DEVELOPMENT OF TILT AND VIBRATION MEASUREMENT AND DETECTION SYSTEM USING MEMS ACCELEROMETER AS A SENSOR

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol/Abbreviations	Description	Unit
A	Sensitivity sense axis at 1g	mV/g
A_X	X axis	-
A_Y	Y axis	-
AC	Alternate current	Volt
B	Sensitivity sense axis at -1g	mV/g
C_{DC}	Decoupling capacitor	piko farad
COM	Common ground	Volt
C_X	Capacitor at output pin x axis	uF
C_Y	Capacitor at output pin y axis	uF
DAQ	Data Acquisition	-
DC	Direct current	Volt
DCM	Duty Cycle Modulator	-
d_0	Sensing gap distance	um
d_1	Sensing gap distance	um
f	Resolved vector	Pa
f_1	Adjusted vector	Pa
f_2	Adjusted vector	Pa
FEM	Finite Element Model	-
FFT	Fast Fourier Transform	-
f_s	Sampling rate	Hz
f_{max}	Highest frequency component	Hz

$2f_{max}$	Nyquist frequency	Hz
g	Gravity acceleration	ms^{-2}
IC	Integrated circuit	-
I_{finger}	Length of comb finger	um
KKF	Kalman Filter	-
L	Length	um
LED	Light Emitting Diode	-
MEMS	Micro Electro Mechanical System	-
N	Possible states	-
n	Number of bits	
NC	No Connection	-
NI	National Instrument	-
Pk – Pk	Amplitude peak to peak	ms^{-2}
PWM	Pulse Width Modulation	-
R^2	Coefficient Determination	-
RMS	Root Mean Square	ms^{-2}
R_{SET}	Resistor to setting signal duty cycle	-
ST	Self Test	-
T2	Pin to setting duty cycle period	-
$t_{proof\ mass}$	Thickness of proof mass	um
U_X	Deflection at x axis	um and nm
U_Y	Deflection at y axis	um and nm
U_Z	Deflection at z-axis	um and nm
USB	Universal Serial Bus	-
V_{DD}	IC power	Volt

V_{TP}	Test point	-
U_{Vector}	Vector deflection	um
V_{OUT}	Output voltage sensor	mV/g
$V_{zero\ g}$	Output voltage sensor when oriented at 0g	mV/g
W	Width of comb finger	um
X_{FILT}	Low pass filter at x-axis	-
X_{OUT}	Pin output at x-axis	-
Y_{FILT}	Low pass filter at y-axis	-
Y_{OUT}	Pin output at y -axis	-
θ	angle	rad
S	Scale factor	V/g
X, Y, Z	Coordinates	-
c	Cosine	-
d	Distance	μm
d_0	Sensing gap	μm
d_1	Sensing gap	μm
σ	Standard deviation	-
μ	mean	-

PEMBANGUNAN SISTEM PENGUKURAN DAN PENGESAN SUDUT MIRING DAN GETARAN MENGGUNAKAN METER PECUTAN MEMS SEBAGAI PENDERIA

ABSTRAK

Dalam projek ini, sistem pengukuran dan pengesan isyarat sudut miring dan isyarat getaran menggunakan meter pecutan MEMS yang mempunyai dua paksi deria X dan Y dibina dengan jayanya. Beberapa isu telah diambilkira semasa membangunkan sistem ini seperti spesifikasi penderia, perisian untuk mengaturcara program, peralatan untuk antaramuka dan kebolehanjalan perisian yang digunakan. Dalam sistem ini, spesifikasi penderia seperti penuras laluan rendah boleh diubah bergantung kepada aplikasi. Penuras laluan rendah ini bertujuan mengurangkan hingar daripada isyarat keluaran MEMS. Penuras laluan rendah ini menggunakan kapasitor bernilai 0.47 μ F dengan jalur lebar 10Hz. Jalur lebar perlu diset dengan teliti bertujuan meningkatkan resolusi dan had isyarat keluaran dinamik. Sistem yang sedia ada menggunakan perkakas berbeza dan perisian berbeza untuk tugas yang berbeza seperti perolehan isyarat, memprosesnya dan memaparkan ia kepada data yang dikehendaki. Dalam projek ini, sistem pengukuran yang dibina menggunakan perisian yang mampu menjalankan tugasan ini dengan serentak. Tambahan pula, sistem yang telah dibangunkan ini dapat diset dengan mudah untuk perolehan isyarat. Daripada eksperimen yang telah dijalankan, sistem pengukuran miring berjaya dibina mengukur sudut miring dengan tepat dari 0^0 ke 90^0. Sudut miring yang diukur dibandingkan dengan sudut sebenar dan formula. Isyarat getaran yang diukur dan kebolehpercayaan sistem pengukuran getaran yang dibina telah dibandingkan dengan alat ukuran komersial IMC-CS8008. Sistem pengukuran getaran ini diuji dengan frekuensi getaran bermula 5Hz hingga 500Hz dengan kadar persampelan 1000Hz, 5000Hz dan 50000Hz. Ciri-ciri isyarat getaran yg diukur dalam bentuk sinusoidal seperti puncak positif pecutan (ms^{-2}), RMS dan amplitud bagi domain frekuensi menggunakan teknik Fast Fourier Transform telah

ditentusahkan. Rumusannya, sistem pengukuran dan pengesan menggunakan MEMS sebagai penderia untuk mengesan isyarat sudut miring dan isyarat getaran telah berjaya dibina dengan jayanya.

