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Comparison of smartphone accelerometer applications for structural vibration monitoring

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Abstract. Recent generations of smartphones offer accelerometer sensors as a standard feature. While this has led to the development of a number of related applications (apps), there has been no study on their comparative or individual performance against a benchmark. This paper investigates the comparative performance of a number of smartphone accelerometer apps amongst themselves and to a calibrated benchmark accelerometer. A total of 12 apps were selected for testing out of 90 following an initial review. The selected apps were subjected to sinusoidal vibration testing of varying frequency and the response of each compared against the calibrated baseline accelerometer. The performance of apps was quantified using analysis of variance (ANOVA) and test of significance was carried out. The apps were then compared for a realistic dynamic scenario of measuring the acceleration response of a bridge due to the passage of a French Train à Grande Vitesse (TGV) in a laboratory environment.

Keywords: accelerometer; mobile app; train-bridge dynamics; experimental data; analysis of variance (ANOVA); fast fourier transform (FFT)

1. Introduction

The prevalence of smartphones and modern society's reliance on smartphone applications (apps) cannot be overestimated. In 2014 alone, sales of smartphones to end users totalled 1.2 billion units, an increase of 28.4% on 2013, and represents two-thirds of global mobile phone sales (Garter 2015). With each new generation of smartphones, there is an increasing array of powerful embedded sensors, such as microphones, cameras, global positioning system (GPS) receivers, accelerometers, gyroscopes and light sensors (Liu 2013). Such sensors detect changes or events in the environment, such as sound, acceleration, temperature or gyroscopic placement and provide an output through the smartphone device (Daponte *et al.* 2013). Due to the open and programmable nature of modern smartphones, software developers have the ability to access such sensors to develop sensing apps, which are increasing in functionality and complexity (Lane *et al.* 2010). While sensor-equipped smartphones with accompanying apps have the potential to revolutionize many sectors of engineering, including biomedical engineering (Steinhubl *et al.* 2015, Song *et al.*

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2014) through detection of conditions such as eye disease (Giardini *et al.* 2014) and heart rate monitoring through electrocardiogram (Haberman *et al.* 2015), debate has arisen over the issue of their reliability.

The accuracy of utilising such smartphone sensing apps and their ability to replace more expensive scientific instruments (Kronbauer *et al.* 2012) has currently been investigated for a wide range of applications. Current apps are being developed in areas such as transport mode recognition (Hemminki *et al.* 2013), traffic safety measurements (Guido *et al.* 2012) and car accident detection with the provision of situational awareness to emergency responders (Thompson *et al.* 2012), as well as a number of applications pertaining to dynamics, such as for earthquake detection (Reilly *et al.* 2013, Dashti *et al.* 2014). The use of such apps as a replacement for more established sensing equipment can only be justified once extensive calibration exercises have been carried out and details such as precision, range and data storage capability are defined. Studies into the use of smart sensing apps have thus far been limited, with relatively few calibration studies been conducted despite the wide range of applications for which such apps could be used for in the field of civil engineering (Sharma and Gupta 2014). One such study involved the evaluation of smartphone apps for sound measurement, which concluded that certain apps, once calibrated, may be appropriate for use in occupational noise measurement (Kardous and Shaw 2014). Smartphones have been used to estimate of the mass and stiffness of a model structure utilising a smartphone acceleration app (Le and Yu 2015). The performance of three smartphones was investigated for applications arising from the response of structures subjected to earthquake loadings (Feng *et al.* 2015). This study is very relevant in terms of warranting further investigations into potential applications of smartphones for civil infrastructure, especially when there are concerns around their condition globally (Pakrashi *et al.* 2018) and cheaper or rapid monitoring options are important for the stakeholders of such infrastructure (Znidaric *et al.* 2011, Cahill *et al.* 2018).

