COMPARATIVE ANALYSIS OF DYNAMIC RESPONSE OF A MODEL BUILDING USING SMARTPHONE ACCELEROMETER APPLICATIONS

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Abstract- Many smartphones offer a wide array of inbuilt sensors capable of recording acceleration responses. This has a promise of applications in a range of fields. High-storey buildings subjected to varying base excitation is one such example. This study investigates the possibility of monitoring the dynamic responses of buildings subjected to base excitation and compares a number of Smartphone Application responses in this regard against the responses of an accelerometer of significantly higher specification recording the same responses. The work also investigates the possibility of these cheap Smartphone Applications to assist or replace high-specification devices. The tests are carried out on a model 6-storeyed building in a laboratory environment for different frequencies and amplitudes of excitation.

Keywords- Smartphone Applications, Accelerometer, Base Excitation, Sensors, Model Building, Vibration

I. INTRODUCTION

According to a recent estimate, there are around 2.6 billion Smartphone users and this number is expected to reach 6.1 billion by 2020 [1]. The number of Smartphones available in the market have coincided with a corresponding increase with Applications (also known as Apps) used for a vast range of purposes. A significant number of Smartphones have in-built sensors (barometer, accelerometer, gyroscope, etc.) which have the ability to detect various physical phenomena like motion, sound, temperature, light and magnetic field [2]. These Smartphone Applications have already been used for pulse rate detection [3], skin galvanometry [4], blood pressure monitoring [5], body posture monitoring and fall detection applications [6], traffic and road condition monitoring [7], intelligent building monitoring [8] and metal detection [9]. Moreover, these smartphones can be connected to other devices through various wireless interfaces, such as, Wi-Fi, Bluetooth and Near Field Communication (NFC).

[10] Different sensor configurations can be assimilated in Smartphones that are being produced by various device manufacturers [2]. Due to worldwide portability and availability, the possibility of using Smartphone Applications as an aid to or even a substitute to expensive gold-standard sensors is a topic that is relevant for investigation [11]. The credibility and the accuracy of these inexpensive Applications seem to be the main criticism in this regard and there is a lack of formal studies in this domain. Benchmarking exercises may help in addressing this issue to a certain extent and even delineate the boundaries for successful use of Smartphone applications.

The accelerometer is a built-in component that measures the acceleration of any Smartphone. Due to a range of filters that the developers use for assessing any vibrational movement through accelerometer sensors fitted in the Smartphone, the accurate and precise value is obtained only by a few Smartphone Applications. High rise buildings can be subjected to base excitations originating from ground movement due to earthquake or other anthropogenic activities (e.g. explosion). Visual inspections can be carried out in this regard but are prone to errors, uncertainties and high costs. On the other hand, long-term continuous monitoring can lead to difficult installation and even higher costs of operation. This paper presents a laboratory study on a six-storey model building subjected to base excitation, where the acceleration response of the building has been measured using various Smartphone Applications and have been compared against a high specification accelerometer at the same location. The aim of this work is to provide a comparative overview highlighting the credibility and the accuracy of smartphone based Applications for purposes of monitoring buildings subjected to base excitation. The results indicate the feasibility of using Smartphone Applications under certain circumstances and emphasize the requirement for carrying out detailed study in this direction.

II. METHODOLOGY

2.1. Mobile Description

The smartphone chosen for the experiment was Moto G (first generation) which carry Android operating system. Moto G packs a Quad-core 1.2 Ghz Cortex-A7 CPU, 4.5 inches IPS LCD Capacitive touchscreen

with an Android v5.1.[12] Moto G has an inbuilt tri-axial accelerometer that allow flexibility in how the content is viewed on the screen[13].