DEVELOPMENT OF TILT AND VIBRATION MEASUREMENT AND DETECTION SYSTEM USING MEMS ACCELEROMETER AS A SENSOR

ABSTRACT

In this project, a measurement and detection system to detect tilt angle signal and vibration signal using MEMS accelerometer which has two sensed axes X and Y was successfully developed. Several issues are considered while developing the measurement system such as sensor specifications, software used for programming, device for interfacing and the flexibility of the software used. In this system the sensor specification such as low pass filter can be adjustable for intended applications. This filter is used for reducing the noise from output signal MEMS. This filter uses a capacitor valued 0.47uF with bandwidth of 10Hz. The bandwidth needs proper setting in order to improve the resolution and range of dynamic output signal. Available systems usually use different device and software for different tasks such as acquiring the output signal, processing and displaying the data into a meaningful signal. In this project the developed measurement system uses software which enables it to perform those tasks simultaneously. Moreover, the developed system can be easily set for signal acquisition. From the experiments carried out, the developed tilt measurement system can successfully measure tilt angle accurately from 0^0 to 90^0. The measured tilt angle signal are compared with real sensed angle, and the results are also compared with equation. The measured vibration signal and the reliability of vibration measurement system developed in this project are compared with commercial device IMC-CS8008. This vibration measurement system is tested under vibration frequency starting from 5Hz to 500Hz with 1000Hz, 5000Hz and 50000Hz sampling rate. The characteristics of the vibration signal measured in sinusoidal form including positive peak acceleration (ms^{-2}), RMS value and the amplitude of frequency domain using Fast Fourier Transform technique are verified. In conclusion, a measurement and detection system using MEMS as a sensor to detect tilt angle signal and vibration signal is successfully developed.

CHAPTER 1
INTRODUCTION

1.0 Overview

In this chapter, an introduction to Micro-Electro-Mechanical-System (MEMS) is firstly presented. This chapter also briefly discusses the analysis of MEMS accelerometer through simulation and the computer based measurement system. The problem definition and the thesis objectives are also highlighted. Finally, the chapter ends with the thesis outlines.

1.1 An introduction to Microelectromechanical System (MEMS)

MEMS technology is a well known abbreviation for Microelectromechanical systems eventhough there exist various names for MEMS technology such as *micromachines* used in Japan and *microsystem* in European (Henry, 2006). Although the name is different, this technology has identical prospect to make the human life better. Since the first MEMS developed in 1970s and then commercialized in 1990s, MEMS has made it possible for all kinds of system to be smaller, faster and energy-efficient and less expensive (Abbas, 2003). The advantages of MEMS depend mostly on their relatively low cost and simplicity of the devices. With the same semiconductor fabrication methods as integrated circuits (IC), thousands of MEMS can be mass produced on a single silicon wafer along with the associated electronic circuits (Madou, 1997). The trend in IC technology since the 1960s has been for the number of transistors on a chip to double every 18 months (Moore's law) and this makes MEMS technology grow better (Stephen et al, 2004).

Richard Feynman was the first person to predict about the existence of small machines with movable and controllable parts on December 29th 1959 (Mohamed, 2006). Since then, remarkable research progress has been achieved in MEMS. Nowadays, MEMS is finding increased applications in various fields. According to Yole (2006), now MEMS leads the chosen sensor especially MEMS accelerometer. On the MEMS functionality, MEMS can be broadly divided into two categories called *microsensors* in order to detect the information (i.e. acceleration signal) or called *microactuators* which act corresponding to detected information (Mohamed, 2006). MEMS accelerometer is one of the most important types of MEMS sensor, which has the second largest sales volume after pressure sensors (Yazdi et al, 1998). The large volume demand for MEMS accelerometers is due to its capability and reliability to be used in a variety of applications.

Since MEMS accelerometers has been used to sense an acceleration signal which is then applied to measure tilt, vibration or shock signal, various applications are able to be developed such as airbag in automotive industry (Tanaka, 2007), and earthquake detection in geotechnical engineering (Bernstein, 1999). Since there are various types of sensor for various applications, there is a need to select the right sensors which fit to the intended applications.

1.2 Analysis of MEMS accelerometer

One of the challenging tasks in the development of MEMS accelerometer device is designing the miniature parts and determining how they best fit together and operate properly. Parts such as fingers, folded beams and other microstructures on the same silicon chip must also survive severe shocks and vibration to adequately perform their mechanical function. Therefore, the MEMS accelerometer needs to be analyzed since MEMS device typically comprises many physical domains such as mechanical, electrical, thermal and optical. All these domains interact and affect each other.

Simulation is perhaps the best solution to carry out the analysis of MEMS model. The motivation for carrying simulation work is to see the effect of various design parameters on the device according to intended specification by the virtual design and to predict the behavior of the intended device. In simulation platform, the parameters of the device can be changed much more quickly rather than during the fabrication step itself. These advantages make the behavior of the device can be quickly understood. According to Stephen et al (2004), any MEMS simulation software use either of these two approaches: *System Level Modeling and Finite Element Modeling (FEM)*.

System Level Modeling approach captures the main characteristics and predicts the main behavior of a MEMS device, whereas *FEM* approach is originated from mechanical engineering where it is used to predict mechanical response to a load, such as forces and moments. For analysis purpose, *System Level Modeling* needs the device described by sets of ordinary differential equations and nonlinear functions at a block diagram level but for *FEM*, the part needs to be broken down into small discrete element called meshing process. Among these two tools, a *FEM* result is more realistic.

