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Performance evaluation of wireless MEMS accelerometer for reciprocating compressor condition monitoring

Z. Mones[1], G. Feng[1], U.E Ogbulaor[1], T. Wang[2], F. Gu [1,2], A.D. Ball[1]
[1]University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK

[2]School of Mechanical Engineering, Taiyuan University of Technology, Shanxi, China, 030024

ABSTRACT: With recent development in wireless communication and Micro Electro Mechanical Systems (MEMS) technology, it becomes easier to monitor rotating machinery conditions by mounting compact wireless MEMS accelerometers directly on the rotor. This has the potential to provide more accurate dynamic characteristics of the rotating machine and hence achieving high monitoring performance. In this paper, a tiny MEMS accelerometer together with a battery powered microcontroller is mounted on the flywheel to acquire the on-rotor accelerations of a two-stage reciprocating compressor. The measured acceleration data is streamed to a host computer wirelessly via Bluetooth Low Energy (BLE) module. The true tangential acceleration is reconstructed by combining two orthogonal outputs of the sensor, which contain gravitational accelerations. To evaluate the performance of the wireless sensor, three different fault conditions including intercooler leakage, second stage discharge valve leakage and asymmetric stator winding of the motor driver are simulated individually on the compressor test rig. To confirm the wireless sensor performance, an incremental optical encoder was installed on the compressor flywheel to acquire the Instantaneous Angular Speed (IAS) signal for comparison with signals from the wireless sensor. The experimental results show that the running status of the compressor can be remotely monitored, allowing different leakages and motor faults to be diagnosed based on the tangential acceleration reconstructed from a wireless on-rotor MEMS accelerometer.

1 INTRODUCTION

Instantaneous Angular Speed (IAS) is a widely used technique for monitoring the dynamic condition of rotating machinery. Many studies have evaluated the condition of rotating machines using IAS measurement based on shaft encoder. In (Renaudin2010), a magnetic encoder was used to measure the IAS of an automotive gearbox in different operating conditions. The results proved that different faults, like pitting in bearing, causing small angular speed fluctuations are measurable with magnetic encoders, meaning abnormal conditions can be detected. Roy et al investigated the behavior of IAS signal for different gearboxes under various speed and load conditions. They concluded that by applying time synchronous averaging (TSA) to IAS signal, faults can be simply detected (Roy 2014). Many other researches have employed an optical encoder to obtain IAS, however, the cost and installation difficulties are issues that make it important to find an alternative to measure IAS. With recent development in wireless transmission techniques and Micro Electro Mechanical Systems (MEMS) technology, it becomes feasible to measure the on-rotor accelerations of rotating machines at low cost for condition monitoring. As the accelerometer is directly mounted on a rotor, it has the potential to capture dynamic characteristics of the rotating part with high accuracy (Arebi 2011 & Feng 2016) making wireless MEMS accelerometers a good alternative to expensive optical encoders. Recently, on-rotor MEMS accelerometer based condition monitoring has attracted a lot of attention. (Albarbar 2008) studied the usage of MEMS accelerometers in condition monitoring and investigated the performance of three different MEMS accelerometers. From their investigation, it is concluded that MEMS sensors could be used instead of standard sensors especially for wireless implementation. (Arebi 2010) developed a wireless MEMS accelerometer that was attached directly on a rotating shaft and the results demonstrated that different degrees of misalignments can be successfully monitored using MEMS accelerometer. Furthermore, (Arebi 2011) studied and compared response from data collected via a MEMS accelerometer and shaft encoder under different degrees of shaft misalignment. Findings from their study showed that the wireless MEMS accelerometer outperforms the shaft encoder in detecting small shaft misalignment. The authors previously mounted a three-axial MEMS data logger on the flywheel of a reciprocating compressor to record the on-rotor accelerations. By combining the acceleration from two axes, the gravitational acceleration was effectively removed and the tangential acceleration was reconstructed with good accuracy (Feng 2016). The focus of this study is to improve on the data collection method by bringing in the wireless data transmission technique which enables online condition monitoring. Furthermore, the reconstructed tangential acceleration signal is compared with the IAS signal from an optical encoder.