2.2. Description and selection of Smartphone Accelerometer Application

The Android platform supports about 1.9 million Applications for varied purposes. [14] Out of them a few Applications involve motion sensor detection. So, initially a huge database of about 90 Smartphone Applications was made. These Applications were capable of measuring the variation in acceleration. An initial calibration exercise was done in which the accuracy of the Application was tested by simply measuring the downwards acceleration due to gravity (g-force) when the smartphone was kept stationary. Based upon the range and the precision offered by the various Applications and upon the facility of obtaining and storing of the data obtained, 8 Applications were selected. Following table provides the descriptive information about these Applications.

Table 1: Description of the selected Smartphone Accelerometer Applications

APPLICATION	DEVELOPER	RANGE	PRECISION	S.F.	PSEUDONYM
Accelerometer Monitor	Mobile Tools	-5g to 5g	0.01	50	Newshell
Sensor Kinetics Pro	Innoventions Inc	-2g to 2g	.00001	25	Kinetic
Physics Toolbox Accelerometer	Vieyra Software	-6g to 6g	0.01	100	Physics
Accelerometer Monitor	Keuwlsoft	-10g to 10g	0.01	100	BGR
Vib Sensor	Now Instrument n Software	-gto g	.00000 1	100	Vibsensor
Accelerometer	ADDA Mecatronics	-3g to 3g	0.001	15	3Wings
G-sensor Logger	Peter Ho	-4g to 4g	0.0001	50	G-Sense
Accelerometer Toy	Chris Pearson	-2g to 2g	0.0001	100	Toy

Where S.F. is the Sampling Frequency

2.3. Test Set Up

Experimental model of a six- storey building was designed and built as shown in Figure 1a. The experimental model of the building consisted of six floor plates of dimensions 400mmx250mmx300mm with 4 rectangular columns of same size with cross-sectional dimensions of 20mmx20mm. The total height of the building was 1800mm. The plates and the columns of the building were suitably welded together to form rigid joints. The combined model was attached to a 4 mm thick base plate by welding. The dimensions of the base plate were 600mmx350mm. 435 MPa High Strength Steel with a 210 GPa modulus of elasticity was used to build all the columns.

The Smartphone was placed on the third floor of the building and was kept in a stationary position with the help of holding device as shown in Figure 1b. The sensor was similarly placed on the same floor.

A mechanical shaker was used to apply base excitation to the model. The shaker platform is capable of detecting independent translations in the horizontal direction.



Fig 1a: Test Building **Fig 1b: Holding Device**

III. EXPERIMENTAL PROCEDURE

The baseline sensor and the smartphone (which was held stationary by the designed holding device) were mounted on the third storey of the structure which was further mounted over the shake table. A sine wave of increasing frequency (keeping the amplitude same) was applied as a base excitation. Moreover, dependence of their feasibility on amplitude of the wave was further checked by increasing the amplitude of the wave at the constant value of the frequency. All the selected eight Smartphone Applications were subjected to three sets of readings: 1. Wave Excitation of 2 Hz frequency and 0.05 m amplitude; 2. Wave Excitation of 3 Hz frequency and 0.05 m amplitude and; 3. Wave Excitation of 2Hz frequency and 0.1 m amplitude.

A Bruel & Kjaer Deltatron Accelerometer Type 4507 was used as a high specification baseline device. The sensor was connected to the computer; where the vibration readings were recorded on Pulse 18.1 Software. The shaker was excited at a certain frequency with particular amplitude and the resulting vibrations were recorded in the Smartphone using various Accelerometer Applications. The process was repeated for all of the Smartphone Applications for 3 sets of the readings. Finally, a comparison of the Applications is presented against those recorded by the baseline accelerometer.

IV. RESULTS

The following figures show the responses of the vibrations recorded by Conventional Sensor, marked as Ideal and that by other Smartphone Accelerometer Applications, marked by respective pseudonym.

