Chapter 2
MEMS Accelerometers: Testing and Practical Approach for Smart Sensing and Machinery Diagnostics

A. Albarbar and S.H. Teay

Abstract Micro-Electro Mechanical Systems (MEMS)-based sensing elements are gaining wider acceptance and adoption for static and dynamic (mobile) applications. Recent increase in demands for reliable wireless sensing nodes has necessitated seeking alternatives to expensive conventional accelerometers to perform multi-control and monitoring tasks. Owed to their size and cost, MEMS accelerometers is one of the alternative options.

This chapter provides insight into the fundamental design, working principles and practical guidance to MEMS accelerometers. Details of experimental set-ups, signal conditioning and data processing are also provided to construct integrated performance assessment system. Performance assessments are carried out using sinusoidal excitations, impulsive (hummer testing) and random excitations. Subsequently, calculations and comments on frequency response functions, signal-to-noise ratios and phase distortions are outlined. Finally, guidelines to practical adoption of MEMS accelerometers such as packaging, establishing smart vibration sensing nodes and extraction of condition-related information are given.

Keywords MEMS accelerometers design and testing • Performance assessment of MEMS accelerometers • Vibration measurement using MEMS sensors • Smart sensor design and implementation • Machinery-condition monitoring

1 Introduction

Vibration analysis is one of the most usable methods in machinery-condition monitoring. It plays a significant role in the dynamic qualification of newly designed structural components, prediction of faults and structural aging-related problems, and several other structural dynamics studies and diagnosis [1–3]. One reason for

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its wide use is its capacity to monitor vibrating machines without interrupting normal operations. In addition, the vibrating mechanisms of most machineries and structures are fundamentally well known, giving rise to the possibility of detecting many faults in accordance with the characteristics of the vibration responses. Furthermore, the progress of vibration signal processing techniques, computing capabilities, reliable performance of vibration instrumentation such as wide-band transducers and portable analysers has caused this technique to be extensively used around the world.

As an example, in machinery-condition monitoring, accelerometers are often used to measure their vibration (acceleration) signals, which may lead to the detection of any deviation from normal signatures. Vibration waveforms are interpreted and processed in a variety of ways such as peak values and variance of the signal in the time domain, and power spectral analysis in the frequency domain [4].

Vibration has traditionally been sensed using piezoelectric accelerometers. These are accurate and reliable, but have some inherent problems: they are difficult to mass-produce, and they have high source impedance, which means that their signals must be very carefully amplified. Moreover, the use of the traditional piezoelectric accelerometers for simultaneous multiple data collection points was considered to be impractical; this is mainly because of their cost as well as the costs of the associated electronic signal conditioning units. Other types such as piezoresistive accelerometers have limited resolution and can be used only for low and medium frequencies. Low resolution is also a disadvantage of electrodynamic accelerometers. The capacitive type accelerometers have low resolution and are fragile. Commercially, several types of accelerometers manufactured by many well-known manufacturers are available all over the world. In vibration-measurement filed tests, accelerometers of mainly Integrated Circuit Piezoelectric (ICP) type, are found not to be able to measure the non-stationary impulsive responses of structures accurately all the time. However, confidence in measuring impulsive signals using the charge-type piezoelectric accelerometers is very good [4, 5].

Obviously, the quality of the vibration-based diagnosis and/or identification of vibration-related problems mainly depends on the measured responses using accelerometers. Therefore, good performance and high reliability of the commercially available accelerometers is very important. Additionally, the use of conventional accelerometers for multiple data collection points may increase the complexity of monitoring system because of the associated electronic units that are externally connected to the accelerometers. Consequently, the need for cheaper and more reliable devices is well recognised.

With increasing demands for wireless sensing nodes used for assets control and condition monitoring; the need for alternatives to those expensive conventional accelerometers in vibration measurements has risen. Micro-Electro Mechanical Systems (MEMS) accelerometers are one of the available options because of their small size, newer technology and low cost, e.g. MEMS accelerometer may be within 10 % of the cheapest commercially available conventional accelerometers that come with a signal conditioning unit [4, 5]. According to Yole's Development report, the total market for MEMS is expected to exceed $20 Billion in 2020.

The average price of MEMS accelerometers across all applications decreases, from an average of $2.50 in 2004 to less than $1.70 in 2015, with consumer applications driving the price down [6]. MEMS technology is used in some sectors such as automotive industry for measuring pressure, temperature and air bags systems. A few earlier researches compared the performance of MEMS accelerometers with the conventional ones. The main differences are mainly in actuation frequencies, amplitudes and phase shifts. In general, the selection of accelerometers is based on their technical specifications and the measurement requirements. The main technical specifications that decide the use of accelerometers are as the following:

(a) **Sensitivity** is the ratio of the electrical output of the accelerometer to its mechanical input. The output usually is expressed in terms of voltage per unit acceleration. The specification of sensitivity is sufficient for instruments, which generate their own voltage, independent of an external power source. The sensitivity of an instrument requiring an external voltage usually is specified in terms of output voltage per unit of voltage supplied to the instrument per unit displacement, velocity, or acceleration, e.g. milli-Volts per *g* of acceleration.
(b) **Frequency range** is the operating frequency range over which the sensitivity of the transducer does not vary more than a stated percentage from the rated sensitivity. The range may be limited by the electrical or mechanical characteristics of the transducer or by its associated auxiliary equipment.
(c) **Amplitude limit** specifies the maximum range of acceleration that can be measured by the accelerometer.
(d) **Shock limit** represents the maximum level of acceleration the accelerometer can withstand without any damage to the unit.
(e) **Linearity** indicates the accuracy of the measured acceleration amplitude within the corresponding frequency range.
(f) **Natural frequency** which is indirectly indicative of the measuring frequency range. In general, a higher natural frequency allows a larger measuring frequency range of an accelerometer.

However, the use of vibration analysis in condition-monitoring is based on three key points:

1. A frequency component identifies the basic problem.
2. The amplitudes of this component and its harmonics indicate the severity of the problem.
3. Phase relationships are used to distinguish between looseness and eccentricity (fault diagnosis).

While a vibration spectrum can reveal much about the ranges of motion and flexibility (resonance) of a machine, the frequency domain does not yield all the answers. The time domain is the only place we can identify peak and peak-to-peak amplitudes of each cycle, phase relationship between signals, and the presence of such distinctive characteristics as truncated waveforms, pulses and modulation. The calibration procedure adopted, generally uses the sinusoidal vibration generator (shaker) with varying frequencies and amplitudes to characterise the accelerometer being calibrated. This is achieved by comparing its measured responses with other well-calibrated accelerometers. Accuracy of sinusoidal response measurement satisfies the calibration procedure requirements. However, accelerometers are in general used for measuring periodic signals (e.g. sinusoidal), as well as impulsive and random signals.

2 Types and Design of MEMS Accelerometer

Generally, MEMS accelerometers are divided into two groups: piezoresistive MEMS accelerometers and capacitive MEMS accelerometers.