2 THEORETICAL BACKGROUND

2.1 IAS measurement based on a shaft encoder

The IAS measurement is widely used in the area of fault diagnosis, condition monitoring and control of rotating machines. By studying the IAS variations, a large amount of information about the health status of the machine can be obtained (Nurmi 2013). Many different methods have been developed for angular speed measurement. Each successive method has attempted to improve measurement performance using a different strategy to process encoder signals based on two basic principles: counting the number of pulses in a given time duration and measuring the elapsed time for a single cycle of encoder signal (Nurmi 2013). In general, average angular speed may be defined as:

$$\omega = \frac{\Delta\theta}{\Delta t} \tag{1}$$

where $\Delta\theta$ is the angular displacement and Δt is the time taken to complete the displacement. A typical and precise way of measuring IAS is installing an optical encoder on one end of the rotor. The encoder working principle is presented in Figure 1 (a). It uses a slotted wheel with a single LED and photo detector pair to generate pulses as the wheel turns and the speed of an object can be calculated by measuring the pulse duration Δt_i (i.e. elapsed time or time span for a pulse i) between successive pulses (Nurmi 2013).

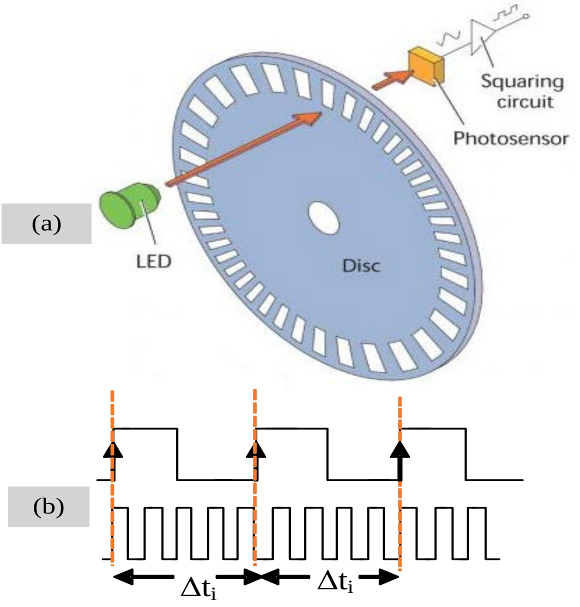

Figure 1 (a) Encoder principle and (b) operations of measuring elapsed time.

Assuming that, M is encoder pulses in one revolution, the duration of the clock cycle is t_s and the number of clock cycles in a speed pulse is N_c, then the IAS in rad/sec can be calculated as:

$$IAS = \frac{2\pi}{\Delta t_i M} \tag{2}$$

where Δt_i is the time interval of the given speed pulse and it is equal to $N_c t_s$. Considering the change in angular variation $\Delta\theta = 2\pi/M$, equation (2) in RPM can be written as (Gubran 2014):

$$IAS = \frac{60\Delta\theta}{2\pi\Delta t_i} \tag{3}$$

Traditional encoders have been used for a long time in industries to monitor a machines performance and for fault detection. However, these sensors are usually expensive, their installation is difficult and not suitable for isolated environment. Therefore, many researches have tried to use MEMS sensors, which are low-cost, small in size and easy to install as an alternative for encoders (Nurmi 2013).

2.2 IAS Measurement based on an on-rotor MEMS Accelerometer

MEMS is a process technology that produces tiny integrated devices which combine mechanical and electrical components. They are fabricated using integrated circuit (IC) batch processing techniques and can be made with a different size from a few micrometers to millimeters. These systems are capable of performing several signal processing tasks in areas including mechanical, electrical, optical, fluidic and other types of signals (Arebi 2011). The measured signal using 3-axis on-rotor MEMS accelerometers contains the required rotor dynamic information as well as gravitational acceleration, which can be successfully removed by combining the phase shifted normal and tangential direction outputs of the MEMS accelerometer. Using property that the gravitational acceleration on X axes (g_x) and Y axes (g_y) have a phase difference of $\pi/2$ for all frequency components, a method was suggested in (Feng 2016) to cancel the gravitational acceleration projection on the Y-axis, i.e. g_y, therefore allowing the tangential acceleration of interest to be reconstructed. The reconstruction steps can be summarized as follows:

1) Remove the high frequency noise by applying a low-pass filter to both $\tilde{a}_x$ and $\tilde{a}_y$.
2) Use a Hilbert transform to add a phase shift of $\pi/2$ to the filtered signal $\tilde{a}_x$.
3) The phase shifted signal is added to the filtered signal $\tilde{a}_y$ resulting in a signal that excludes the gravitational components and only includes the tangential acceleration components:

$$a_{tx} = \sum_{n=1}^{\infty} (n+2) r\, \omega_O A_n \cos(n\, \omega_O t + \varphi_n) \tag{4}$$

4) Scale the amplitude of nth harmonic component to be $n/(n+2)$ in a_{tx} in the frequency domain and get the true tangential acceleration a_t. Consequently,

$$a_t = \sum_{n=1}^{\infty} nr\, \omega_O A_n \cos(n\, \omega_O t + \varphi_n) \tag{5}$$

Then, the IAS can be computed by finding the integration of tangential acceleration signal a_t:

$$IAS = \frac{60}{2\pi r} \int a_t \, dt \tag{6}$$

where r is the distance of accelerometer to the wheel center.

3 WIRELESS TRANSASSION

According to signal range, wireless network standards can be divided into four categories which are wireless wide area network (WWAN), wireless metropolitan area network (WMAN), wireless local area network (WLAN) and wireless personal area network (WPAN) (Feng 2013). Networking standards usually address the physical layer and the lower part of the data link layer, which is also known as the medium access controller (MAC) sub layer. The physical layer addresses modulation, frequency use and transmission, whereas the MAC layer mentions to access points and maintains the order of signal flow to avoid signal collision and cancellation (Townsend 2014). The most popular wireless communication protocols include Wi-Fi, ZigBee, Bluetooth and Bluetooth Low Energy (BLE), which operate on Industrial, Scientific and Medical (ISM) bands (Lin 2007 & Sidhu 2007). These standards have their own advantages and can satisfy specific application requirements. In recent years, BLE has gained wide application in smart phones, tablets and wearable devices due to its inherent features like low power consumption, low cost and good community support (Dementyev 2013 & Kun 2013).

In this work, the sensor node is mounted directly on the rotor, making it not convenient to change battery. Thus, low power consumption becomes the main concern for designing the sensor node. On this basis, BLE is employed for wireless data transmission mainly because of its low power consumption feature and good development support. In the future, wireless charging techniques will be employed to improve the life-span of the sensor node, making such on-rotor condition monitoring more practical.

