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Development and evaluation of a calibration procedure for a 2D accelerometer as a tilt and vibration sensor

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ABSTRACT

Measuring tilt and vibration are two of the major applications of accelerometers. An experimental method to calibrate a commercially available 2D accelerometer (ADXL202JQC) as a tilt and a vibration measuring device is discussed in this publication. Calibration of tilt measurements (measuring acceleration due to the gravity - the static case) was done by rotating the accelerometer in a vertical plane. Also the effect of minor inclinations of the plane rotation of this experiment was investigated and observed to be minute. Based on the calibration for the static case, the accelerometer was tested in a dynamic case. A known type of motion; the motion of a tip of a cantilever, was used to test the calibration of the accelerometer for the dynamic case. Motion of the tip of a cantilever was considered as a damping oscillation thus the variation of acceleration of the tip of the cantilever was considered a decaying sinusoidal. The measurements obtained through accelerometer agreed to this proposed model with R^2 values in the range of 0.93 to 0.98. The frequency of oscillation of the cantilever was varied by changing the length of the cantilever. The periods of oscillation obtained by the accelerometer agreed with the same values obtained from a stroboscope to maximum percentage deviation of approximately 3%.

Abbreviations:

a_x - Acceleration sensed by the accelerometer x axis (ms^{-2})
a_y - Acceleration sensed by the accelerometer y axis (ms^{-2})
DC_x - The duty cycle value given by the accelerometer x axis output
DC_y - The duty cycle value given by the accelerometer x axis output
g - Gravitational acceleration (ms^{-2})
T_s - Period of oscillation obtained by the stroboscope (s)
T_a - Period of oscillation by the accelerometer (s)

1. INTRODUCTION

Apart from measuring the acceleration an accelerometers' ability to sense acceleration can be utilized to measure a variety of quantities such as acceleration, tilt, rotation, vibration, impulse, gravity, etc. In general accelerometers find applications ranging from entertainment devices to sophisticated military devices [1], [2]. Self balancing robots, Tilt mode game controllers, Seismic monitoring systems, Car alarm systems, Crash detection/Airbag deployment systems, Human motion sensors and leveling tools are some of the end products that use the versatility of this device. In order to deploy accelerometers in these varieties of applications their performance must be evaluated in accordance with the required accuracy. Different evaluation methods have been used for evaluating accelerometers for different purposes. Gratham Pang and Hugh Liu [3], Piedrahita Andres et al [4] have suggested methods to evaluate accelerometers as an odometer for either measuring distances or as inertial navigation systems for mobile robots [4], [5]. M J Forrestal et al. has suggested a technique to evaluate the performance of an accelerometer in measuring large amplitude pulses which are in the order of 20000 g; where g is the earth's gravitational acceleration (9.81 ms^{-2}), used in projectile penetration tests [6].

Both periodic (motion of a pendulum, cantilever, etc.) and random (movement of a tire on a gravel road) oscillations which occur about an equilibrium point are referred to as vibrations [7]. There are various techniques that measure the properties; Frequency and Amplitude of a mechanical vibration, which encompass sensing of strain/stress, displacement, pressure, acceleration, magnetic flux change, etc. Sensing of these variables can be done by corresponding sensors/transducers. The frequency response is a key parameter that must be considered in such a sensor/transducer when it is to be used as a vibration measurement device. The measuring variable of a sensor/transducer has a direct impact on the frequency response. The versatility of an accelerometer enables it to be used as a vibration sensor given that the acceleration measurements are sampled at specific time intervals throughout a period of time. These logs must be processed in order to obtain the above mentioned properties; frequency and amplitude. Typical low cost accelerometers are capable of sampling the acceleration that it experiences in sampling rates ranging from 0.01 Hz to 6 kHz [3]. In order to make such a sensor function real-time, the data acquisition systems must be capable of either processing and manipulating the acceleration data to obtain frequency and/or the amplitude, in equally likely rates or either logging the data in equally likely rates to be processed later.