4.1. Sweep Test

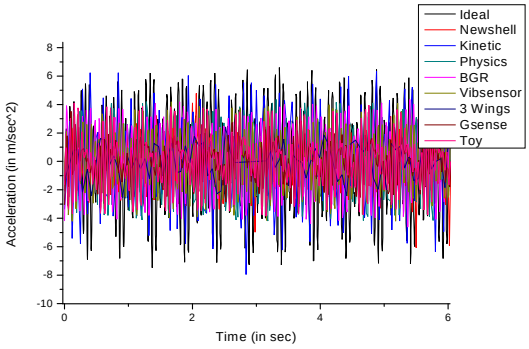


Fig. 2: Results of excitation of frequency of 2 Hz and amplitude of 0.05m

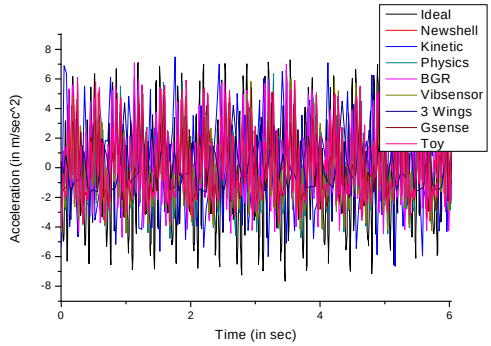


Fig. 3: Results of excitation of frequency of 3 Hz and amplitude of 0.05m

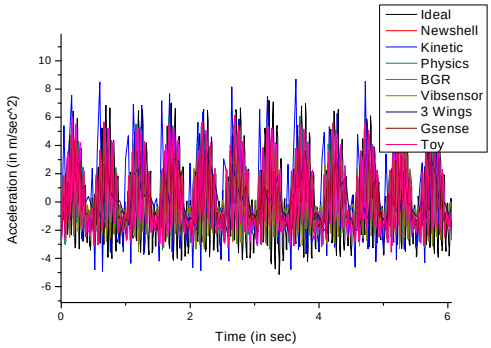


Fig. 4: Results of excitation of frequency of 2 Hz and amplitude of 0.10 m

4.2. Frequency Response Functions

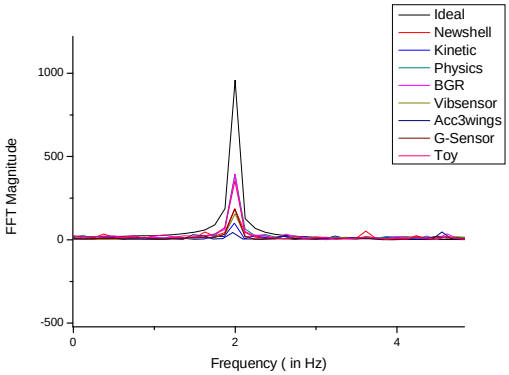


Fig. 5: Results of excitation of frequency of 2 Hz and amplitude of 0.05m

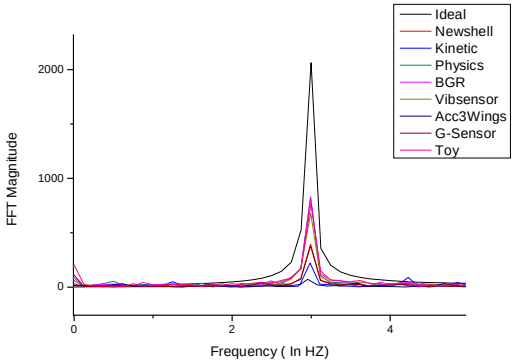


Fig. 6: Results of excitation of frequency of 3 Hz and amplitude of 0.05m

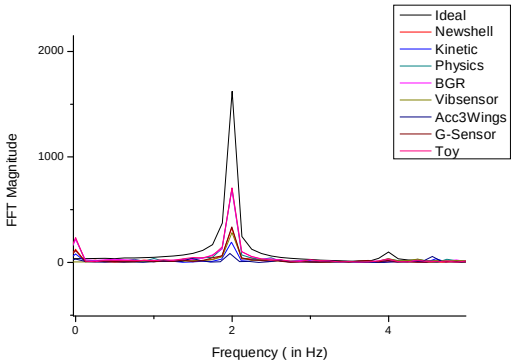


Fig. 7: Results of excitation of frequency of 2 Hz and amplitude of 0.10m

4.3. Statistical Analysis

A comparative study of Accelerometer Applications and the sensor was conducted to examine the accuracy and sufficiency of these Applications. The standard deviation of both the Accelerometer Applications and sensor was calculated for all of their readings. Reading of the sensor was taken as the base value and the normalised mean was determined.