CoventorWare®, IntellSuite, ANSYS® and MEMS Pro are among the software used as the *Finite Element tool* to develop and analyze the MEMS model. Well known *Finite Element tool* is well suited for the analysis of complex geometries by dividing parts into a finite number of more simply shaped elements. CoventorWare® software is one of the MEMS simulation software and it is a fully integrated design environment for MEMS design. The latest version of the software used in this work is the CoventorWare 2006. CoventorWare® generally follows a simulation and design procedure starting with the drawing of device layout, then the definition of the fabrication flow, generating a two and three dimensional solid model, meshing the structure and analyzing the device.

Drawing of the device layout is especially suited in Designer layout editor. The 2-D layout editor is a masking design for real fabrication step and it features all angle drawing and variety of polygon creation and editing tools. The definition of fabrication flow can be done in Process Editor which the information needed to create a three dimensional MEMS device from two-dimensional mask information. Once the layout and fabrication step have been generated, *Solid Model* tool is used to build three-dimensional layout geometry from the mask files and the information from Process Editor. The 3-D model design then performs the finite element creation and generates meshes in Preprocessor. The Preprocessor is in an interactive model that enables the meshed device to be viewed in any angle and edit the 3-D model. The boundary conditions can be created here by setting the name faces or parts for interest area of the developed device.

The developed device then can be analyzed in various solvers such as MemElectro, MemMech, CoSolveMem and other specialized solvers. All these solvers use finite element and boundary element for solving the differential equations for each of the devices displacement.

1.3 Computer based measurement system

Measurement is a method to collect the quantitative information in order to understand the physical world and then to evaluate with any theory or design (Beckwith et al, 2007). In this century, most measurements are conducted by using computer instead of high cost measuring device (Bilski et al, 2002). Obviously in research fields, types of applications need different type of measurement system. Therefore by using computer based measurement, the researcher could develop their own measurement system for their intended applications.

The basic equipment for computer-based measurement system consists of sensors, a data-logger and a computer (Beckwith et al, 2007). Usually, the sensors are plugged into the data-logger circuit (e.g. DAQ) which in turn is connected to the computer. Optionally, a printer is also useful for printing out graphs on paper. The most important is a program for the computer which is needed to manage the capturing of signal from sensor to be stored, monitored and analyzed.

The purpose of the sensor is to convert a physical quantity into an electrical signal which can be translated by the computer into numerical values and graphical images (David et al, 2004). A wide variety of sensors are now available, for example, temperature, light intensity, sound level, angle of rotation, vibration, shock, position, relative humidity, pH, dissolved oxygen, pulse (heart rate), breathing, wind speed, and motion.

The term "logging" describes the measurement, collection and storage of information from sensors. A data-logger contains an electrical circuit which acts as an intermediary between the sensors and the microcomputer (Hermans et al, 2005) and (Timothy et al, 2006). Its first purpose is to ensure that the magnitude of the voltage from the sensors is made compatible with the computer to allow safe connection at a useful range of measurement. The data- logger also provides several intelligent functions:

- It can be programmed to collect data automatically.
- It contains its own memory for storing data
- It contains circuits for timing and measuring voltage

In order to use sensors for taking readings in experiment, a data-logging program must be loaded into the computer. The purpose of the program is to enable users to analyze the captured signal and then display and store the signal obtained from the sensors. The common functions of data logging program is to take reading from the sensors at regular intervals. Then the reading signal is loaded to program for display on the screen. Various types of software were used by previous researchers to develop programs which enable logging the data from sensors, process and display them. Recently, there already exist softwares which provide easy means program, less expensive, with better capabilities and flexibility such as LABVIEW® and MATLAB®.

The development of computer based measuring system not only requires basic elements such as sensor, data logger and computer but also other components such as external circuitry including resistor and capacitors to form a complete package of measuring system. This development requires throughout investigation and it is not a straight forward job. Proper analysis and experiment are also needed to be carried out so that accurate and reliable measurement system can be used for the intended applications.

1.4 Problem statements

Presently, there are various measurement systems especially to detect and analyze an acceleration signal by incorporating MEMS accelerometer as a sensor has been or is being developed with specific or intended purposes. In order to sense the output signal, each researcher has developed his/her own measurement system including different built-in algorithms, different external components and circuitry, and others. The system needs to be accurate, reliable, flexible and easy to use for intended purposes. Because of this complex nature and the uniqueness of the developed system, many issues need to be considered in the development of the measurement system. These issues include the capabilities of software used, the programming language, external circuitry, types of output signal and experimental verification. The software use needs to be programmed in order to perform multi tasking operations such as to capture, analyze and display the meaningful signal. In order to achieve this goal, the developed program needs to be tested so that the reliability functionality of the program can be investigated. Moreover different program need to be developed for different applications and subsequently this will make the integration between the device and software used is increasingly complex. Since the sensor needs an external circuitry for signal conditioning, the correct components to complete the sensor requirement need to be determined so that it is suited with the intended applications. Therefore, sensor operational ranges need to be investigated in details. Types of output signal need to be selected in order to match with the data logger and make it compatible with each other. Disturbance signal may affect the output reading. Therefore, this disturbance needs to be reduced because the system needs accurate signal input to produce the accurate meaningful signal. Experimental set up is then needed to be developed so that the measurement and detection system can be verified and the system developed can accurately measure the intended measurements.

1.5 Research objectives

There are several objectives to be achieved in this project and these objectives are listed as shown below:

- To develop a reliable system for tilt and vibration measurement using MEMS accelerometer as a sensor. This system must easily capture the signal, process the signal and display the analyzed signal by using the same programming platform and profoundly accurate measuring. It must also be simple for signal acquisition from the output MEMS accelerometer.
- To investigate the response of MEMS accelerometer sensitivity and linearity between two types of mounting method; vertically and horizontally for tilt application.
- To do simulation studies on the response of the displacement of MEMS accelerometer subjected to static and dynamic loading.