Accelerometers in commercially available products are either built in to the product itself or are sold as pre-calibrated mountable modules thus application of an accelerometer IC in construction or research level requires a certain calibration and evaluation technique.

The manufacturer's specifications of the device may have slight deviations due to the differences in environmental conditions. These deviations must be taken in to account in the calibration. The objective of this study is to devise a calibration and evaluation methodology for accelerometers. If the interfacing of the accelerometer is considered as a preliminary step this calibration procedure can be non device specific. The accelerometer used in this study; the ADXL202 is a low cost accelerometer produced by Analog Devices, Incorporation. It is a 2-axis acceleration sensor on a single IC chip. It is capable of measuring static acceleration as well as dynamic acceleration. Once the ADXL202 chip is implemented using the relevant hardware it has to undergo sufficient evaluation as a vibration sensor, in order to be used in specific applications. The axes selection is a crucial part of this evaluation procedure.

2. MATERIALS AND METHODS

The accelerometer used in the study is an ADXL202 developed by Analog Devices, Incorporation. It is a low cost, low power, complete 2-axis accelerometer capable of measuring accelerations in the range of ±2 g. It has 2 digital outputs (pins 9, 10) whose duty cycles and 2 analogue outputs (pins 11, 12). The duty cycles of the 2 digital outputs and the voltages of the analogue outputs are proportional to the acceleration the chip experiences along each of the 2 sensitive axes [3]. This study uses the digital outputs as the measure instead of the analogue in order to maximize the sampling rate by eliminating an analogue to digital conversion step. The accelerometer was mounted on a printed circuit board with consideration being made to the sensing axes. The sensing axes of the constructed device as a whole were selected arbitrarily since a calibration process is carried out later in the study thus minute tilts of the chip while mounting, were neglected.

2.1 Axes Selection and Calibration

The constructed circuit (accelerometer with the relevant electronics) was mounted together with the battery as a single standalone unit (the accelerometer kit). The x and y axes of this accelerometer kit was marked approximately parallel to the respective axes of the accelerometer IC which will be treated as the measurement axes. The accelerometer kit was fastened firmly to one end of a wooden bar with a suitable technique in order to reduce relative motion between the kit and the pointer. A perfectly vertical plane was selected for this experiment. A wooden board was mounted in a vertical plane with the help of a plumb-bob pair and a spirit level. The wooden bar was hinged to the centre of this vertical plane at the other end allowing the pointer to rotate about the hinge along the plane as shown in
Figure 1 which illustrates the experimental setup used for the calibration of the axes of the accelerometer kit.

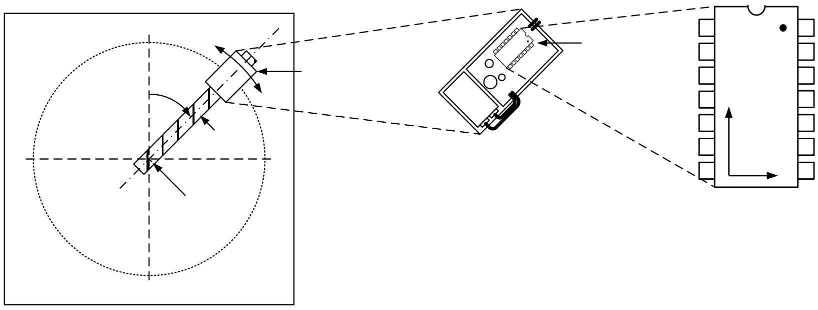

Figure 1- Accelerometer evaluation kit affixed on the vertical plane

A spirit level was used to set the wooden bar to the horizontal (θ = 90°) position in order to get the initial measurement. Rests of the measurements were obtained in intervals of 10° for a full cycle along the vertical plane. The measurements made were of duty cycles of the two output pulses that correspond to the 2 sensing axes of the IC. The experiment was repeated by keeping the accelerometer kit with an inclination of +5° or and -5° to the plane rotation (
Figure 2).