2.1 Piezoresistive MEMS Accelerometers

Piezoresistive MEMS accelerometer is also known as strain gauge MEMS accelerometer. Unlike piezoelectric-typed sensor, piezoresistive MEMS accelerometer changes in resistance across the piezo material when stress is applied. The history of piezoresistive MEMS accelerometer could be found in late 1970s. Roylance et al. have successfully developed a first prototype of silicon-based strain gauge accelerometer at Stanford University [7]. The mechanism of piezoresistive MEMS accelerometer is simple. The first design of silicon piezoresistive MEMS accelerometer consists of a frame, a proof mass and a thin beam as shown in Fig. 2.1. The strain gauge is placed on the top layer of the beam, forming a half bridge connection. When acceleration is applied to the sensor, the normal force causes the beam to bend, leading to a change in resistance of the strain gauge. The half bridge configuration gives proportional output to the acceleration. The proposed design has become a fundamental topology of piezoresistive MEMS accelerometer. Multiple beam-mass system has been introduced to improve the accelerometer's merit of figures [8]. Technically, piezoresistive MEMS accelerometer provides good sensitivity. However, their low tolerance on ambient temperature conditions and self-heating characteristics have been the development bottleneck [9]. Benefitting from recent micro-fabrication technology, such difficulties could be overcome and nowadays, there are relatively robust piezoresistive MEMS accelerometers available in the market [7].

Using similar design techniques, higher number of axis, e.g. three-axis piezoresistive accelerometers, could also be manufactured as shown in Fig. 2.2. Four beams with eight piezoresistors configuration are integrated to sense acceleration in three different directions. This configuration could be visualised in an equivalent Wheatstone bridge topology as shown in Fig. 2.2c. The parallel accelerations along x, y and z-axis introduce beam deformation and cause compressive and tensile stress

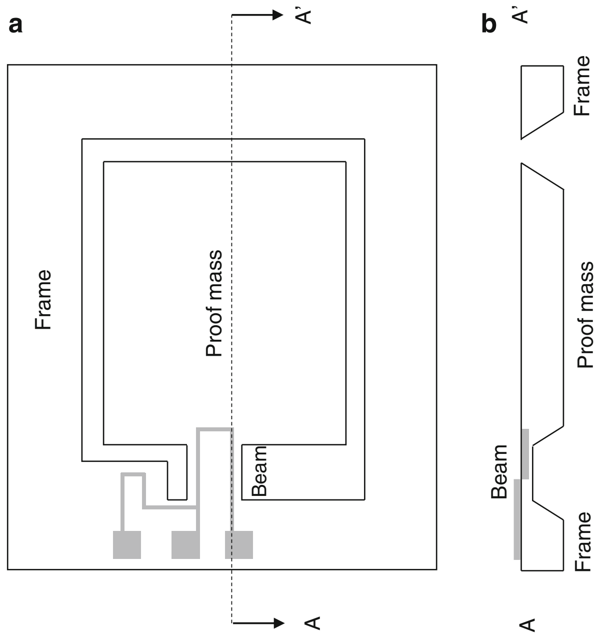

Fig. 2.1 Schematic diagram of piezoresistive MEMS accelerometer (**a**) top view, (**b**) cross-sectional view [7]

in each piezoresistor. The corresponding changes are outlined in Table 2.1. One additional rationale of using Wheatstone bridge is to nullify the defects caused by temperature drifts in piezoresistors [7, 8].

For packaging design, the piezoresistive MEMS accelerometer is wafer encapsulated with etched glass caps, preventing over-range protection and fluidic squeezed-film damping. To ensure better measurement experience, the transfer function between sensor surface and glass gap can be evaluated using their damping coefficients based on mass-spring-damper mechanical system analysis [8].

2.2 *Capacitive MEMS Accelerometer*

Silicon design of capacitive MEMS accelerometer allows low cost mass production due to the mature technology on surface micromachining. ADXL series from Analog Devices is one of dominant capacitive MEMS accelerometers in the market [4]. Application of capacitive MEMS accelerometer include smartphone devices, smart sensor system and low cost embedded monitoring system. Essentially, the schematic diagram of capacitive MEMS accelerometer is illustrated in Fig. 2.3. The movement of the proof mass due to an acceleration of the device changes the capacitance value between electrodes on stationary fingers. This difference in

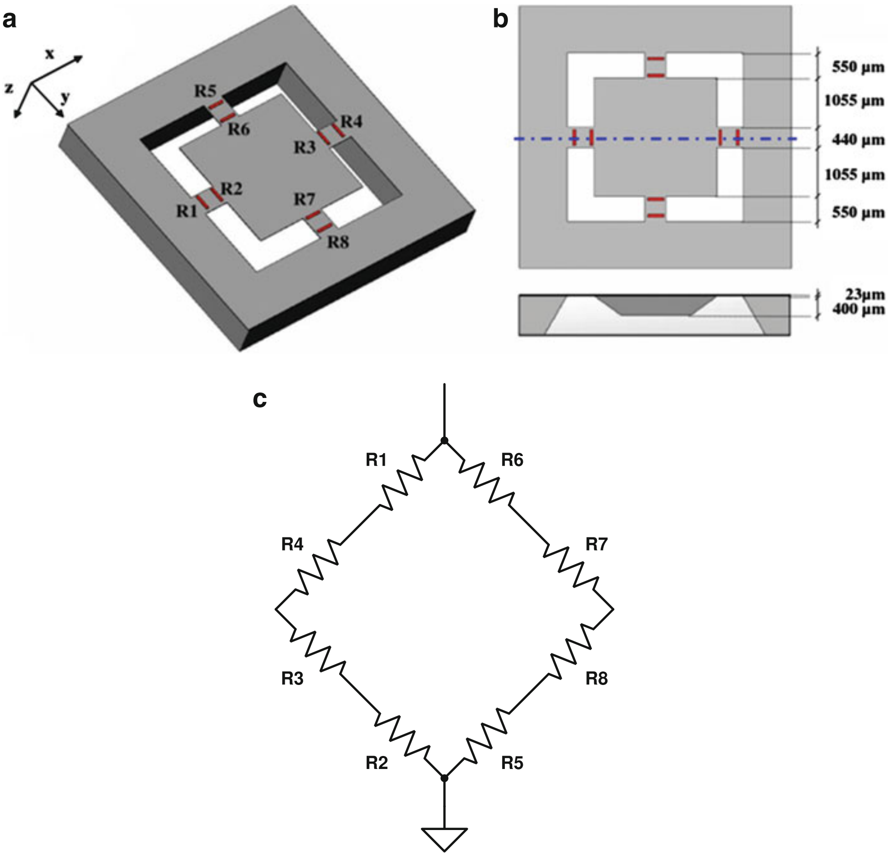

Fig. 2.2 Structural schematic of three axis piezoresistive MEMS accelerometer [9] (**a**) model view, (**b**) top and cross-sectional view, (**c**) equivalent Wheatstone bridge model

capacitance can be used to measure acceleration. An equivalent electronic circuit incorporated with the capacitive model in Fig. 2.3 is shown in Fig. 2.4. The part inside the rectangular box represents which its output is the differential capacitance value from electrodes. The equivalent circuit contains signal source, a buffer amplifier, a filter, a synchronous demodulator and electro-mechanical feedback loop with a feedback amplifier. This model has the sensitivity of 20 mV/g for an operational range of 0–50 g [9, 13]. To improve accuracy, symmetric design and differential sensing are able to reduce the effect of thermal mismatch to a minimum and linearises the capacitance different to acceleration relationship. In modern design, Zhou et al. have proposed an MEMS capacitive accelerometer with fully symmetrical double-sided H-shaped beam, of which the sensitivity of the device is 0.24 V/g with nonlinearity of 0.29 % over the range of 0–1 g [14].