1.6 Thesis outline

This thesis is presented in five chapters which include introduction, literature reviews, methodology, result and discussion and ended by conclusions. The first chapter discusses an introduction to the Micro-electro-mechanical-system (MEMS) and their usage as sensors in various applications. Brief information on the measurement system is also discussed. This proceeds with the problem statements and thesis outline.

In Chapter two, a literature reviews for type of accelerometer with high reliabilities performance is discussed regarding the applications to measure tilt, vibration/shock signal. Several possibilities to improve measurement system were reviewed.

The methodology of research is explained in details in Chapter three. In this chapter, simulation works is carried out to analyze the MEMS accelerometer model. Meanwhile, the experimental set-up and procedure to measure tilt and vibration is also explained in details in order to test the reliability of the developed measurement system. The development of graphical programming for measurement system is described clearly in this chapter. The result from simulation and experiment is discussed in chapter four. Finally, the thesis will end with conclusion in chapter five.

CHAPTER 2
LITERATURE REVIEW

2.0 Overview

Literature review for three main scopes of the thesis is presented in this chapter. The scopes covered are shown as below:

- MEMS accelerometer
- Measurement and analysis system
- Remarks on existing measurement systems

2.1 MEMS accelerometer

MEMS accelerometers can be grouped into several types according to their sensing element such as piezoresistive, capacitive, tunneling, resonant, and thermal devices used as acceleration sensor. Among them, capacitive accelerometer has several advantages that make it very attractive for numerous applications (Yazdi et al, 1998).

2.1.1 Capacitance accelerometer as the most successful type of micro - accelerometer

Since MEMS capacitive accelerometer has several advantages for numerous applications ranging from low cost, high sensitivity, good dc response and noise performance, low drift, low temperature sensitivity, low power dissipation and simple structure (Yazdi et al, 1998) and (Bernstein et al 1999), it has been used in many applications for sensing and measurement. Various commercial capacitive MEMS accelerometers are available in the market, with similar performance specifications, but with different mechanical sensing element designs, materials, packaging, fabrication technologies and price ranges. Because of these varieties, the right choice of MEMS capacitive accelerometer should be made. Therefore once a type of MEMS accelerometer is chosen, characterization is usually carried out, so that the performance of this chosen accelerometer can be measured.

2.1.2 The ADXL202 MEMS accelerometer

Several studies have been carried out by various researchers to find and compare the best performance of available MEMS accelerometer capacitive accelerometer to detect and measure acceleration. Acar et al (2003) carried out the experiments to characterize and compare the most usually used commercial MEMS capacitive accelerometer. The MEMS accelerometer that were studied were Endevco 7290A, Analog Devices ADXL202, Silicon Designer SD2012-10 and Motorola 1220D. Under standardized tests, the performance in terms of the sensitivity, resolution, linearity, frequency response, temperature response, noise level and long term stability was investigated. The result shows that ADXL202 is one of the most recommended sensors because of the least deviation in sensitivity for DC measurement, no deviation in the 30 day period for long term stability test, and the most linear behavior after Endevco 72920A in the specified input range with the least maximum non-linearity and the least difference between positive and negative direction sensitivity. Furthermore, ADXL202 is the most versatile sensor because of the adjustable bandwidth resolution through different capacitor value used and the available output is analog and Pulse Width Modulation (PWM) type. Because the ADXL202 output is in PWM which has a special design compatible with microcontroller; Reverter et al (2005) investigated the effect of power supply on the interference rejection effect. The result shows power supply decoupling capacitors are more effective at high frequencies (30Hz and above) than at low frequencies (10-20Hz). This definition of high and low frequency is also agreed with Stein et al (2007). Therefore, by using the right capacitor value, interference effects can be avoided. Based from the above advantages, ADXL202 is the most suitable sensor which fulfills the specification needed in many respective applications especially for signal detection and measurement. Hence, this MEMS accelerometer ADXL202 is chosen in current work.

2.1.3 Use of MEMS accelerometer in measuring systems

Acceleration is well known to be the basic output for MEMS accelerometer. By capturing the acceleration signal, tilt, vibrations and shock can be detected. Then, the velocity and displacement information can also be determined from the measured acceleration. Therefore, many researchers have used and applied these signal for their respective measurement applications.

Tilt is usually applied to be used for balancing and positioning detection especially in biomedical field in order to study human movement. Lyons et al (2005), Bliley et al (2005) and Juvanov et al (2005) are among the researchers who used MEMS accelerometer for monitoring the body posture by detecting the sitting, standing, lying and trunk position. These types of posture can be distinguished by recognizing the dynamic and static activities. The dynamic activities correspond to rapid movement such as walking and running (known acceleration) while static activities correspond to sitting, standing and lying position. These static activities were studied by rotating the sensor to provide a signal output corresponding to +1g, 0g and -1g. The standard deviation was computed while rotating the sensor. If the signals analyses were above the standard deviation, the activity was considered to be dynamic and if it was below standard deviation, the activity was static. When the activity was taken as static, the mean acceleration was converted to a corresponding inclination angle. The inclination angle ranges were already calibrated for sitting, standing and lying. Therefore, the postures can be determined if the converted angle from output MEMS accelerometer matched with calibration angle. So, tilt signal generated from slow acceleration can be successfully used to monitor and measure any part of human movement especially part of body which contributes to the angular movement such as knee, hip and trunk.