A recent study into the use of a smartphone for structural health monitoring (SHM) of civil infrastructure proposes using a single app which is developed to access the sensors of an iPhone for monitoring structures (Yu *et al.* 2012). An external sensor board which has been developed to be attached to a smartphone for such monitoring has also been proposed (Yu *et al.* 2015b), as has the use of cloud based monitoring, whereby structures are monitored using the inbuilt sensors and transmitted to a centralised source (Zhao *et al.* 2015c). The use of a specially created app has shown to be accurate in monitoring the dynamic response of a bridge structure (Zhao *et al.* 2016). Estimation of cable tension forces for bridges (Zhao *et al.* 2015a, Zhao *et al.* 2015b) have been carried out with smartphones with some success and the possibility of using smartphones for bridge monitoring has received initial discussions (Morgenthal 2012). Initial studies have demonstrated some initial evidence around SHM using smartphones (Yu *et al.* 2015a) and an attempt to create phase space using a smartphone (Monteiro *et al.* 2014) has been investigated. Despite the recent interest in smartphones for assessing or monitoring dynamic responses of structures, the accuracy of commercially available apps which utilise the inbuilt sensors of smartphone is yet to be established or compared on the same hardware platform. Issues and challenges in relation to using smartphone for measuring and monitoring vibrations have been discussed in this regard (Höpfner *et al.* 2013). These existing studies indicate that at least under limited circumstances, individual smartphone apps might be used to enhance testing schemes and influence measurement strategies (O'Donnell *et al.* 2015) and can be used in conjunction with efficient algorithms related to energy saving for monitoring purposes (Srbinovski *et al.* 2016). While most studies concentrate till date on the effects of performance of different mobile phones, there is not enough work till date on investigating the varying performance of acceleration measurement when the phone and other hardware aspects are kept constant as reasonably as possible, and for varying test setups.

This paper addresses the abovementioned issues and opportunities through the investigation of the accuracy of smartphone apps for vibration monitoring of civil structures. A number of apps are selected and their performance is investigated against a reference accelerometer of significantly higher specification for a range of frequencies. The results are statistically examined to quantify their variability and assess comparative performance. Performance of the apps is compared when subjected experimentally in a laboratory environment to acceleration data from a train traversing a bridge. It is expected that this study will contribute to the evidence base around the applicability and limitations for smartphone accelerometers and will stimulate an interest towards understanding variabilities from choosing different apps from various providers.

2. Selection and experimental setup of accelerometer apps

The smartphone chosen for this investigation was the Motorola Moto G (1st Generation) with a Quad-core 1.2GHz Cortex-A7 CPU, Android v5.1 operating system with inbuilt tri-axial accelerometer, with +/- 2g with 12 bit resolution and a typical sensitivity of 1024 counts/g. A total of 90 acceleration measurement apps were initially chosen for the Android platform. Subsequently, three criteria were established to select the best candidates for monitoring vibrations of civil structures. The criteria which were to be met were:

1. Data storage: Apps which did not possess storage capacity of the measured acceleration response were discounted.
2. Tri-axial Capability: Apps which were uniaxial only were discounted.
3. Static Calibration: Apps which failed to register a negative G force accurately under static conditions upon the smartphone being inverted were discounted.

A total of 12 apps satisfied all three criteria in the initial list of 90 apps and were selected for further investigation, with the selected apps outlined in Table 1.

Table 1 Details of selected accelerometer apps

Application	Developer	Abbreviation	Quoted Range
Accelerometer Monitor	Mobile Tools	Newshell	-5G to 5G
Accelerometer	Alexander Ponomarev	ACC	-8G to 8G
Sensor Kinetics Pro	Innovations Inc	Sensor	-2G to 2G
Physics Toolbox Accelerometer	Vieyra Software	Physics	-6G to 6G
Accelerometer Monitor	Keuwlsoft	BGR	-10G to 10G
Accelerometer Acceleration Log	Alfa V	Log	-2G to 2G
Vib Sensor	New Instrument Software	Vib	-1G to 1G
Accelerometer	ADDA Mecatronics	3Wings	-3G to 3G
Ludo Accelerometer	LudoFox	Ludo	-10G to 10G
G-sensor Logger	Peter Ho	GSense	-4G to 4G
Accelerometer Toy	Chris Pearson	Toy	-2G to 2G
Accelerometer Monitor	Apotheosis Development	Orange	-3G to 3G