4. EXPERIMENTAL SETUP

4.1 Test rig setup

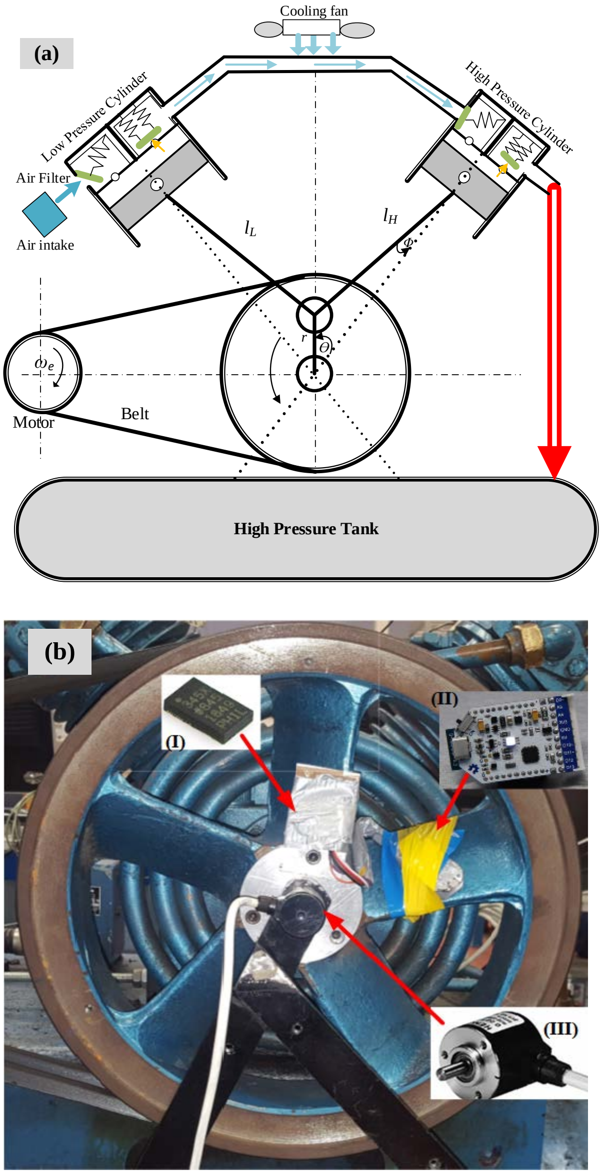

Figure 2 (a) schematic of a two-stage reciprocating compressor and (b) installation of (I) MEMS accelerometer, (II) microcontroller board and (III) optical encoder.

To confirm the performance of the wireless accelerometer sensor, a compression experimental study with incremental encoder was performed on a two-stage, single acting Broom Wade (Model TS9) reciprocating compressor. Figure 2 (a) presents a diagram of a two-stage reciprocating compressor, which mainly consists of three parts; an electric motor, a compression unit and a high pressure tank to store the compressed air. The compression part is composed of two cylinders, two pistons, two connecting rods, a crankshaft, four self-acting valves and an intercooler. The compressor is driven by a three phase 2.5 kW induction motor KX-C184, whose power is transferred to the flywheel through a pulley belt system with a transmission ratio of 3.2:1. The rated speed of the motor is 1420 rpm (revolutions per minute), thus the rated speed of the flywheel is about 440 rpm. As shown in Figure 3 (b), an incremental shaft encoder RI32 is installed on the end of the flywheel to measure the IAS. The encoder provides two outputs: 100 electrical pulse trains per revolution and one pulse per revolution known as index signal. Besides, a MEMS accelerometer, ADXL345, is attached directly to the flywheel to measure the on-rotor acceleration. This sensor is a low-power, 3-axis MEMS accelerometer module with both I2C and SPI interfaces. A detailed description of the ADXL345 sensor is listed in Table 1.

Table 1 Specification of ADXL345

Accelerometer sample rate	10-3200Hz configurable
Accelerometer range	±2/4/8/16g configurable
Accelerometer resolution	10-13 bit (3.9mg/LSB)
Dimensions	3 x 5 x 1 (mm)
Weight	30mg

As shown in Figure 3, the data from ADXL345 is read by a low power microcontroller (MCU) and then forwarded to a BLE module. The power is provided by a 270 mAh lithium battery.

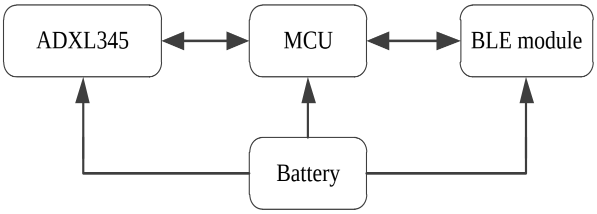

Figure 3 Schematic of wireless sensor node.

4.2 Test procedure

During the test, ADXL345 is configured to operate with a dynamic range of ±16g and a sampling rate of 200 Hz to allow sufficient inspection of the rotor dynamic characteristics. The acquired data is transmitted wirelessly to a remote computer. Simultaneously, encoder signals and the tank pressure are also recorded via a CED 1401 data acquisition system with a sampling rate of 49019 Hz. In this experimental work six groups of data were collected for different compressor conditions, including one healthy condition (BL) and five faulty conditions. These cases are listed in table 3 and performed one by one.