Expanding the capabilities of tilt signal which are generated from slow acceleration, Zhu et al (2006) used MEMS accelerometer as a tilt input for Kinematic Kalman Filter

(KKF). This detection and measurement system is used for estimation of velocities and motion control. It is found that the accelerometer employed with KKF provides an accurate velocity estimate even with low speed. Further application of tilt signal is also used in the consumer products such as mobile phone, PDA and touch screen application (Chaturvedi, 2005). The capabilities of measuring tilt by MEMS accelerometer are used successfully to develop functions such as scrolling phone number list, navigating through menus, map scrolling and gaming. However, the method of how the signal is detected and then converted is not explained in details because of the confidential issue pertaining to the product.

Previous studies as mentioned above used acceleration tilt signal known as slow acceleration to evaluate the human movement considered to be static such as sitting, standing, lying and trunk position. Extended from these studies, there are groups of researchers who are interested to study human movement based on fast acceleration signal. Yuriko et al (2005) studied on the walking balance and stability by putting dynamic shoe insoles for those who have sport injuries to the feet or lower back. The relationship of the lower-back and knees and the rate of increase in stability were quantitatively analyzed by using two axis MEMS accelerometer. These two axis MEMS accelerometer can measure acceleration of the knee and lower back at the same time and from that, the displacement is obtained. By using these two dimensional displacements, the reciprocal spatiotemporal contributions between the lower back and knee of patients was quantitatively analyzed. Thies et al (2007) also investigated movement analysis of human parts by attaching two MEMS accelerometer on upper arm and forearm. The study compared the accelerations obtained from two commercially available MEMS accelerometer with 3D camera motion system. A pulse signal was captured from the MEMS accelerometer output and the data were analyzed within MATLAB®. The result showed the linear acceleration trajectories were closely approximated with each other.

Several researchers have broken the dominance of studying the human movement by using MEMS accelerometer. Alan et al (2002) used MEMS accelerometer to replace the mouse and keyboard known as input device for computer. This novel invention called MIDS (micro-input devices system) used MEMS accelerometer to measure multi dimensional force and acceleration for each finger and hand. For instance, signal generated from MEMS accelerometer which is attached on the fingertip can make an action such as click and draw a circular motion. Jerome et al (2002) also used MEMS accelerometer to develop wireless monitoring for structures in Geotechnical Engineering field. This research was conducted to understand structural response under normal and extreme loadings. By calculating the frequency response function, sophisticated damages for structures can be detected. Maxwell et al (2001) also used MEMS accelerometer for seismic acquisition to replace the conventional sensors; geophone. They found that extra benefits were achieved by using MEMS accelerometer such as direct digital output, inherent high vector fidelity and superior low-frequency response.

MEMS accelerometer is also very well known to be applied to activate safety system, based on shock detection. Meanwhile, there are varieties of applications based on shock detection. Williams et al (1998), Mathie et al (2003), Thomas et al (2003) and Chen et al (2005) applied MEMS accelerometer to study human movements which focus on fall detection. The fall signal occurred during the falling of the patient will generate shock acceleration. The normal activities and falling experiment were carried out in order to investigate the pattern output signal to distinguish between normal acceleration signals and shock acceleration signals. The result showed that the magnitude of shock acceleration in falling is generally greater than that in normal acceleration signal. Because of these signal characteristics, shock acceleration is also applied in critical applications such as in military studies which were carried out by Brown (2003) and Stauffer et al (2006). Colin et al (2007) investigated the use of low cost MEMS accelerometer for shock vibration based on damages detection and compared with the high performance transducers, with the subject test was

Airbus A320 aircraft. Test results were compared both qualitatively and quantitatively and excellent correlation was achieved. Thus the low cost MEMS accelerometer sensor has sufficient characteristics for use in shock detection.

The most usable and applicable feature obtained from capturing acceleration is vibration signal. Roberto (2007) used MEMS accelerometer as vibration sensor on hard disk drives. The occurrence of uncertain vibration signal will cause the off track motion of the heads of hard disk. To overcome this off track problem, Roberto (2007) used vibration signal generated from MEMS accelerometer to control the heads of hard disk to return to the right position. Keith et al (2006) also applied MEMS accelerometer in geotechnical engineering field in order to monitor the wave propagation in soils. The vibration produced from wave propagation can be detected by MEMS accelerometer. This detected signal can be used to evaluate construction progress and to avoid costly failures. Kwon et al (2006) used MEMS accelerometer for tunnel construction and maintenance to monitor the vibration during construction. The data obtained from monitoring could be used to provide a guide of modification for construction method in order to build tunnel more safely and economically. Besides, the data record may be used for the research purpose and the design of similar tunnel construction in the future. Due to the reliabilities of MEMS accelerometer, this sensor is regarded to be an enabling technology for future smart engines concepts in the Aero-Engine Industry since these devices can be applied in the harsh environment. Due to the versatility of MEMS sensors and their small size, vibrations in several parts of engines could be monitored (Grauer et al, 2004). Meanwhile in this decade, MEMS accelerometer is used widely as a sensor for the commercially available device to detect and measure vibration. According to Clifford (2005), it is forecasted that more than 100 accelerometer applications would be established soon especially for vibration. Therefore, many applications could be carried out by using MEMS accelerometer since this sensor is reliable to sense vibration which is obtained from the acceleration signal.

2.2 Measurement and analysis system

The signal detected by MEMS accelerometer needs to be converted into meaningful measurement system and the system developed needs to be analyzed. Therefore, the significance of measurement and analysis system and the work carried out is discussed in the following pages.