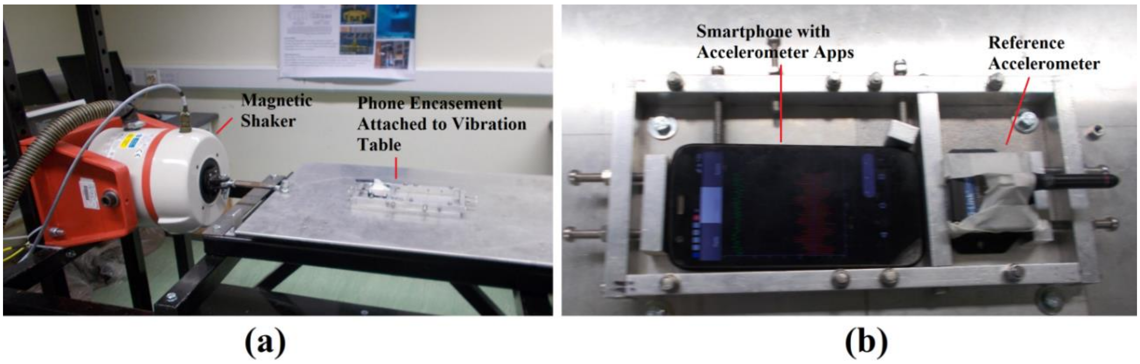

Fig. 1 Experimental Setup including (a) Vibration table and (b) Arrangement for smartphone and baseline accelerometer

For the 12 apps selected, initial experimental calibrations were conducted to determine the accuracy of the individual app in a laboratory environment for sinusoidal excitations. Sinusoidal loading at a frequency of 2Hz, 5Hz, 7Hz and 10Hz were applied at a constant magnitude 0.5g (where g is acceleration due to gravity and equal to 9.81m/s^2) and to determine the apps performance for real-world applications, the acceleration response of a bridge under operational loading conditions was applied for each app. The simulated dynamical response of a model bridge due to the induced vibrations due to the passage of a French Train à Grande Vitesse (TGV) train travelling at 100km/hr (Cahill *et al.* 2014) was utilised in this regard as the base excitation applied to the smartphone. Finally, to determine the apps ability to accurately measure the frequency domain, Fast Fourier Transform (FFT) was carried on the measured app acceleration responses also. The ability of each app to measure accurately the acceleration profile of such interaction was established, as was the frequency response, and the suitability of the apps for civil infrastructure applications was determined.

For the purposes of the laboratory-based calibration testing, the smartphone was mounted onto a vibration testing table, which was driven using a permanent magnet shaker (Fig. 1(a)) with the desired excitation profile being applied by means of an electronic wave generator. The inclusion of a baseline accelerometer, which is calibrated and of a much higher specification than the smartphone accelerometer, allows for the base excitation applied to the smartphone to be known. The baseline accelerometer chosen for this experimental calibration was a MicroStain G-Link LXRS with a +/- 2g triaxial range, with quoted accuracy of 10 mg and 12-bit resolution and was mounted in a back-to-back arrangement with the smartphone (Fig. 1(b)) on top of the vibration table. The accelerations were recorded simultaneously by both the baseline accelerometer and each of the accelerometer apps for all four excitation frequencies for the steady state excitation and for the train bridge interaction.

While more popular studies of comparing smartphone accelerometer include a variation in the hardware (Mourcou *et al.* 2015), there is no study where the phone is kept constant along with as much hardware conditions as is reasonably possible, but the variation is performance is assessed for different apps. This study attempts to develop a first estimate on this aspect. While it is difficult to exactly isolate the effects from app alone from such a test, by keeping as much hardware condition as possible constant and carrying out the same tests protocol, the study is expected to capture variations due to the use of different apps. In keeping with civil infrastructure, the target frequencies are kept low, with frequencies typically below 10Hz (O'Donnell *et al.* 2017) and