Optimisation problem is always a concern in designing a robust capacitive MEMS accelerometer. General design criteria include manufacturing costs,

Table 2.1 Piezoresistance value corresponding to acceleration direction

Acceleration direction	R1	R2	R3	R4	R5	R6	R7	R8
X axis	Decrease	Increase	Decrease	Increase	Unchanged	Unchanged	Unchanged	Unchanged
Y axis	Unchanged	Unchanged	Unchanged	Unchanged	Decrease	Increase	Decrease	Increase
Z axis	Decrease	Increase	Increase	Decrease	Decrease	Increase	Increase	Decrease

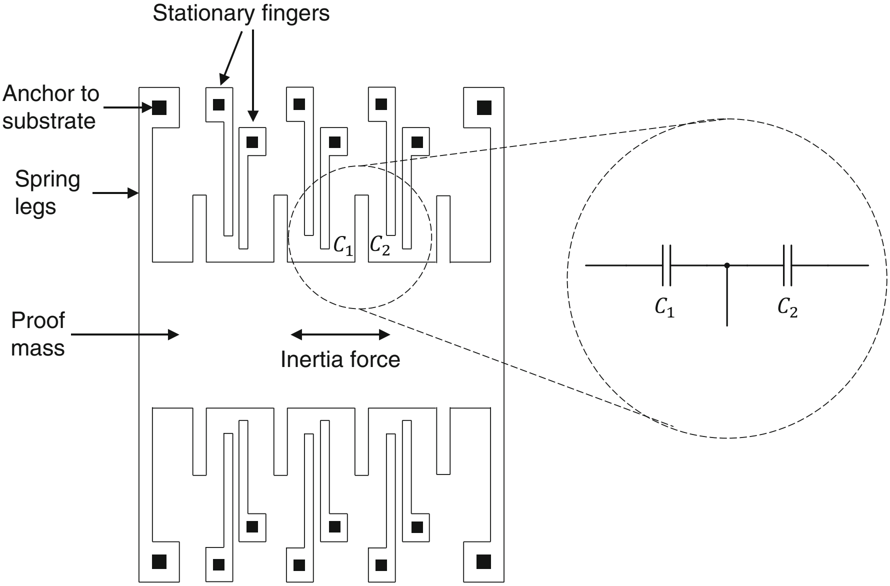

Fig. 2.3 Schematic diagram breakdown respective circuit model of capacitive MEMS accelerometer [10]

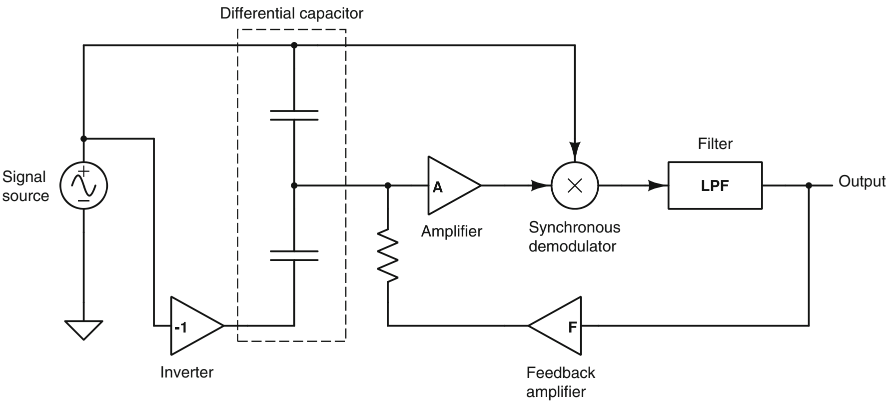

Fig. 2.4 Equivalent circuit of the integrated MEMS accelerometer [11, 12]

full-scale range, structural geometry and threshold acceleration [15]. Due to the complexity of the mechanism, the performance of capacitive MEMS accelerometer is still far from trivial. Various techniques have been carried to study the variables of capacitive MEMS accelerometer to optimise its performance and robustness [16, 17].

3 Testing and Calibration

Calibration is carried out on a variety of equipment in different situations to ensure that the equipment will produce results, which meet pre-defined operating criteria. In the context of calibration of devices (MEMS accelerometers), a calibration involves determining the performance of the sensor in reference to a known standard. Adjustment of the overriding system may be a part of a calibration, but not always.

In practical applications, accelerometers are usually used for measuring the periodic (sinusoidal, sweep-sine, step-sine, multi-sine, etc.), impulsive and random signals. Hence, these tests are usually carried out on a similar test set-up to that shown in Fig. 2.5, and subsequently the outputs of MEMS accelerometers are compared with well-calibrated accelerometers.

3.1 Performance Evaluation

In order to assure meaningful outputs, the performance of MEMS accelerometers have to be critically assessed and calibrated. Albarbar et al. have conducted a comprehensive study on performance of MEMS accelerometer for machinery-condition monitoring [4, 5]. Three MEMS accelerometers (denoted as A, B and C) have been validated by comparing their performance with a well-calibrated, conventional accelerometer and subsequently were utilised to measure the vibration signals of CNC machine in real industrial environment. Their respective technical specification is listed in Table 2.2. The tested devices output frequency response functions (FRS) and phase of the outputs of the tested devices are shown in Fig. 2.6a, b, respectively.

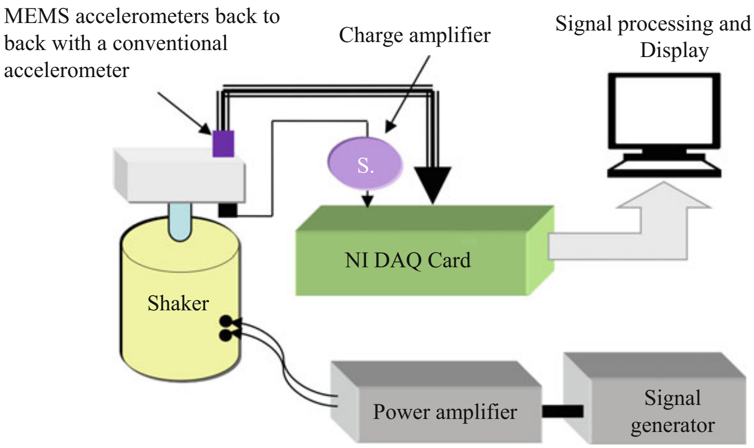

Fig. 2.5 MEMS accelerometer’s calibration experimental set-up

Table 2.2 Technical specifications of accelerometers

	Conventional accelerometer	MEMS (A)	MEMS (B)	MEMS (C)
Sensitivity (V/g)	0.1	Supply voltage/7	Supply voltage/5	Supply voltage/5
Frequency range (Hz)	1–2000	1–6000	1–10,000	1500
Amplitude limited (g)	±50	±5	±3	±3
Linearity	Less than ±5 %	±1 %/1 kHz	±1 %/5 kHz	±1 %/1 kHz
Shock limit (g)	5000	250	1000	100

As anticipated, there were clear differences between the tested accelerometers due to their design, sensitivity and noise contents of their outputs. For more details, the reader is advised to see [4, 5].