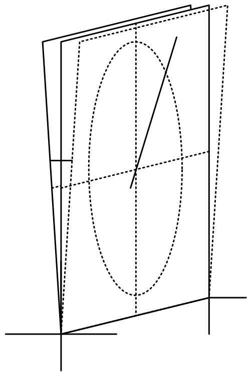

Figure 2 - Inclinations of +5° or -5°

2.2 Capturing the Movement of the Tip of a Wooden Cantilever

+5° -5°

The accelerometer kit was mounted on the tip of a wooden cantilever and it was vibrated. An indicator was affixed aligned to the equilibrium position after the accelerometer is mounted as a reference to count the number of oscillations (Figure 3). The data gathering was similar to the above experiment; the oscillations logged manually and using the PC. This experiment was repeated for 9 different cantilever lengths.

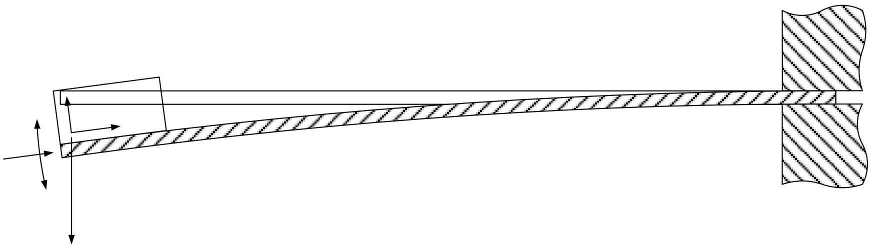

Figure 3 - The cantilever mounted on the tip of a wooden cantilever

3. ANALYSIS

3.1 Axes Selection and Calibration

Figure 4 is a depiction of the components of accelerations that the accelerometer experiences. As suggested in the diagram these accelerations can be varied by varying the angle (θ). The duty cycles for various accelerations in the range of ±1g were obtained and acceleration vs. duty cycle analysis was performed.

A_y A_x

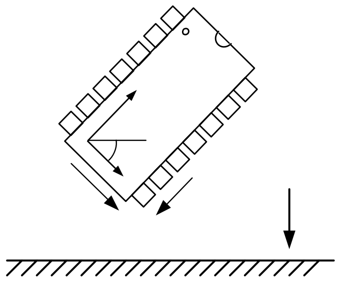

Figure 4 - Schematic of the accelerometer evaluation kit on the vertical plane

According to Figure 4 the components of acceleration experienced by the accelerometer, a_x and a_y, relative to a system coordinates which is at rest with respect to the body of the IC chip and is given by,