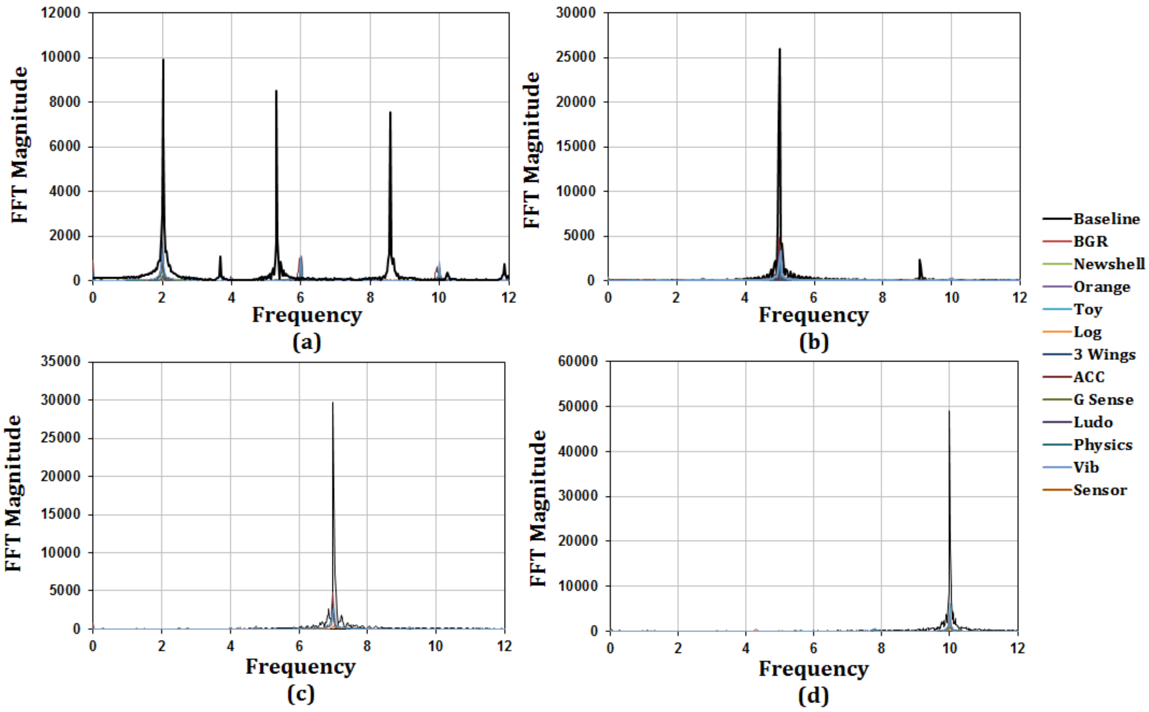

Fig. 2 Frequency response of baseline accelerometer and Apps at excitation frequencies of (a) 2Hz (b) 5Hz (c) 7Hz and (d) 10Hz

consequently the sampling for the phones and the accelerometer are high. Additionally, the ability of the apps to detect the correct frequencies is checked first to ensure that the main variation is from the estimate of the acceleration levels, while frequencies are well-determined.

3. Comparison of performance of apps during experimental calibration

The acceleration responses of the selected apps were compared for all single frequency loadings and for the train-bridge interaction loading, with the recorded app measurements calibrated to the reference baseline. Comparisons of the recordings were carried out by investigating them in the frequency domain and through analysis of variance (ANOVA) tests on the time domain responses. In this regard, the null hypothesis, H_0, is that all means are equal from the acceleration responses. A confidence interval of 0.95 was chosen corresponding to a p value of less than 0.05. When H_0 was rejected, the data was analysed further using the Tukey Kramer Multiple Comparison method. Statistical approaches of this type have been suggested by existing literature (Stiros 2008).

For all single frequency excitation tests, it was found that the frequency response of all apps considered were in agreement with the baseline accelerometer (Fig. 2). Each app showed the dominant frequency at the frequency of excitation to which the smartphone was subjected to, as did the baseline accelerometer app. Note that the capability of testing for low frequencies were limited to 2Hz, although the main peak at 2Hz is still identified correctly by different apps.

