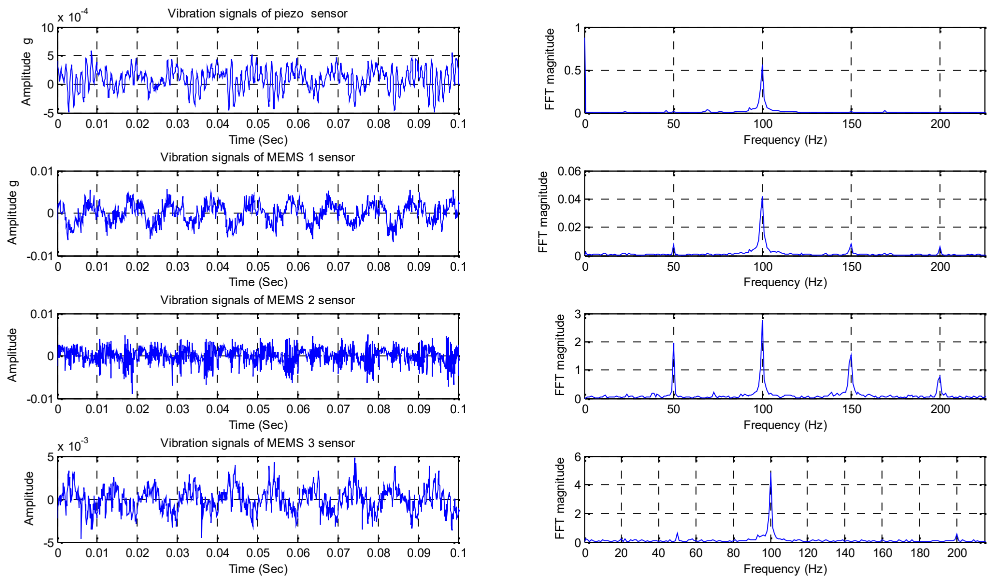

Figure 15 Time and Power spectra of the signal of the piezoelectric accelerometer and MEMS accelerometers. The motor at full load is equipped with 25% voltage drop at 1500 rpm speed.

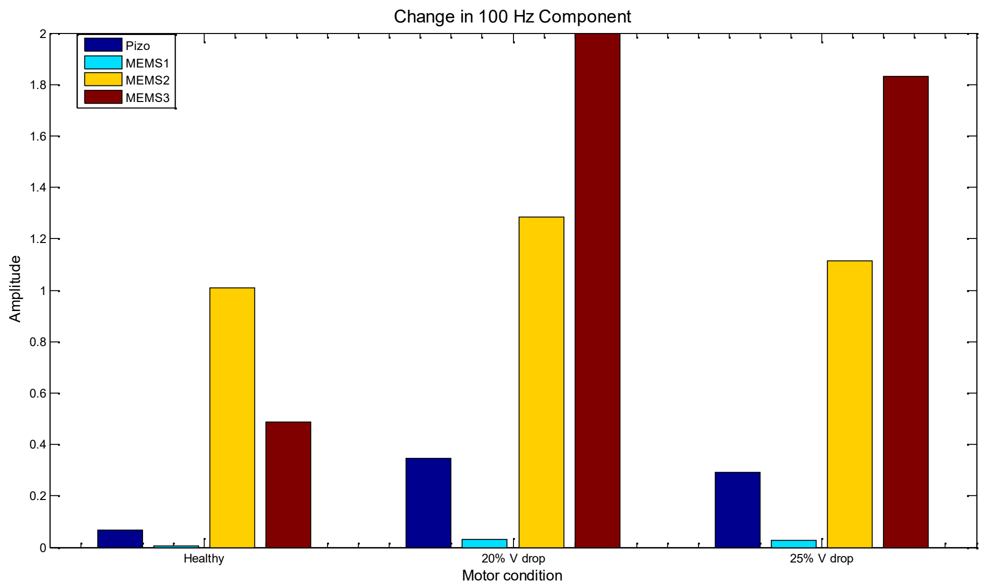

Figure 16 Changes in 100Hz components from healthy and 20% & 25% voltage drop. The motor is at full load and 1500 rpm speed.

A comprehensive comparison of the ability of each sensor, in detecting a phase imbalance fault and assessing its severity based on the change in the amplitude of the 100Hz component is shown in figure 16 (for both 20% and 25% voltage imbalance). The plots show that the MEMS2 sensor is more capable of detecting the faults.