Table 2 Test cases description

Test case	Description
BL	Baseline signal
DVL	Discharge valve leakage on the high pressure cylinder
ICL	intercooler leakage
ASW	Asymmetric stator winding of the motor
DVL+ASW	Discharge valve leakage on the high pressure cylinder + asymmetric stator winding of the motor
ICL+ ASW	intercooler leakage + asymmetric stator winding of the motor

4 RESULTS AND DISCUSSION

Figure 4 displays the periodic wireless sensor outputs in both X and Y axes as well as their frequency spectrums when the high pressure tank is around 80 psi.

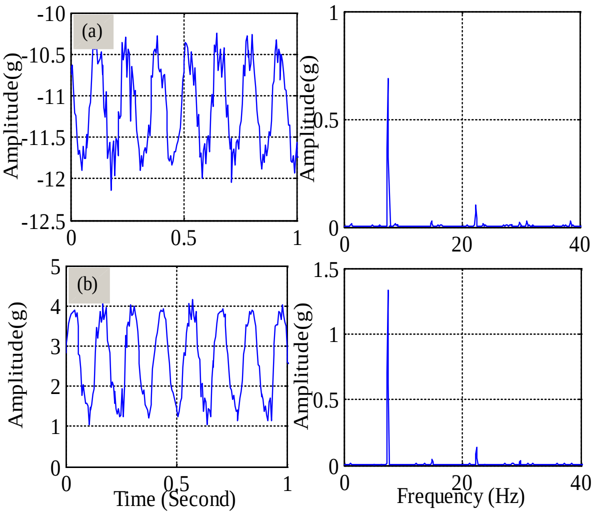

Figure 4 Acceleration signals and their spectra at pressure of 0.55 MPa (80 psi) (a) X-axis and (b) Y-axis

From these frequency spectrums, it can be seen that the peak value is at around 7.4 Hz, which is actually the compressor speed. The tangential acceleration can be reconstructed by combining the acceleration in X-axis and Y-axis using the method explained in Section 2.2. To verify the reconstructed signal, an integration operation is performed on the obtained tangential acceleration so as to get the alternating IAS signal. In the meantime, the multiple pulse signal from the encoder is also computed using the method explained in Section 2.1.

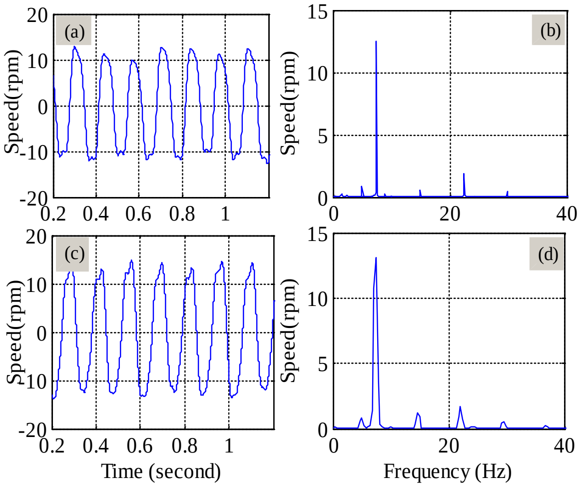

Figure 5 IAS comparison from the wireless sensor and encoder. (a) wireless sensor time domain, (b) wireless sensor frequency domain, (c) encoder signal time domain, (d) encoder signal frequency domain

The computed IAS signals are compared in Figure 5 in both time domain and frequency domain. Note that the presented IAS signal only contain alternating components. It can be seen that the IAS signal from these two sensors have good match in waveform shape, amplitude and very similar frequency components. This verifies the accuracy of the reconstructed signal obtained from wireless accelerometer. To classify the compressor condition using the reconstructed tangential acceleration, the harmonics changes with discharge pressure for all test conditions are presented in Figure 6. It can be seen that the amplitude from the fundamental and the 3rd harmonic frequency components show a linear increasing trend with the tank pressure from 0 to 0.82 MPa (120 psi). Therefore, these two components are employed for further condition classification.

Figure 7 (a) shows the relationship of third harmonic with the fundamental frequency for tank pressure ranging from 0.41 MPa to 0.83 MPa (60 psi to 120 psi). Based on the relationship between fundamental and third harmonic, the fault signals are classified in Figure 7 (b).