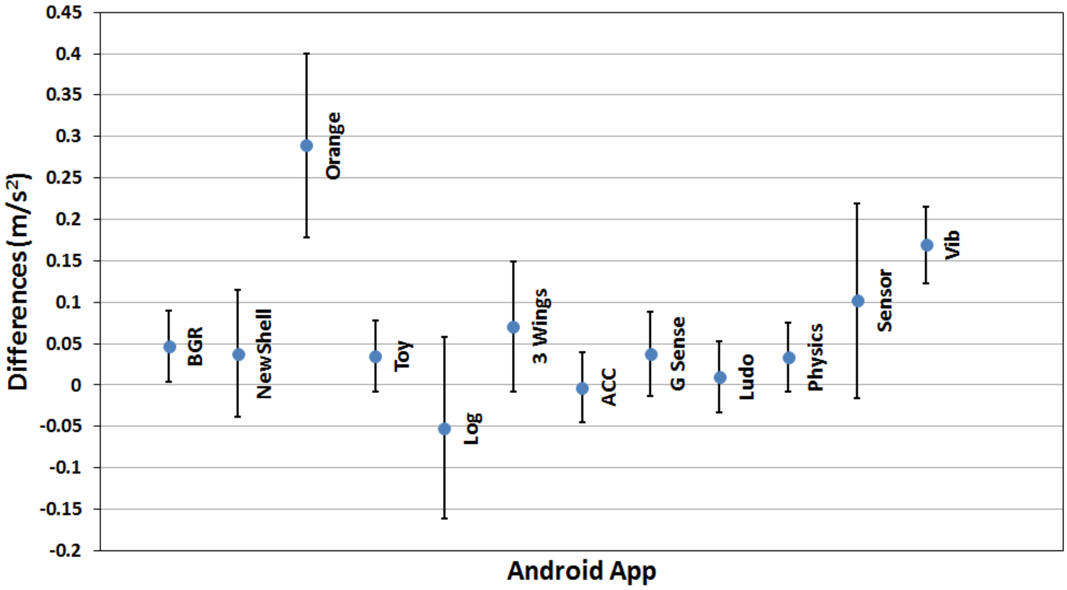

Fig. 3 Mean differences between App measurements and baseline accelerometer for excitation at 2Hz

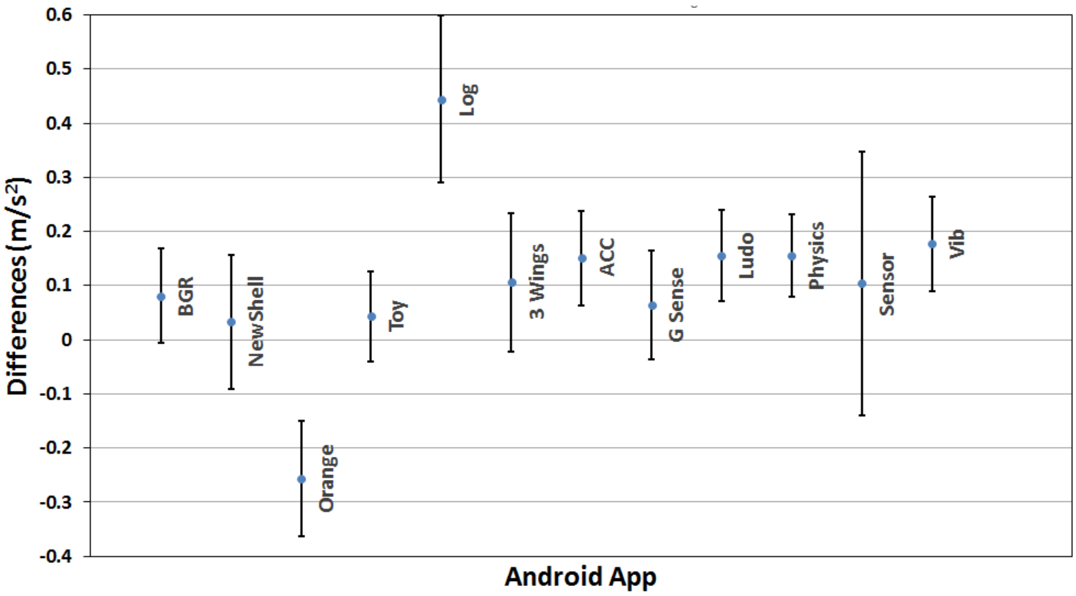

Fig. 4 Mean differences between App measurements and baseline accelerometer for excitation at 5Hz