Excitation of frequency of 2Hz and 0.05m Amplitude

Reading	Mean	Standard Deviation	Normalised Mean	Normalised Standard Deviation
Ideal	0.00876	3.34457	1	1
Newshell	-0.05144	1.62649	-5.872146119	0.486307657
Sensor Kinetic	0.04254	3.50426	4.856164384	1.047746048
Physics Toolbox	0.02288	2.16357	2.611872146	0.646890333
BGR	0.00215	2.12267	0.24543379	0.634661556
Vibsensor	0.00353	1.98719	0.402968037	0.594154107
Acc3Wings	-0.05039	1.20512	-5.752283105	0.360321357
G-Sensor	0.02954	1.26449	3.372146119	0.378072518
Toy	0.03213	1.74204	3.667808219	0.520856194

Table 2: Excitation of frequency of 2 Hz and 0.05m amplitude

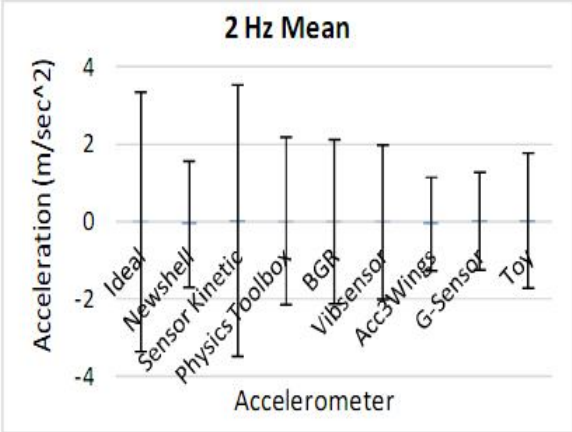


Fig. 8(a): Plot of variation in acceleration recorded by different Smartphone Applications for the frequency of 2Hz and amplitude 0.05m and corresponding mean and standard deviation

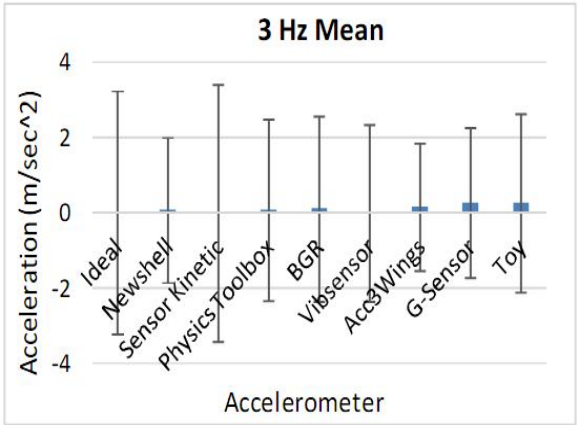


Fig. 9(a): Plot of variation in acceleration recorded by different Smartphone Applications for the frequency of 3Hz and amplitude 0.05m and corresponding mean and standard deviation

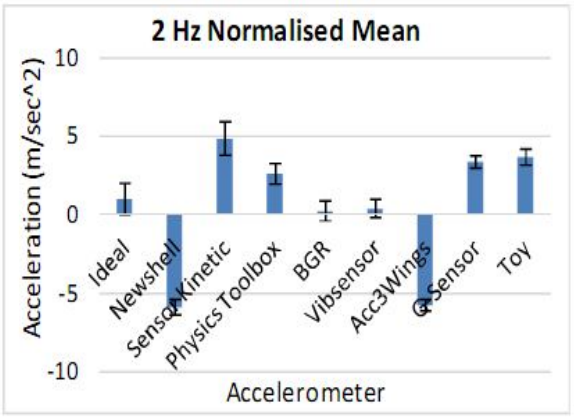


Fig. 8(b): Plot of variation in acceleration recorded by different Smartphone Applications for the frequency of 2Hz and amplitude 0.05m and corresponding normalised mean and normalised standard deviation