$$a_x = -g\cos\theta \quad \text{......} 1$$

$$a_y = g\sin\theta \quad \text{......} 2$$

As suggested by the manufacturer the duty cycles, DC_x and DC_y,

$$DC_x = m_x a_x + n_x \quad \text{......} 3$$

$$DC_x = m_x(-g\cos\theta) + n_x \quad \text{......} 4$$

Similarly,

$$DC_y = m_y(g\sin\theta) + n_y \quad \text{......} 5$$

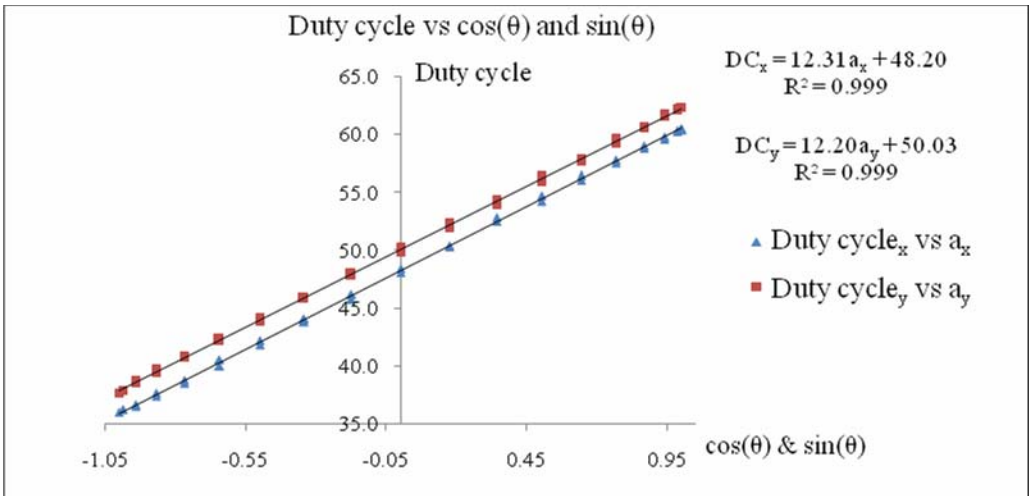

Figure 5 - Angle vs. duty cycle

The gathered data was fitted to a linear relationship between the components of gravity that the accelerometers axes experienced, and the respective duty cycles. From the graph,

$$DC_x = 12.31a_x + 48.20 \quad \text{......} 6$$

Thus for a given x axis duty cycle the x axis acceleration of the accelerometer can be obtained by

$$a_x = \left(\frac{DC_x - 48.20}{12.31} \right) g\ ms^{-1} \quad \text{.........} 7$$

Similarly for the y axis

$$a_y = \left(\frac{DC_y - 50.03}{12.20} \right) g\ ms^{-1} \quad \text{.........} 8$$

After the inclinations of +5° and -5° were introduced to the vertical plane as illustrated in

Figure 2 and the obtained data were once again plotted, fitted and analyzed similar to the previous experiment. The obtained plots were found to be almost identical to their respective non inclined variations. It indicates that the effects of inclinations of +5° or -5° were negligible. However when the plots were made on expanded scales a relationship was apparent between the curves as illustrated in
Figure 6.

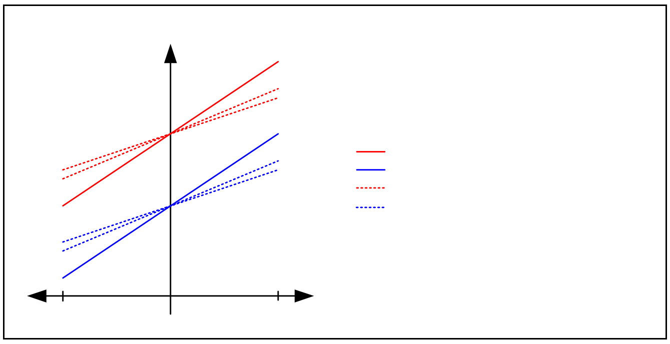

Figure 6 - Exaggerated gradients of the plots for angle vs. duty cycle with inclinations

Table 1 - Variations of the gradients and intercepts in tilting

	+5°	0°	-5°
m_x	12.29	12.31	12.27
n_x	48.18	48.20	48.21
m_y	12.16	12.20	12.15
n_y	50.05	50.03	50.05

The gradients and the intercepts related to the curves in
Figure 6 are summarized in the above table. Even though the effect of tilting the accelerometer had a minute affect on the readings it was clearly visible that the gradients corresponding to y axis acceleration variations had a maximum of 12.20 at the vertical position and the inclinations reduce this gradient by a 0.04 for +5° and a 0.05 for -5° (a variation of about 0.4 %). Similarly the gradient corresponding to the x axis acceleration variations had a maximum of 12.31 at the vertical position. A decrease of around 0.4 % in this gradient was observed for inclinations of both +5° and -5°.