Following this, the time domain response of each app was investigated using ANOVA. For the tests at excitation frequencies of 2Hz, 5Hz and 7Hz, p values of 0.136, 0.898 and 0.777 were obtained respectively. Thus, the resultant means of the accelerometer apps were not significantly different from each other and H0 was accepted. This result indicated that the accelerometer apps may provide comparable measurements when compared to the baseline measurement at frequencies of 2Hz, 5Hz and 7Hz.

Table 2 Mean differences and standard error for selected apps for single frequency excitation

App	2Hz		5Hz		7Hz		10Hz	
	μ (m/s²)	*σ* (m/s²)	*μ (m/s²)*	*σ* (m/s²)	*μ* (m/s²)	*σ* (m/s²)	*μ* (m/s²)	*σ* (m/s²)
BGR	0.04693	0.04295	0.08113	0.08762	0.15731	0.08512	0.17306	0.07771
NewShell	0.03796	0.07635	0.03283	0.12332	0.14913	0.11538	0.04816	0.09504
Orange	0.28912	0.11065	-0.25687	0.10660	0.18172	0.15575	0.04788	0.32793
Toy	0.03484	0.04323	0.04313	0.08316	0.15210	0.08524	0.15684	0.07712
Log	-0.05181	0.10973	0.44423	0.15411	0.08629	0.16889	0.17765	0.07542
3 Wings	0.07010	0.07857	0.10615	0.12733	0.16468	0.10988	0.19535	0.09814
ACC	-0.00295	0.04207	0.15053	0.08656	-0.00457	0.08813	-1.86409	0.04569
G Sense	0.03765	0.05080	0.06427	0.10031	0.16238	0.08978	0.17022	0.07393
Ludo	0.00970	0.04279	0.15576	0.08458	-0.00723	0.08431	0.07768	0.08459
Physics	0.03334	0.04147	0.15520	0.07565	0.13973	0.08738	0.16015	0.07184
Sensor	0.10198	0.11733	0.10382	0.24354	0.05844	0.24509	0.21414	0.24810
Vib	0.16911	0.04578	0.17701	0.08773	0.18073	0.08552	0.22658	0.08423

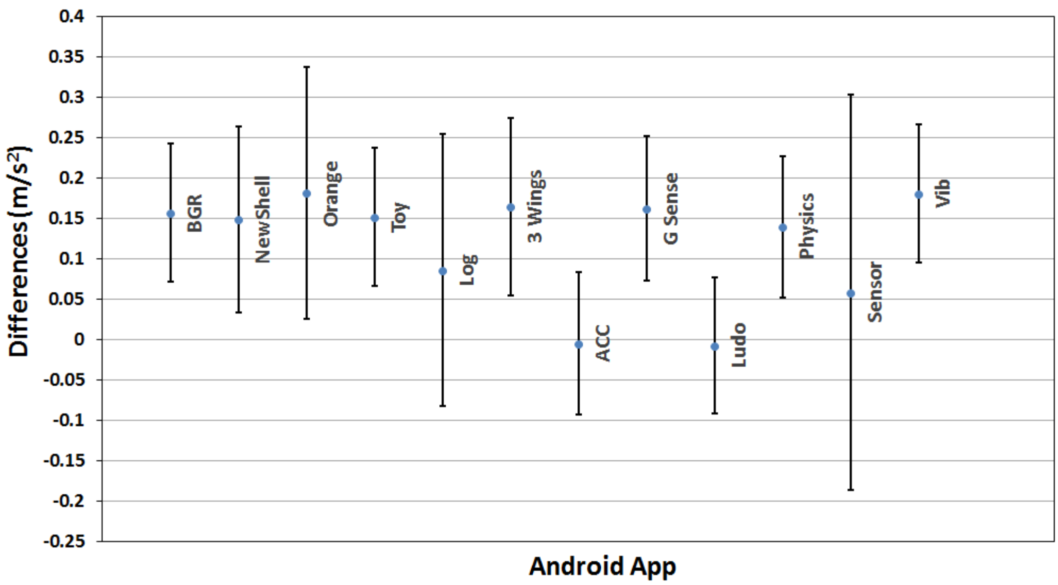

Fig. 5 Mean differences between App measurements and baseline accelerometer for excitation at 7Hz