3.2 Calibration of MEMS Accelerometers

In this section, the calibration is performed using recently developed MEMS accelerometer (ADXL001-70) (http://www.analog.com/media/en/technical-documentation/data-sheets/ADXL001.pdf). An accelerometer calibrator type-4291 by Brüel & Kjær is used to generate reference mechanical vibration at 1 g (10 ms^{-2}) peak ±2 % with 79.6 Hz. A conventional Brüel & Kjær piezoelectric accelerometer was used as a reference and a commercial data acquisition system by National Instruments recorded the outputs. Both accelerometers are attached on the mechanical shaker, which excites at different frequency and amplitude. A photo of the calibration set-up is shown in Fig. 2.7. The calibration results are shown in Table 2.3 and in Fig. 2.8.

In the other test, the mechanical shaker was set to oscillate at 50 Hz. The sampling frequency is set to 5 kHz. Accelerometers outputs are shown in Fig. 2.9. Note that both the power spectrums have their peak values at 50 Hz, which comply with the dominant mechanical frequency from the shaker. The coherence of the measured signals of both ADXL001-70 and conventional accelerometer is shown in Fig. 2.10. It has the highest correlated coefficient when the frequency is close to 50 Hz. This shows that both sensors have successfully obtained the important dominant frequency information. The magnitude for harmonic frequencies between the two signals deviates when the frequency is getting larger (100 and 150 Hz) probably due to cross talks and noise contents [18].

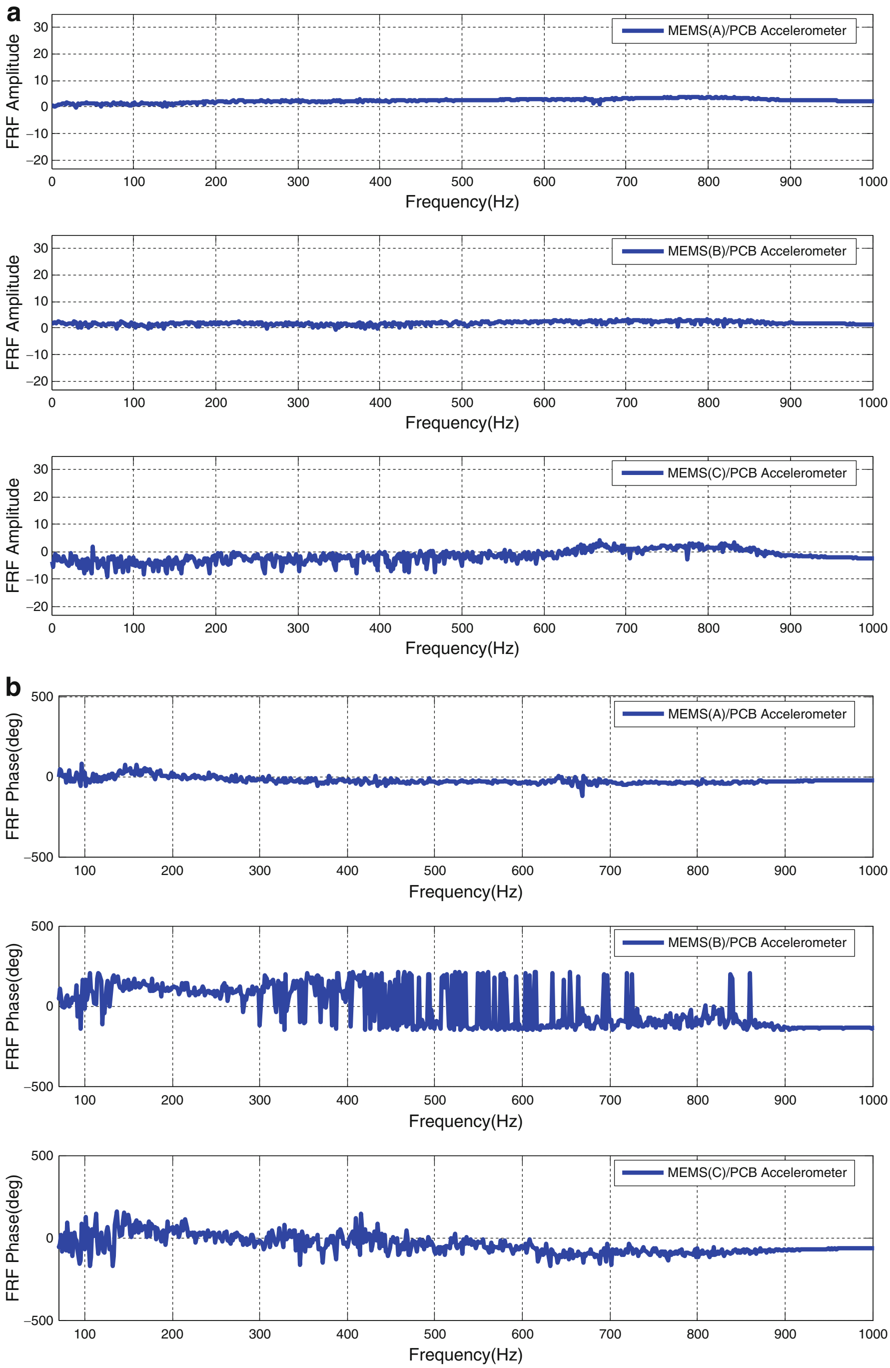

Fig. 2.6 MEMS accelerometer's response (**a**) magnitude and (**b**) phase of the frequency [4]

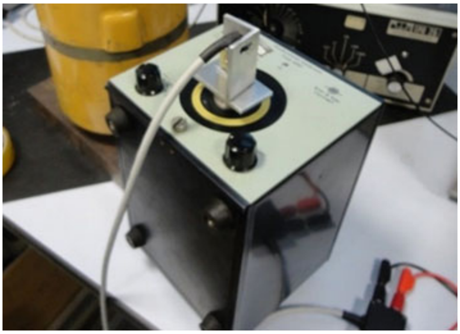

Fig. 2.7 Accelerometer calibrator with mounted ADXL001-70

Table 2.3 ADXL001-70 calibrated result

	Parameter	
Specification	0 Hz, 0 ms^{-2}peak	79.6 Hz, 10 ms^{-2} peak
Average voltage	2.62 V	2.64 V
Peak–peak voltage	200 mV	800 mV
RMS voltage	2.66 V	2.62 V
Dominant frequency	0 Hz	80.4 Hz (1 % deviation)

4 Packaging Technique

The delicate nature of MEMS accelerometers structures necessitates the use of suitable packaging techniques to allow them to survive harsh conditions they would face when used to acquire machinery vibrations in real industrial environments. Benefits of proper packaging are to provide:

- Mechanical protection for the chip and components
- Stable temperature operating environment
- Ease of identification of sensors
- Means of mounting the sensor to equipment under test

Details of packaging typical MEMS accelerometer chip (ADXL202AE) are explained in Figs. 2.5 and 2.6. The connections (Fig. 2.11) and components (Fig. 2.12) for implementing the MEMS' chip in an analogue voltage output configuration were determined from the supplier data sheet.