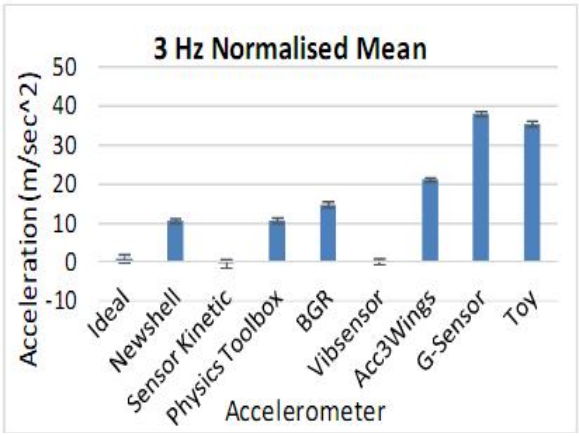


Fig. 9(b): Plot of variation in acceleration recorded by different Smartphone Applications for the frequency of 3Hz and amplitude 0.05m and corresponding normalised mean and normalised standard deviation

Excitation of frequency of 3Hz and 0.05m Amplitude

Reading	Mean	Standard Deviation	Normalised Mean	Normalised Standard Deviation
Ideal	0.00727	3.23023	1	1
Newshell	0.07661	1.92917	10.53782669	0.597223727
Sensor Kinetic	-0.00273	3.41466	-0.375515818	1.057095006
Physics Toolbox	0.07775	2.41987	10.69463549	0.749132415
BGR	0.10726	2.47232	14.75378267	0.765369649
Vibsensor	8.38E-04	2.34889	0.11524663	0.727158747
Acc3Wings	0.15386	1.69087	21.16368638	0.52345189
G-Sensor	0.27664	1.98642	38.0522696	0.614946923
Toy	0.25764	2.37014	35.43878955	0.733737226

Table 3: Excitation of frequency of 3 Hz and 0.05m amplitude

Excitation of frequency of 2Hz and 0.10m Amplitude

Reading	Mean	Standard Deviation	Normalised Mean	Normalised Standard Deviation
Ideal	0.01739	2.75155	1	1
Newshell	0.30778	1.75254	17.6986774	0.636928277
Sensor Kinetic	0.39851	3.60237	22.9160437	1.309214806
Physics Toolbox	0.27933	2.29596	16.0626797	0.834424234
BGR	0.27405	2.30937	15.75905693	0.83929785
Vibsensor	0.00708	1.95719	0.407130535	0.711304537
Acc3Wings	0.27864	1.52497	16.02300173	0.554222166
G-Sensor	0.28212	1.76963	16.22311673	0.643139321
Toy	0.29613	2.32378	17.02875216	0.844534899

Table 4: Excitation of frequency of 2 Hz and 0.10m amplitude

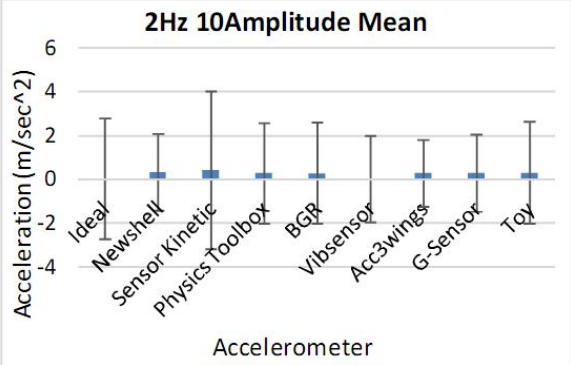


Fig. 10(a): Plot of variation in acceleration recorded by different Smartphone Applications for the frequency of 2Hz and amplitude 0.10m and corresponding mean and standard deviation