Fig. 3 shows the box plots of the distribution of differences between baseline and app acceleration readings at 2Hz frequency. It can be seen that the ACC app had the best agreement with a mean difference (μ) of -0.003m/s^2 from the actual reference value as obtained from the baseline app. The Orange app had the lowest agreement with μ = 0.289m/s^2. It was found that for the excitation frequency of 5Hz, the Newshell app has the best agreement with μ = 0.0328m/s^2 being obtained, while the poorest performing app was Log, with a μ = 0.444 m/s^2 (Fig. 4).

As with the 2Hz, it was found for an excitation frequency of 7Hz the best performing app was the ACC, which had μ = -0.005m/s^2, and the worst performing app was Orange, resulting in μ =

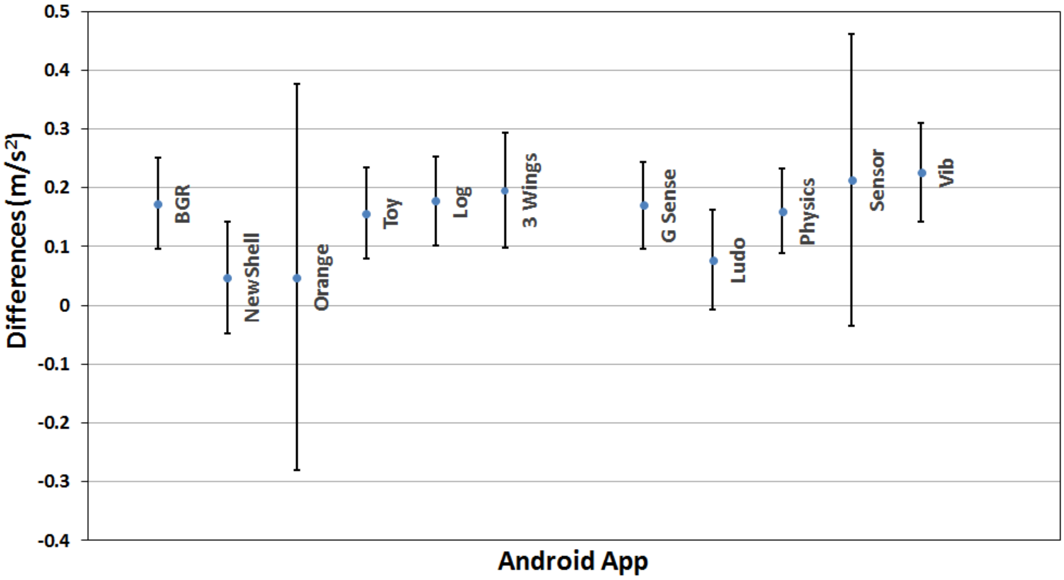

Fig. 6 Mean differences between App measurements and baseline accelerometer for excitation at 10Hz