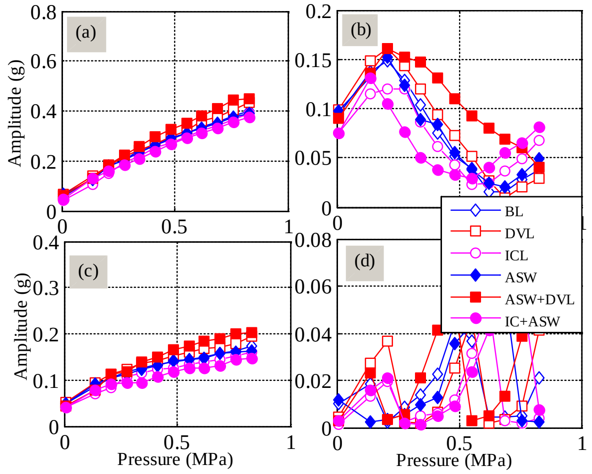

Figure 6 Harmonics amplitude of the reconstructed acceleration signal vs. tank pressure. (a) fundamental frequency, (b) 2nd harmonic, (c) 3rd harmonic and (d) 4th harmonic.

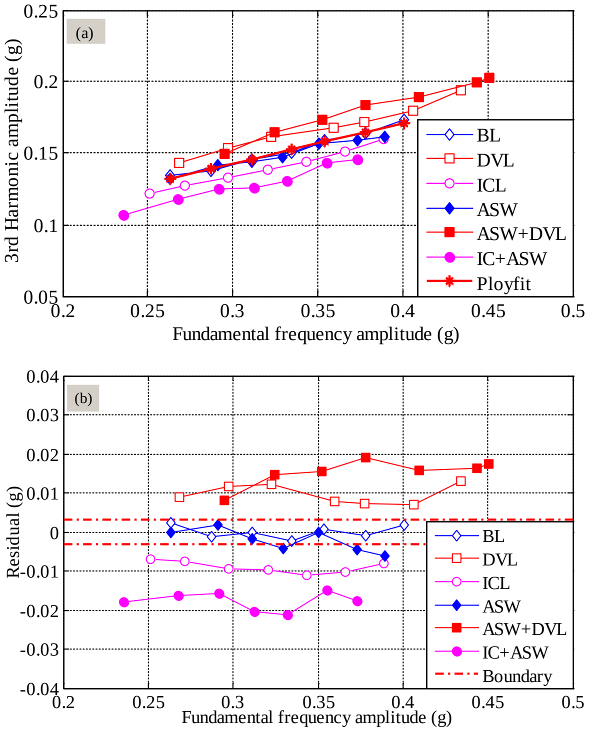

Figure 7 Fault signal classification (a) 3rd harmonic vs. fundamental frequency (b) residual vs. fundamental frequency

It is clear that the intercooler fault (ICL), the discharge valve leakage fault (DVL) and both combined faults (IC+ASW, DVL+ASW) can be well separated from the baseline signal (BL). However, some part of the asymmetric stator winding fault (ASW) classification still falls within the set boundaries, making it difficult to detect or properly classify them. Furthermore, the residual of DVL related fault, i.e. DVL and combined fault (DVL+ASW), is positive whereas that of ICL related fault, i.e. ICL and combined fault (ICL+ASW), are negative. It can also be noticed that the effect of the combined fault in both cases are clearly evident while the combined faults make the residual more deviated from the boundaries.

5 CONCLUSION

In this paper, a performance test of a wireless MEMS accelerometer is carried out for different common faults appearing in a reciprocating compressor. The measured signals of the wireless sensor are compared with signal obtained from a traditional optical encoder. The experimental results demonstrate that, acceleration signals from the wireless sensor and the encoder are similar and there is a very good matching in both waveform and spectrum, proving that the reconstructed tangential acceleration from on-rotor accelerometer is accurate and reliable. Furthermore, a remote condition monitoring and common fault diagnostic for a reciprocating compressor can be achieved by using only one MEMS accelerometer.

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