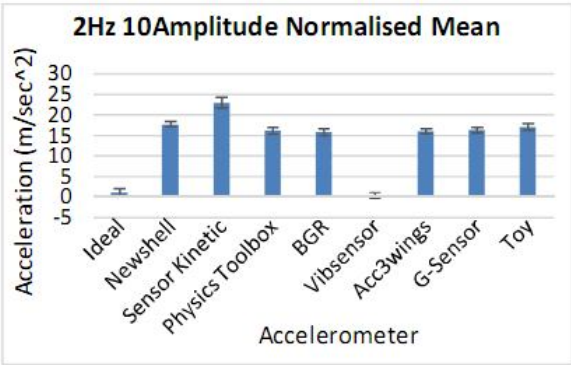


Fig. 10(b): Plot of variation in acceleration recorded by different Smartphone Applications for the frequency of 2Hz and amplitude 0.10m and corresponding normalised mean and normalised standard deviation

DISCUSSIONS

MicroElectroMechanical Systems (MEMS) are the sensors which combine microelectronics and micromechanical structures. The MEMS technology is needed for the development of the sensors, such as accelerometers, gyroscopes and magnetometers [15]. The Application developers have aptly used this technology to design the Applications. It is observed from Figs 5, 6, and 7, the Fourier Transform of the time domain responses recorded by all Applications correctly correspond to the frequency to which they were excited. Notwithstanding the disturbances, all the Applications coincided to a sharp peak at the exciting frequency. The results obtained from the above 3 sets of readings suggest that Vibsensor Application could be useful based on its relatively close match with that responses recorded by the baseline accelerometer. As per the Table-2 corresponding to the statistical analysis for the excitation of frequency of 2 Hz, the results obtained by Vibsensor Application were within the range of 60% from the ideal reading which increased to 90% when the frequency of excitation was increased to 3 Hz (Table-3).

It was observed for most of the Applications that with increase in the frequency of the vibration, the deviation from the ideal values or the error recorded in the data obtained by the smartphone increased singificantly which is quite evident from Table-2 and Table-3. If we consider the case of Physics Toolbox Application, the error in the recorded data is 261% for the excitation at a frequency of 2 Hz which increases to approximately 5 times of the previous error and becomes 1069%, when the frequency of the excitation is increased to 3 Hz.(Figs 8(a),8(b),9(a) and 9(b))

A similar trend of amplification of error could be observed when the amplitude of the vibration of shake table was increased i.e. as the amplitude was increased error in the recorded data gets increased. If we consider Table-2 and Table-4, the error of 261% in the recorded data get amplified by approximately 8 times of the previous value and becomes 1606% in the case of Application Physics Toolbox (Fig 8(a),8(b),10(a) and 10(b)).

CONCLUSION

A smartphone may be contemplated as ‘‘a computer linked to sensors’’ [16]. The modern smartphones could be employed as the measurement instruments in various field due to various sensors mounted on it [17]. Taking advantage of their portability and ubiquitous presence in our lives, they could be used in the field of Structural Dynamics to measure the intensity and magnitude of the vibrations experienced by the building structures.

This paper presented a comparative study of a number of Smartphone accelerometer Applications amongst themselves and against a baseline high specification accelerometer when a six-storey model building was exposed to base-excitation by a mechanical shaker. One of the accelerometer Applications was observed to be helpful in aiding the high specification accelerometer while none where observed to be in a position to replace the performance of the high specification accelerometer. This study provides a basis to investigate such Smartphone accelerometer Applications for a wider range of testing and comparison. Additionally, the possibility of these cheap Applications being able to assist a high specification accelerometer opens up the debate of using a number of cheaper sensors to replace a gold-standard sensor even further. Finally, the study also encourages further work in understanding under what circumstances these Applications are helpful and if a full-scale deployment is possible for useful purposes.

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