5 MEMS Implementation on Machinery Diagnostics

In this section, MEMS accelerometers are used to collect vibration data from two types of rotating machinery: a DC motor and a CNC machine. These two types of machines are widely used in today's industry, and it would be of great importance

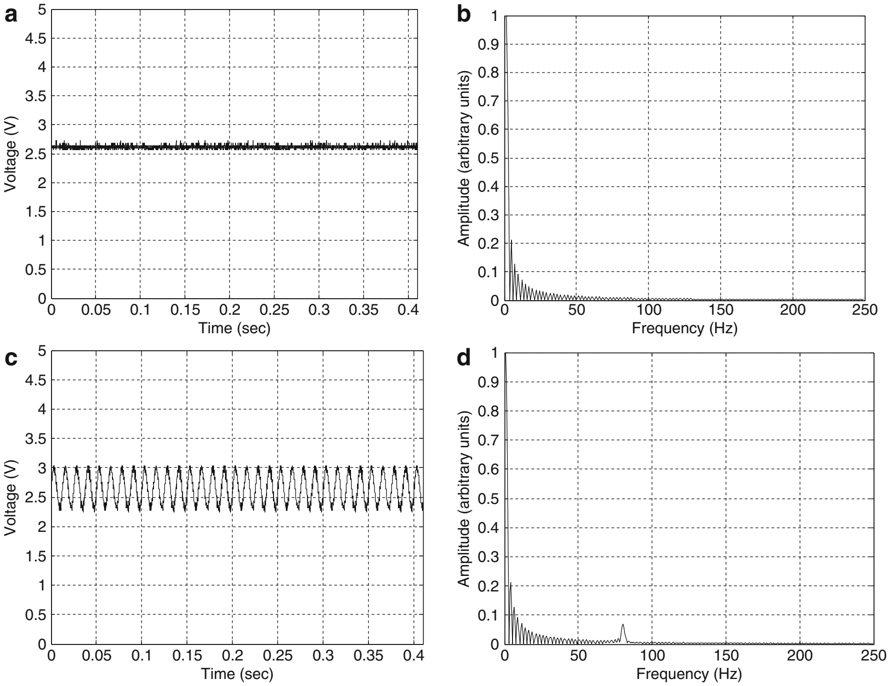

Fig. 2.8 Calibrated vibration waveform of ADXL001-70: (**a**) 0 Hz, 0 ms^{-2}, (**b**) frequency domain, (**c**) 79.6 Hz, 10 ms^{-2}, (**d**) frequency domain

if their incipient failures were successfully detected by the cost-effective MEMS accelerometers. In other words, the adopted MEMS accelerometer has to clearly show fundamental frequencies and harmonics of the monitored machines.

5.1 Vibration Measurements of DC Motor Test Rig

The DC motor test rig is shown in Fig. 2.13. It consists of a DC motor attached to a shaft supported by three roller bearing and holds a metallic disk. The motor's speed is controlled by a speed controller, which varies from 0 rpm to a maximum rotational speed of 2864 rpm. An ADXL001-70 MEMS accelerometer, placed on drive end bearing housing, is used to collect the vibration data at five different speeds: 280, 914, 1602, 2281 and 2864 rpm. Time and frequency domains of collected vibration data are shown in Fig. 2.14. The respective harmonics could be seen, in particular, at rotational speeds higher than 1602 rpm.

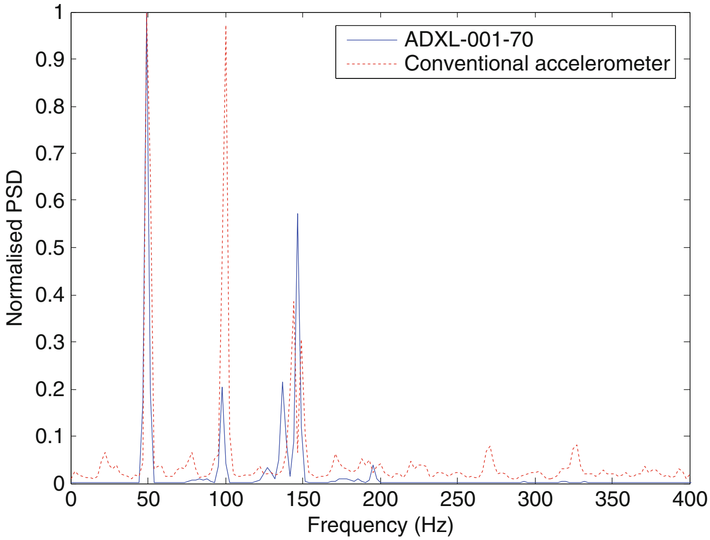

Fig. 2.9 Frequency spectrum of acquired vibration signal using ADXL001-70 and conventional accelerometer at 50 Hz

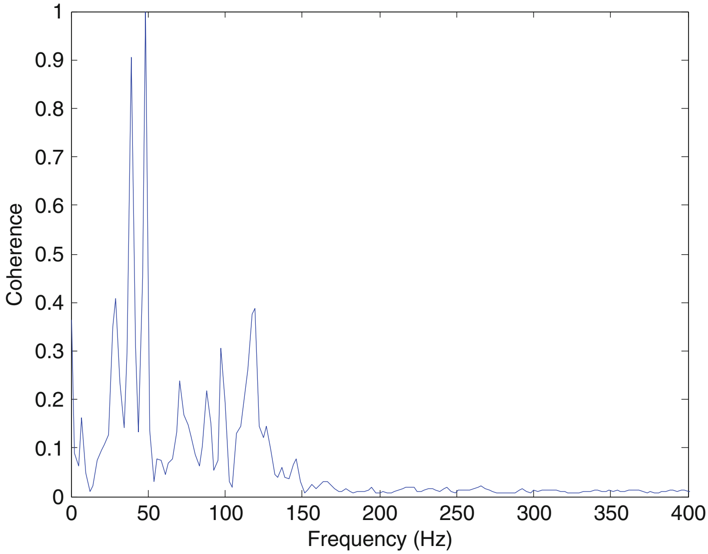

Fig. 2.10 Coherence between the vibration signals acquired using ADXL001-70 and conventional accelerometer