2.2.1 Standard elements of measurement and analysis system

A measurement system consists of three basic parts as illustrated in Figure 2.1. The sensor, in this case MEMS accelerometer is a device that converts a physical input into an output, usually voltage or PWM. The signal processor performs signal conditioning and signal analyzer on the sensor output. Finally, the computer is used to display sensor data for real time monitoring and subsequent processing.

Figure 2.1: Elements of a measurement system

Based on these elements of a measurement system, various applications as mentioned in section 2.1 take the advantages of MEMS accelerometer as a sensor to detect dynamic and static acceleration. In order to detect these accelerations, each researcher has developed his/her own measurement system which consists of different built-in algorithms for different applications.

Figure 2.2 illustrates the standard interface for hardware detection system in a typical measurement system. Generally, the system developed uses MEMS accelerometer as a sensor device in order to convert the acceleration input into an output signal represents in voltage or PWM. Then, microcontroller is programmed to capture the desired signal from the output of MEMS accelerometer. The desired signal is then sent to computer through serial or parallel cable and is analyzed by using computer. Several researchers such as Kostas et al (2003), Viktor et al (2004) and Clifford et al (2005) used this standard interface for respective applications. However, these system performances can be upgraded by using higher data rate transfer cable and appropriate microcontroller.

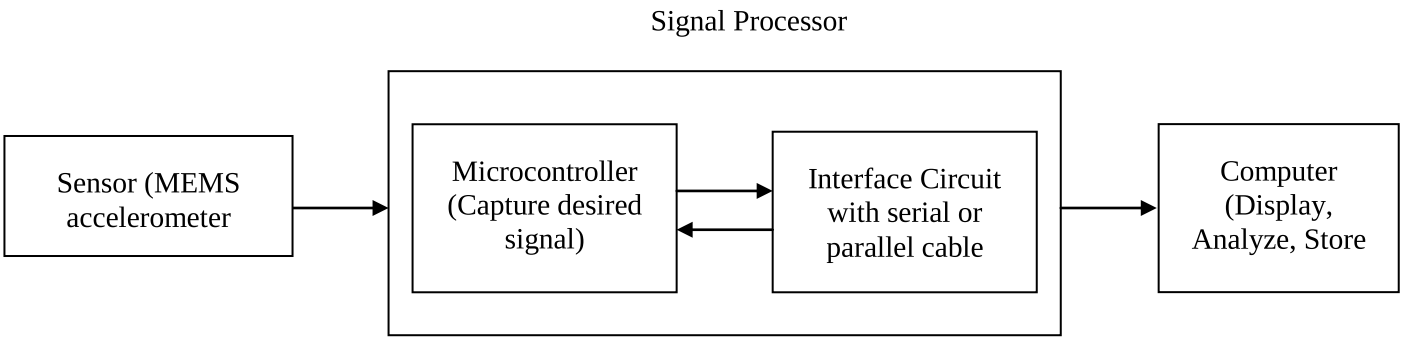

Figure 2.2: Standard interface for hardware detection system

2.2.2 Cable as a connection for interfacing between computer and hardware

Conventional cable such as serial or parallel cable known as Bus is a medium for communication between computer and external devices. In this case, external devices include MEMS accelerometer and microcontroller. Serial cable has the capability to transmit one bit of information at a time and the transfer rate is 20kilobits/s while parallel cable performs better than serial cable in which it is maximum transfer data rate is 150 kilo bits/s. However, the transfer data rate from serial or parallel cable is still weak because recently there exist variety of cable technologies such as USB that have higher data transfer rate than the conventional cable of either serial or parallel. USB (Universal Serial Bus) recently becomes the most superior technology for computer peripherals. Hi-Speed USB has a maximum transfer rate of 60 MB/s, making it an attractive alternative for instrument connectivity. The ease of connection and relatively high data rate makes this technology very useful for portable data acquisition units. One of the researchers that realized this advantage is Litwhiler et al (2004) which used USB connection to monitor the variance of temperature and tilt angle. Koutroulis et al (2003) also found this findings using serial interface (RS232) compared with USB interface for his renewable energy sources monitoring system. The comparison shows that by using cable connection, data logging lacks flexibility and serial data transmission limits the system performance if an advanced control is used. Therefore, the use of data bus transmission performance USB for computer interface nowadays becomes a necessary since it has high speed data transfer rate, smaller size of board circuit and accurate data transmission especially for real time monitoring system.

2.2.3 Data Acquisition as a device for capturing the signal

Capturing acceleration signal produced by MEMS accelerometer is one of the most important parts should be considered in developing a measuring system. Since most MEMS accelerometers are specially designed to work with microcontroller, many researchers have successfully demonstrated their system. However, there are several microcontroller limitations such as complex instructions set and the limitations of microcontroller specifications themselves. Its worst limitation is no flexibility to adding up new sensor or new featuring circuit in order to enhance the capabilities of the developed system. Moreover, it becomes more complicated if the previous circuit is suited on the same PCB. Consequently, the system circuit may need reprogram and rewiring. Therefore, most researchers are looking for new alternative to overcome these problems.