Duty cycle vs cos(θ) and sin(θ)
Duty cycle

3.2 Capturing the Movement of the Tip of a Wooden Cantilever

The sampling rate of the data acquisition system is 81.73 samples/s. The variation of acceleration at the tip of a cantilever was obtained for known periods of time. These variations were obtained for 9 cantilever lengths. The cantilever displayed damping oscillations; thus the obtained acceleration variations were fitted to a decaying sinusoidal model.

$$a(t) = ae^{-bt}\sin(\varpi t + \phi) + c \qquad \ldots 9$$

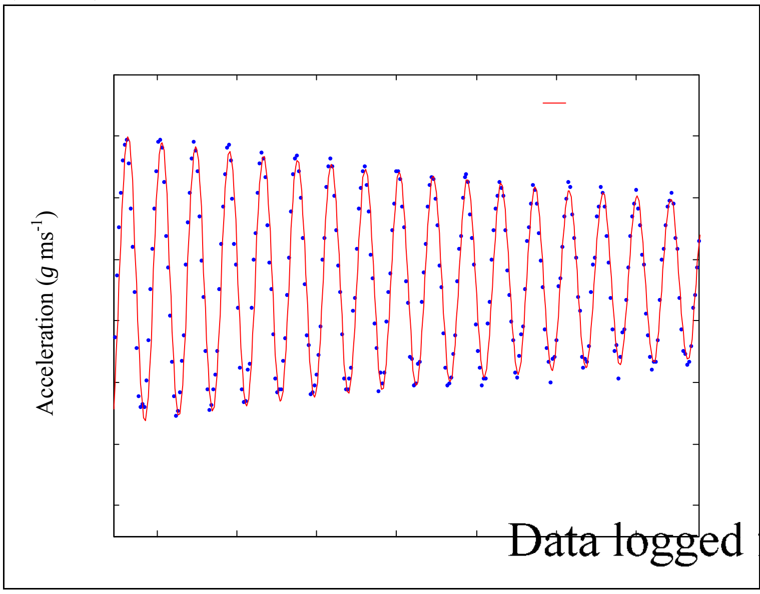

Figure 7 - Data logged from the accelerometer fitted to a decaying sinusoidal

An example for a fitted curve is displayed on
Figure 7. The data obtained by the accelerometer were fitted to the proposed model with R^2 values as follows.

Table 2 - Frequencies and respective periods obtained by the two methods

Cantilever length	ω (fitted curve)	$T_a = \omega/2\pi$ (accelerometer)	R^2	$T_s = f^{-1}$ (stroboscope)	$(\lvert T_a - T_s \rvert / T_a)\times 100\%$ Percentage deviation
63 cm	37.0319	0.16967	0.9319	0.17107	0.82%
73 cm	29.5127	0.2129	0.9708	0.21976	3.12%
76 cm	29.43915	0.21343	0.9700	0.21433	0.42%
83 cm	23.64449	0.26574	0.9804	0.26303	1.03%
86 cm	23.54641	0.26684	0.9631	0.27501	2.97%
89 cm	23.45651	0.26787	0.9303	0.27199	1.51%
93 cm	19.09213	0.3291	0.9815	0.33025	0.35%
96 cm	19.02674	0.33023	0.9812	0.33359	1.01%
99 cm	18.96136	0.33137	0.9413	0.32883	0.77%

The frequencies were obtained by the fitted curves, and the periods of oscillation were calculated. Since the experiment was conducted in order to evaluate the accelerometer a set of values for time periods of oscillation, for the 9 cantilever lengths were also

obtained using the stroboscope. The results obtained from the stroboscope are also given in
Table 2 along with the results obtained from the fitted curves. The percentage variations of time periods are calculated using the two values. According to the obtained values the maximum percentage deviation is around 3%.