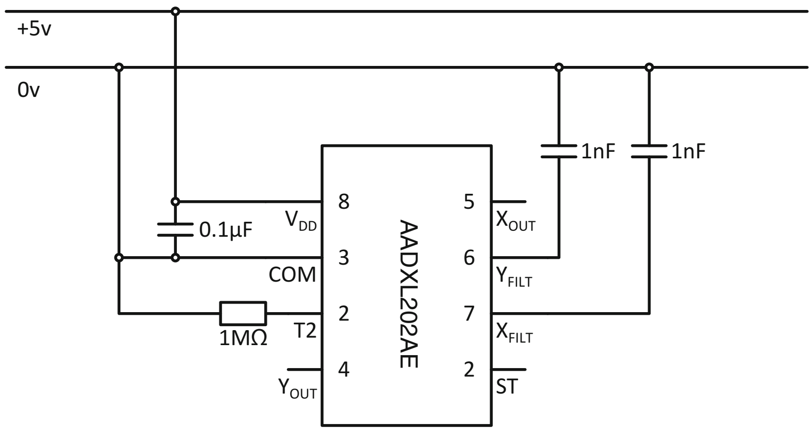

Fig. 2.11 MEMS accelerometer wiring diagram

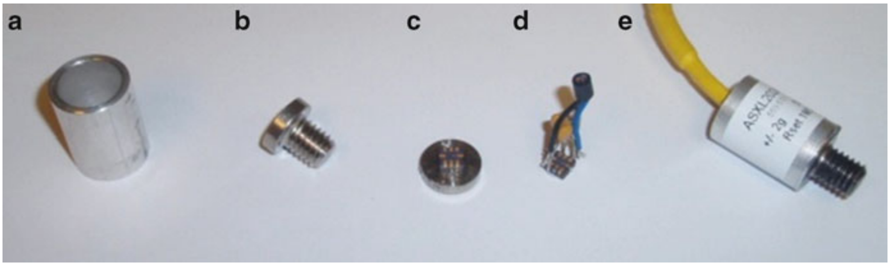

Fig. 2.12 MEMS packaged sensor components: (**a**) sensor outer casing (mild steel), (**b**) threaded mounting bottom plate, (**c**) flat mounting bottom plate with MEMS affixed, (**d**) MEMS with components attached, (**e**) Packaged MEMS sensor

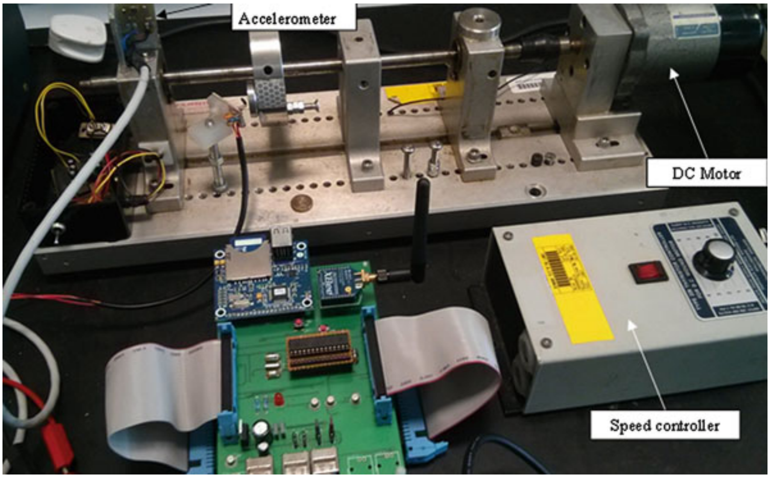

Fig. 2.13 Experimental set-up of DC motor vibration monitoring

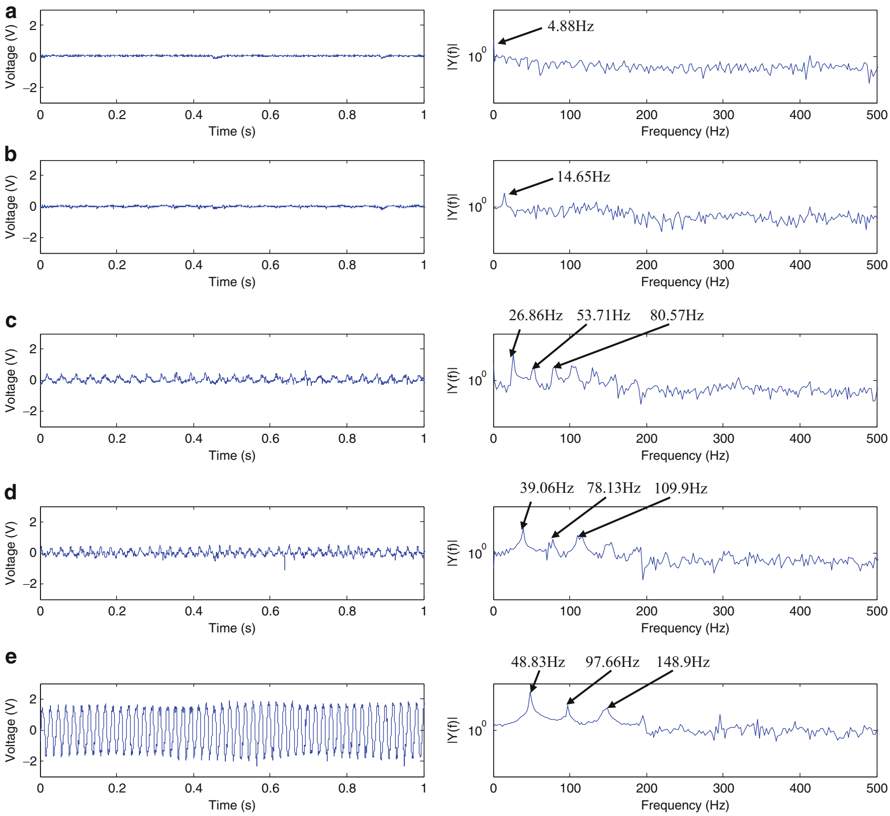

Fig. 2.14 DC motor vibration and power spectrum measured by ADXL001-70 at different rotating speeds: (**a**) 280 rpm (4.67 Hz), (**b**) 914 rpm (15.23 Hz), (**c**) 1602 rpm (26.7 Hz), (**d**) 2281 rpm (38 Hz), (**e**) 2864 rpm (47.73 Hz)

5.2 *Vibration Measurements of CNC Machine*

The MEMS accelerometer is placed on CNC machine in a typical industrial environment as shown in Fig. 2.15. The CNC machine operates under a speed of 2400 rpm. Respective time and frequency domains of the vibration signals are plotted in Fig. 2.16. Experimental results show that the important fundamental frequencies and their harmonics are captured by the MEMS accelerometer.

The actual vibration amplitude for the machine was about 0.2 *g* peak (±0.01 *g*—using hand-held commercial vibration monitoring device) which gives clear evidence on the correctness of the vibration amplitude indicated by the MEMS accelerometer.