DAQ (*Data Acquisition)* provided by National Instrument is one the most favourite choice for recent researchers. Bilski et al (2002), Koutroulis et al (2003), Disilvestro et al (2004), Dastoori et al (2005), Subramanian et al (2007) and Li et al (2007) are among the researchers who used NI DAQ LabVIEW for their studies in respective application systems. The developed application systems were integrated with different module applications such as monitoring system, measurement system, control system and analysis signal system. The NI DAQ card is chosen because it offers extra benefits such as portable acquisition card (if suit with USB) and it provides 5Volt source for external circuit. In this case, this 5Volt can be used to power up MEMS accelerometer. Therefore power source from the external devices such as battery is not needed. Another important factor is that NI offers different types of input signal pin such as I/O analog, I/O digital and counter. This is very useful for interfacing between software and hardware. Moreover, a high sampling rate device is needed in order to capture the MEMS accelerometer signal since micro device generally has a small mass and large elastic modulus and high natural frequency (Wang et al 2007). Therefore NI DAQ card so far is the perfect choice according to the reliabilities and capabilities of capturing the signal generated by MEMS accelerometer.

2.3 Remarks on existing measurement systems

It is really difficult to evaluate the performance of the available measurement system and to compare them with the developed system in current study. Since the developed system is unique for the intended applications which consists of different built-in algorithms for respective applications, each researcher develops his/her own measurement system. In other words, every developed system proposed by previous researcher is uniquely developed depending on the purpose of their study. From the literature reviews it is seen that MEMS accelerometer is used as sensor to detect tilt, vibration and shock in various applications such as in health or medical products, consumer products, civil engineering, military, automotive and condition monitoring for machine failure. Therefore, it can clearly be seen that every application needs a specific system for specific objectives. Moreover, several companies already have marketed their measurement system to detect acceleration signal especially for vibration/shock. It is almost impossible to list out the limitations of the commercially available system since every available system needs to be tried and tested. However, there are some rooms for improvement that can be overcome in order to optimize the measurement system performances such as the sensor used, output signal conditioning, and software for signal processing.

2.3.1 Sensors limitations

In many available developed measurement systems, a conventional sensor which is not based on MEMS technology is still commonly used. For tilt measurement, the most popular sensor is Electrolytic. According to Puccio et al (2004), electrolytic is one of the most enduring sensor and the operating principles are still valid and these types of sensors are still in the market. Electrolytic contains an electrically conductive fluid sealed in a glass and the sensor functions like a liquid potentiometer with conducting variable resistance between the electrodes. However the total sensing range is approximately $\pm$ 70^0, compared with MEMS accelerometer which has a total range of $\pm 90^0$. Besides, since the electrolyte conducts ion current, therefore the sensor has to be powered with an ac source only in order to avoid electroplating of the electrolyte that may be damaging to the sensor. Consequently, the requirement for an ac source increases the complexity and cost of the signal conditioning (Dai et al, 1996). When compared with MEMS accelerometer especially ADXL202, ADXL202 only needs a ranges 3V-5.25V which can be taken from low cost 9VDC battery.

Due to many advantages over conventional sensor, MEMS accelerometer is used as a sensor to detect vibration/shock signal either for commercial devices or for particular developed functions. Asanuma et al (2001) has carried out the study to compare the performance of the conventional sensor and MEMS sensor under sensitivity and frequency testing. Besides the advantages in cost and size, MEMS sensor also has high sensitivity and wide band nature brought by small driving force of micro sensors. Speller et al (2004) also studied the conventional coil-and magnet based velocity transducer and MEMS sensor for unattended ground sensor (UGS) applications. Since UGS requires a compass to determine deployment orientation with respect to magnetic north, conventional sensor with sensing technology based on a permanent magnet can cause interference with a compass when used in close proximity. Besides that, this coil-and magnet based velocity transducer have a poor phase and amplitude for any signal between 0 to 10Hz. Under DC response analysis, conventional sensor shows a limited response at low frequencies due to AC coupling.

Therefore, it can be concluded that MEMS sensor is the most stable and has a potential to drastically enhance the number of applications. Now, MEMS leads the chosen sensor since the total accelerometer market value has been estimated to be $393million in 2005 and $869 million in 2010 for a production of 161M and 502M units respectively (Yole, 2006).

2.3.2 Sensor conditioning

Once the acceleration has been detected, it is necessary to modify the signal with the appropriate signal. Since the sensor element is capacitive, the sensor detects the acceleration by a change to the capacitance. However, all the external devices connected with the sensor only compatible with voltage output types. Therefore, there are needs to modify the output generated from the sensed element from capacitance form to voltage form. In order to modify the output sense, the signal should be going through the signal conditioning stage first.

MEMS accelerometer technology design features an embedded signal conditioning which includes the amplifier to amplify the signal, an oscillator to protect the system from high voltages, and a filter to create a simple first order RC low-pass filter. For the MEMS accelerometer, the most concern for the signal conditioning is the filtering circuit. Since analog bandpass filtering is very simple and requires no software when overhead from the microcontroller, most of the previous researchers using this analog bandpass filter to reduce the noise. However there are several weaknesses by using the analog band pass filter rather than digital band pass filter. Smith (2007) carried out the experiments to compare the performances between digital and analog filter. The results shows that the analog filter has a 6% ripple in the passband, while the digital filter is perfectly flat (within 0.02%). The flatness achieved with analog filters is limited due to the accuracy of their resistors and capacitors. Under frequency response on log scale, the digital filter shows better results for stop band attenuation. This can be achieved with simple modifications to the windowed-sinc for digital filter, but impossible for the analog circuit. Therefore, an approach using digital filter should be taken as a method to improve the quality of a sensed signal.

2.3.3 Software for signal processing

Microcontroller is well known device to store, compare and select the data. Microcontroller programs usually integrate with other software to perform signal analysis. However, integrating different software for capturing signal and perform signal analysis is quite complex. Therefore, microcontroller is not used in the current study. In this current study, it is intended to develop a system that has the capabilities to capture acceleration signal generated by MEMS accelerometer and at the same time can analyze the sensed signal.