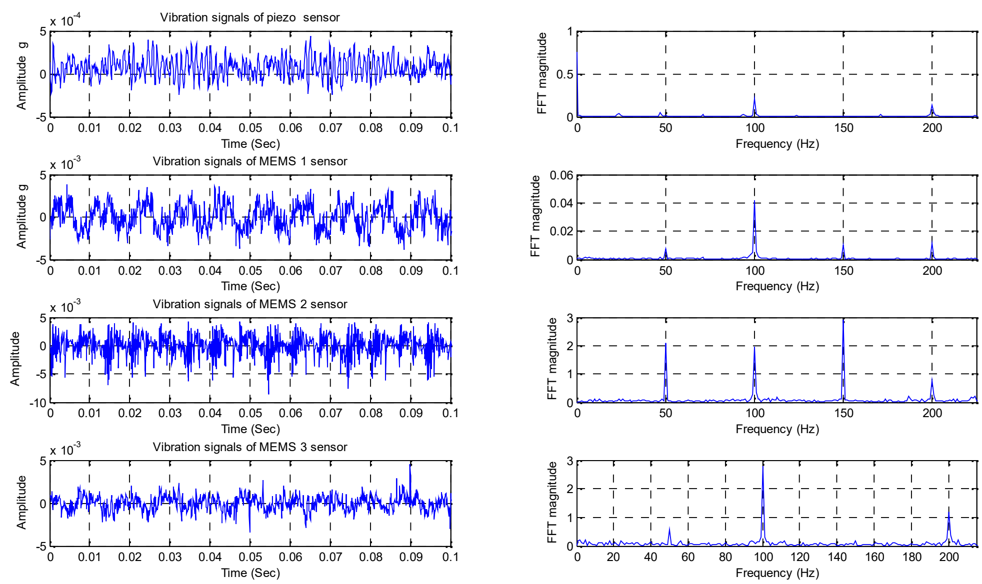

Figure 17 Time and Power spectra of the signal of the piezoelectric accelerometer and MEMS accelerometers. The motor at full load is equipped with 1mm misalignment at 1500 rpm speed.

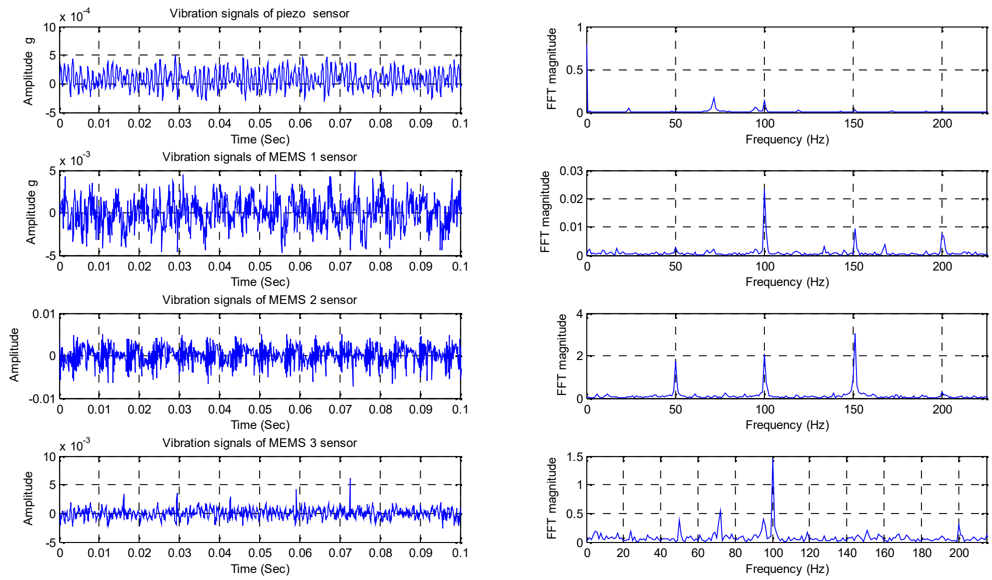

Figure 18 Time and Power spectra of the signal of the piezoelectric accelerometer and MEMS accelerometers. The motor at full load is equipped with 2mm misalignment at 1500 rpm speed.

Figure 17 and 18 show the spectra of vibration from the piezoelectric sensor and 3 different MEMS sensors for healthy operation, with 1mm misalignment and 2mm misalignment. In line with the theory, the 1st, 2nd and 3rd harmonics of rotational speed in vibration change in amplitude between healthy operation and faulty conditions. These changes are shown in figure 19.