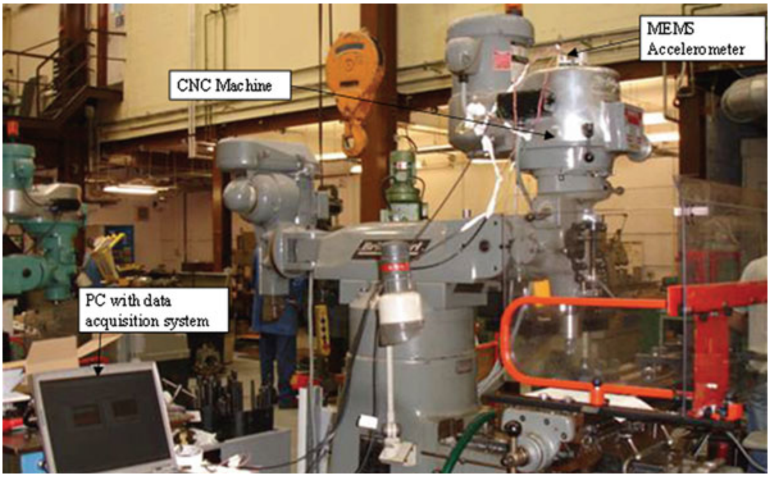

Fig. 2.15 Experimental set-up of CNC machine vibration monitoring

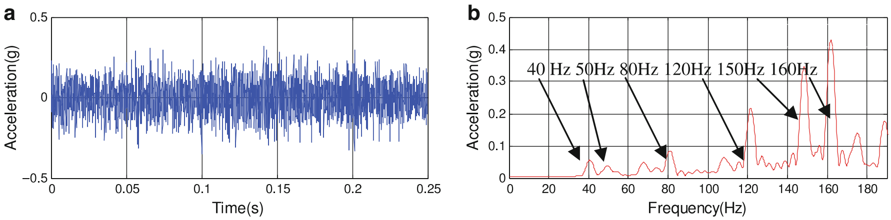

Fig. 2.16 CNC machine vibration measured by ADXL001-7 at speed of 2400 rpm (**a**) time domain and (**b**) frequency domain [4]

The CNC machine was run at 2400 rpm, and at this speed the fundamental speed and harmonics are 40, 80 and 160 Hz which were clearly presented in the frequency domain of Fig. 2.16.

6 Design and Implementation of MEMS-Based Smart Sensors

Previous sections have outlined the characteristics and fundamentals of MEMS accelerometers. MEMS accelerometers are envisioned as future candidates in realising the practical deployment of smart sensing technology. Smart sensor/transducer provides more complex functions than raw signal acquisition by integrating embedded system into the sensing architecture. Possible features of smart sensors include programmable signal conditioning, on-board signal processing and analysis, simple decision-making and remote communication. Generally, there are two major advantages of using MEMS accelerometers over their conventional counterparts for smart sensing development:

- *Low power consumption*: A conventional accelerometer requires charge amplifier to amplify the induced acceleration by conventional accelerometer. Such an amplifier usually requires a supply voltage higher than that of an embedded system (which average operational voltage is between 1.65 and 5 V and about 15 mA).
- *Low cost of deployment*: The cost of an MEMS accelerometer could be less than 10 % compared with commercially available accelerometers. The average price of MEMS has been declining since 2009, and it is believed that it will continue to do so in the next few years (predicted figure from $1.01 to $0.90). High performance accelerometer such as ADXL001 has an average market price at $30, which is at least 50 % cheaper than commercially available conventional accelerometer.

To validate the feasibility of MEMS accelerometer for smart sensing application on rotating machinery diagnostics, working system architecture is designed and developed. Its respective hardware architecture could be partitioned into five main modules: sensors, embedded microcontrollers (peripheral integrated circuit and core computational unit), external data storage module and wireless communication module. The architecture design is shown in Fig. 2.17. The working prototype is also developed as shown in Fig. 2.18.

The sensing element—MEMS accelerometer—is responsible for transducing physical movement into electronic signals. The resulting electronic measurements are then sent to the peripheral computational unit, where necessary analogue signal conditioning is carried out. The processed analogue signals are then transmitted to computational core for signal processing, analysis and fault diagnostics. The quantised data is logged and interrogated in removable data storage device (universal serial bus (USB) flash drive or secure digital (SD) card) through data storage module. The end-result and diagnosis report is transmitted to another system platform through wireless communication module. A flowchart to represent the workflow of the developed smart sensor is illustrated in Fig. 2.19.

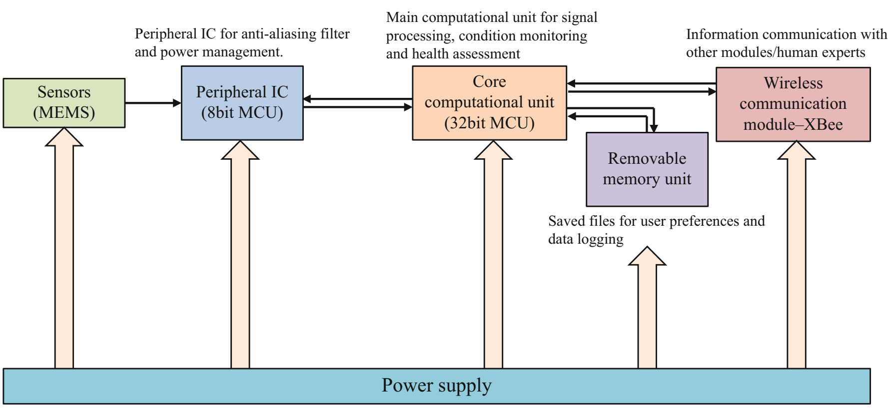

Fig. 2.17 System architecture of MEMS-based smart sensor

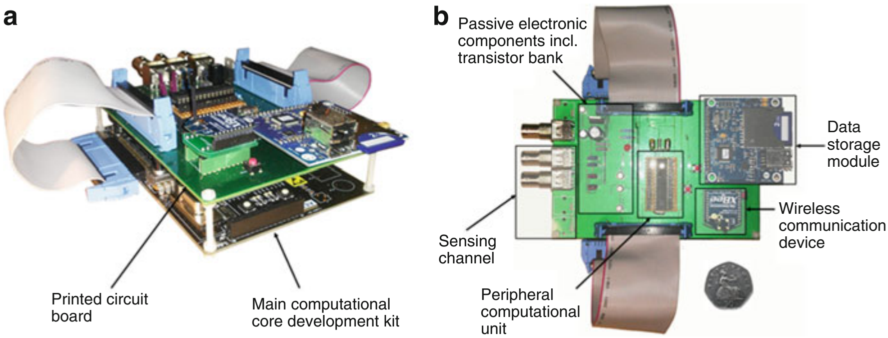

Fig. 2.18 Working prototype of MEMS-based smart sensor system (**a**) prospective view and (**b**) top layout view

On-board vibration measurement is one of the crucial elements for MEMS-based smart sensor. For example, to sample a 16-bit (2-byte) vibration signal for 3 s in 5 kHz requires at least 30 kB data memory ($2 \times 3 \times 5000 = 30$ kB). Such data load is hectic to be logged into internal memory of commercially available microcontroller, as tabulated in Table 2.4. To tackle the above design challenge, an external data storage module is necessary. The end terminal of data storage module is removable mass storage device, such as USB thumb-drive or secure digital (SD) card. This has extended high volume of data storage, which has flash memory counted in gigabyte.