4. DISCUSSION

The accelerometer calibration was conducted using earth's gravitational acceleration. The parameter measured was the duty cycle of the output signal. Based on data obtained by varying the accelerations along the two axes of the accelerometer two relationships were obtained to transform the output duty cycle in to acceleration along each axes. According to the relationships the duty cycle of the studied y axes signal displayed a variation of 12.31 % per 1 *g* while the x axes signal displayed a variation of 12.20 % per 1 *g*, instead of the given 12.5 % per 1 *g* variation given by the manufacturer. The duty cycles that correspond to 0 *g* on y and x axes also displayed slight shifts of -1.80 % and +0.03 % respectively from the manufactures value of 50 %. The variation of the accelerometers duty cycles was logged, with respect to time in order to observe the acceleration variation of the tip of the vibrating cantilever. The data acquisition system used was capable of logging the duty cycle data from the accelerometer kit at a rate of 81.73 samples/s. The vibration measurements of the cantilever were also obtained using the stroboscope which was used to validate the data from the accelerometer. Once the experiment is setup according the
Figure 3 it was observed that in the equilibrium position the accelerometer is slightly tilted due to the bending of the cantilever by the weight of the accelerometer kit. Therefore the decaying harmonic displayed a variation centered on a value less than 1 *g*. (In case of no tilting the accelerometer axes will be aligned with the earth's gravitational acceleration and will give a value of 1 *g*). This equilibrium position acceleration (the static acceleration) can be obtained by the c values of the proposed decaying harmonics (Equation 9) of fitted curves. The frequencies obtained from the two methods displayed considerable deviations but the periods being the reciprocal of the obtained frequency, displayed very little deviations.

5. CONCLUSION

Even though the manufacturer proposes that both axes are identical in sensing acceleration a noticeable shift was seen experimentally. Both of the axes displayed a similar variation in duty cycles with respect to the change in acceleration but at 0 *g*, x axis gives a slightly higher duty cycle than that of the y axis. This defect must be taken in to account especially when using this device for accurate measurements. The vertical case gives the maximum gradient for the acceleration to duty cycle relation and either the inclination or a declination of an equal angle decreases the duty cycle consistently. Thus the accelerometer cannot distinguish between inclinations and declinations; hence it is impossible to employee this two axes accelerometer to make tri-axial measurements. Thus the data obtained from the accelerometer proved to be in agreement with the stroboscope values. It can be concluded that the documented methodology has calibrated the accelerometer properly. Furthermore it can be noted that this technique is independent of the type of the accelerometer (analog or digital) and the format of the output. Since the methodology does not require any device specific features this technique can be used to calibrate and evaluate any accelerometer.

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REFERENCES

1. Yiannakopoulos G. and Van der Schaaf P.J. (1998). Evaluation of accelerometer mechanical filters on submerged cylinders near an underwater explosion, *Shock and Vibration*, *5 (4)*, 255-265.
2. Amarasinghe R., Viet Dao D., Toriyama T. and Sugiyama S. (2007). Development of miniaturized 6-axis accelerometer utilizing piezoresistive sensing elements., *Sensors and Actuators*, *A 134*, 310–320.
3. ADXL202: Low-Cost ±2 g Dual-Axis Accelerometer with Duty Cycle Output. (Analog devices, Inc.) Retrieved November 26, 2008 from Analog devices, Inc.: http://www.analog.com/en/mems-and-sensors/imems-accelerometers/adxl202/products/product.html#specs
4. Andres P., Guayacundo G. and Marcela D. (2006). Evaluatin of accelerometers as inertial navigation sysytems for mobile robots., *IEEE 3rd Latin American robotics symposium*, *26*, 84-90.
5. Pang G. and Liu H. (2001). Evaluation of a low-cost MEMS accelerometer for distance measurements., *Journal of intelligent and robotic sysems, 30*, 249-265.
6. Forrestal M.J., Togami T.C., Baker W.E., and Frew D.J., (2003). Perfoermance evaluation of accelerometers used for penetretion experiments., *Experimental Mechanics*, *43 (1)*, 90.
7. *Vibration*. (2008, November 14). Retrieved November 26, 2008 from Wikipedia: http://en.wikipedia.org/wiki/Vibration