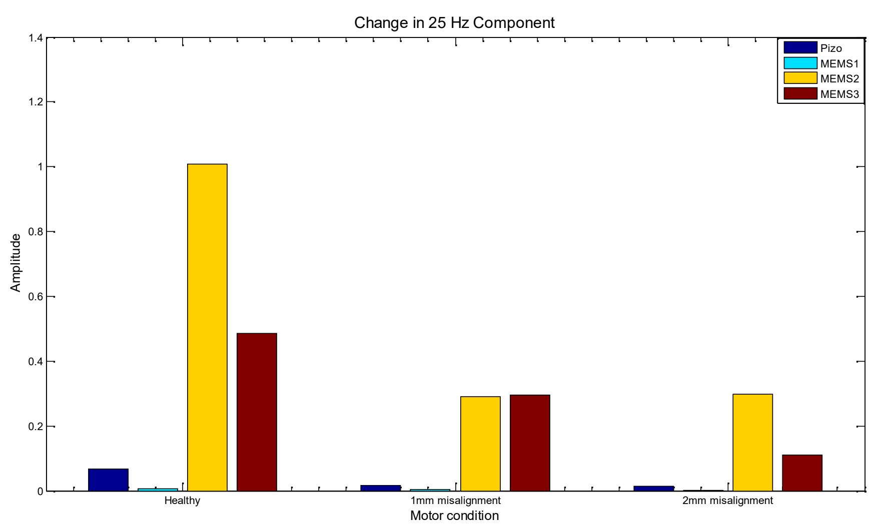

Figure 19 Change in 100Hz components from healthy and 20% & 25% voltage drop at 100. The motor is at full load and at 1500 rpm speed

A comprehensive comparison of the ability of each sensor to detect a misalignment fault and assess its severity based on the change in the amplitude of the 25Hz component (rotational speed) is shown in figure 19 (for both 1mm and 2mm misalignment). The plots show that the MEMS2 sensor is more capable of detecting the faults.

The presence of the frequency peaks is consistent in MEMS 1 and 2 responses with the reference accelerometer; however, the peaks amplitudes are not exactly the same. For MEMS 3 the frequency components and their amplitudes are not the same.

A satisfactory performance is achieved by the MEMS (2) accelerometer as expected and this was comparable and in good agreement with the conventional accelerometer. The first frequency component is at 25 Hz, rotor rotation speed. The second is at 50 Hz, due to the power supply or the second harmonic of rotor running speed. The third was at 100Hz, which could be the second harmonic of power supply frequency or fourth harmonic of the rotor as measured by both accelerometers. Line frequency and its multiples also exist in the frequency domain spectrum.

5. Conclusion and future work

The fabrication, packaging and testing of a vibration monitoring using MEMS accelerometers are presented in this study. Preliminary tests proved that the developed measurement device is capable of measuring machine vibrations for machine condition monitoring while the sensor has several advantages in terms of its compact size, low cost and high sensitivity. The results obtained from MEMS sensors are in close agreement with the conventional sensor results.

Future work will be related to building up the intelligent monitoring system in terms of developing an on-board low-power method of performance analysis and fault diagnosis using MEMS sensors, developing a low-power wireless communication system based on MEMS technology and designing, building and testing a working prototype which is programmable and has the ability to perform on- board fault detection and diagnosis and act accordingly.

References:

[1] Maruthi G.; Vittal K. Electrical fault detection in three phase squirrel cage induction motor by vibration analysis using MEMS accelerometer. IEEE pesd 2005.

[2] Sabin, E. Vibration of dry pumps. Semicond. Int. 1995, 18(8), 249-250.

[3] Albarbar,A; Samir M.; Andrew S. and Robert P.; “Suitability of MEMS Accelerometers for Condition Monitoring: An experimental study”. Sensors 2008, 8, 784-799.

[3] Albarbar,A; Samir M.; Andrew S. and Robert P.; “Suitability of MEMS Accelerometers for Condition Monitoring: An experimental study”. Sensors 2008, 8, 784-799.

[4] Badri A. , Sinha J. K. ,Albarbar A. ; “A Method to Calibrate the Measured Responses by MEMS Accelerometers”; International Journal for experimental mechanics

[5] Coiln R.; Drik H.;Roger C.; Carl K.; “Investigation into the use of low cost MEMS accelerometer for vibration based damage detection” . composite structure 82(2008) 61-70

[6] Siddique,G A.. Yadavan S., Singh. B., 2005, " A review of stator fault monitoring techniques of induction motors", IEEE Transactions on Energy Conversion, Vol. 20, No. 4, pp. 106-113.

[7] Shnibha R. , Albarbar A., Ibrahim G.R., Badri A. . "Three Phase Induction Motors Phase Imbalance Severity Evaluation Based on Acoustics Measurements and Energy Calculations." The 5th Libyan Arab International Conference on Electrical and Electronic Engineering LAICEEE 23-26/10/2010

Bibliography:

[1] First...

[2] Second...