The developed smart sensor has the ability to collect raw vibration, compute statistical features and send analysed result to user interface autonomously. Advanced signal processing or artificial intelligence could be performed on-board for complex machinery diagnostics. Such system has significant advantage in reducing power, cost and communication overhead in future sensing technology.

In terms of sustainability, MEMS-based smart sensor has potential to integrate energy harvesting technology in the future, which is another trending topic in modern engineering. Most commercial digital integrated circuit provide programmable sleep/hibernate mode to conserve energy consumption. Respectively, the power characteristics of developed smart sensor are tabulated in Table 2.6.

MEMS-based smart sensor integrates a wireless communication module such as XBee or XBee-PRO. Its modular design architecture and direct digital interface have enabled relatively fast transmission between the smart sensor and other sensing platform. Several customised commands are pre-programmed to access smart sensor through computer's user interface as tabulated in Table 2.5. They are coded in 8-bit ASCII character data-type, providing good readability for the user to monitor the console.

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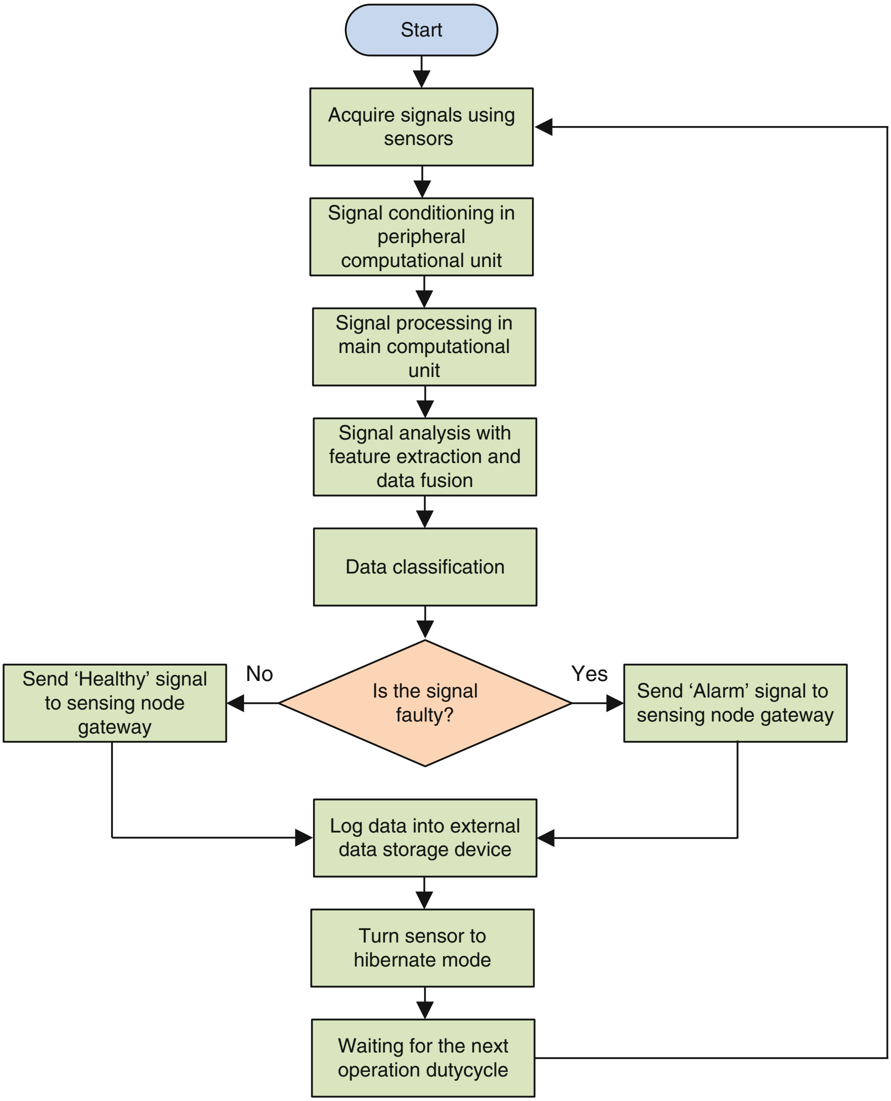

Fig. 2.19 Workflow of smart sensor

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Table 2.4 Available memory capacity of various commercial microcontrollers

Microcontroller	Manufacturer	Maximum flash memory (kB)	Data memory (RAM) (kB)
PIC32MX575F512L	Microchip	512	64
dsPIC33EP512MU814	Microchip	536	52
AT32UC3C0512C	Atmel	512	64
MC56F84789	Freescale	256	32
CY8C5868AXI-LP032	Cypress	256	64

Table 2.5 Commands to communicate with IMSEM through XBee module

Commands	Description
Menu	Shows menu of the IS
Initialise	Reset or initialise the IS together with the SD card module
Read	Read data that has been stored in the SD card of IMSEM
Auto	Start monitoring process with time-driven mode
Calculate	Calculate feature components of target signals in SD card
Debug	Reserved for debugging purpose

Table 2.6 Power budget of smart sensor

Parameter	Value
Maximum rated voltage (Identified from the system modules' data sheet)	7.5 V
Rated voltage	5.6 V
Minimum voltage	4.8 V
Current drawn (Operation mode)	Average 0.22 A
Current drawn (Idle mode)	Average 0.2 A
Current drawn (Inactive mode)	8 μA
Rated power consumption (Operation mode)	1.232 W
Rated power consumption (Idle mode)	1.12 W
Rated power consumption (Inactive mode)	44.8 μW

7 Concluding Remarks

MEMS accelerometers offer excellent alternatives to conventional types of those transducers as there is no need to carry heavy charge amplifiers, but the choice has to be made according to specifications and through validation tests. MEMS sensors have also to resist harsh environments using an appropriate packaging.

There are a number of MEMS accelerometers that could be used for monitoring machinery vibrations. The technical specifications for each of them should be well understood and must be suitable for the intended application. MEMS accelerometers are of sensitive and breakable structure, and thus they should be suitably packaged to withstand harsh environments without affecting their specifications. Sensitivity, resolutions and frequency range are the most important specifications that should be taken into account when choosing MEMS accelerometers

Adequate performance tests of MEMS accelerometers should be conducted under different excitations signals including sinusoidal, impulse and random. The measured responses of the MEMS accelerometers shall also be compared with a well-calibrated type accelerometer. Moreover, their outputs contain high amount of noise and extra un-interpretable peaks which necessitate full understanding of the measured vibration signals.

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