Available commercial measurement systems usually develop their own embedded platforms and language programming. In related research area, in order to perform signal analysis especially for vibration, many researchers usually used well known software such as MATLAB. This is carried out by several researchers such as Lyons et al (2005) and Mclnerny et al (2003). MATLAB offers an intuitive language and a flexible environment for technical computations which integrates mathematical computing and visualization tools for data analysis and development of algorithms and applications. However, one of the disadvantages by using MATLAB is the graphical user interface needs to be programmed. Some simulations are simply too complex and time consuming to be programmed in MATLAB. Furthermore MATLAB gives quite poor performance in part of interfacing hardware and software. Therefore, current work tries to increase the graphic resolution while at the same time at least to have the same performance with other software in signal processing and definitely eases procedure for interfacing between hardware and software. Therefore, LabVIEW is used instead of MATLAB since it can overcome several disadvantages as mentioned above. Moreover, according to Kyle (2007), LabVIEW program can accomplish more in shorter period of time by working with flowcharts and block diagrams rather than text-based function calls and complicated syntax.

2.4 Summary

In this chapter, a literature review is carried out in order to investigate the research area about measurement system. The measurement system is divided into three parts such as sensor, signal processor and data display, and some related literature was discussed. Several aspects can be improved in order to overcome the several weaknesses of the available measuring system. The reviews are categorized into three parts for better reading. From the literature review carried out, it was revealed that many aspects on system development currently available can be further improved. This is highlighted in the Section 2.3. The following chapter will describe the methodology developed in carrying out the research work in this thesis.

CHAPTER 3
METHODOLOGY

3.0 Overview

In this chapter, the methodology of the research is discussed. The main topics discussed in this chapter are shown below:

- Analysis of MEMS accelerometer by using CoventorWare® software
- Hardware development
- ADXL202 calibration procedure
- Program development
- Interface set-up
- Experiment set-up and procedure

3.1 Analysis of MEMS accelerometer by using CoventorWare® Software

The analysis is carried out to investigate and understand the mechanical displacement of the MEMS accelerometer under pressure loading at the directional angle and diverse gravity accelerations. The structural analysis of the accelerometer is investigated by using the finite element package, CoventorWare® version 2006. The model of MEMS accelerometers with capacitive element is developed based on the work by Chae et al (2004) and Wong et al (2006). Further explanation about the methodology simulations works is explained in the following sections.

3.1.1 Use of published MEMS accelerometer model to do simulations works

Before modeling the MEMS accelerometer, the complete dimension and material properties are needed. Published model is used in this work in order to verify with the MEMS model built in CoventorWare® (Chae et al, 2002) and (Wong et al, 2006). The MEMS accelerometer analyzed in this research has an overall device size of

$2.2mm \times 3.0mm \times 120\,\mu m$ suspended by four folded beams, 56 pairs of comb finger in the size of $650\,\mu m$ long $\times 15\,\mu m$ width and sensing gap distance of $2\,\mu m$ as shown in Figure 3.1 and the parameters are given in Table 3.1.

Table 3.1: Input parameters of accelerometer

Length of comb finger (L_{finger})	650 μm
Width of comb finger (W_{finger})	15 μm
Number of comb finger	56 pairs
Sensing gap distance (d_0)	2 μm
d_1/d_0	6
W/I for the proof mass	2/13
Mass of device (m)	0.5 mg
Thickness of proof mass ($t_{proof\ mass}$)	120 μm
Device size	2.2 mm × 3.0 mm

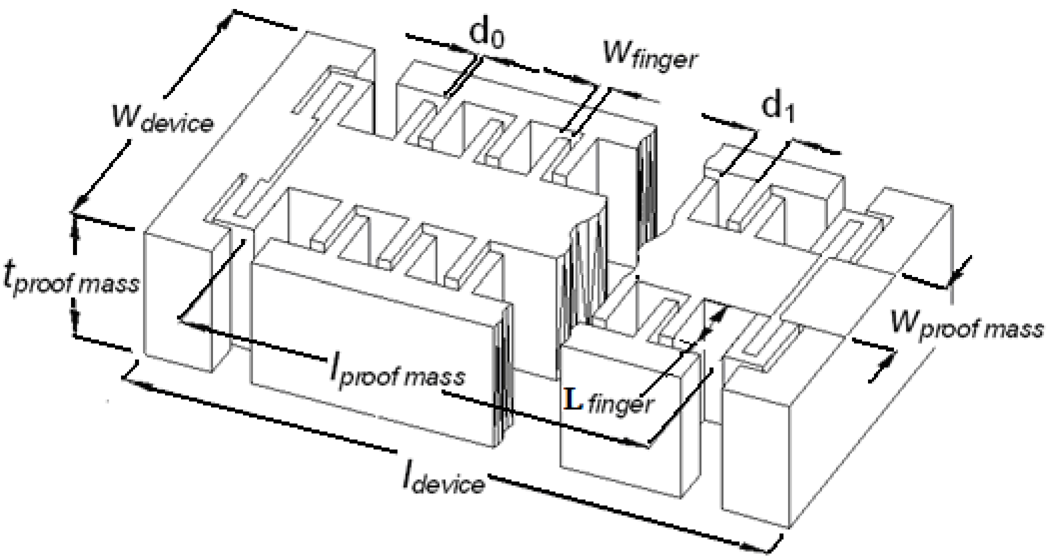

Figure 3.1: Dimensions of an accelerometer (Wong et al, 2006)