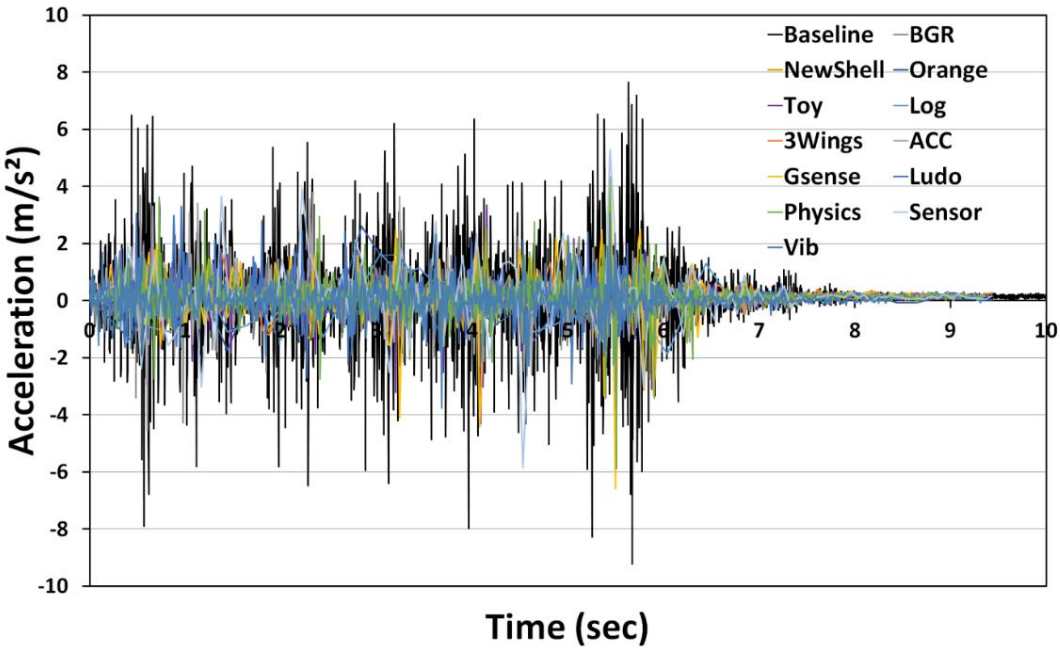

Fig. 7 Measured acceleration response of each app under experimental excitation from simulated train-bridge interaction

$0.182m/s^2$ (Fig. 5). In the case of the tests at 10Hz, a p value of less than 0.05 was obtained and H0 was rejected. A Tukey Kramer Multiple Comparisons Test indicated that the mean difference between the ACC app and the baseline accelerometer was significant, indicating the ACC app does not measure with accuracy at 10Hz. The remaining apps had insignificant differences of mean,

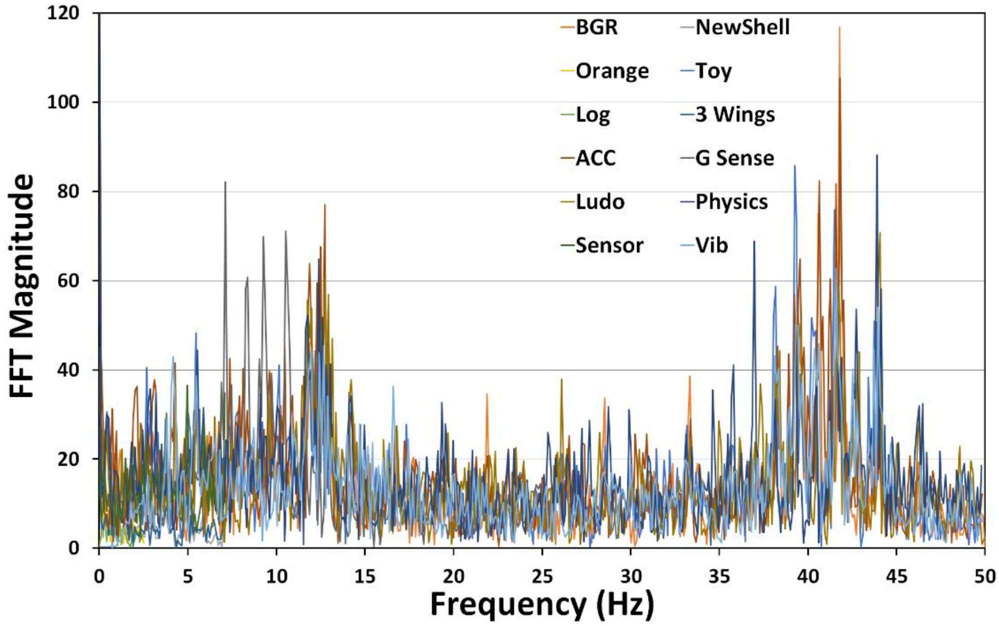

Fig. 8 Frequency response of each app under experimental excitation from simulated train-bridge interaction

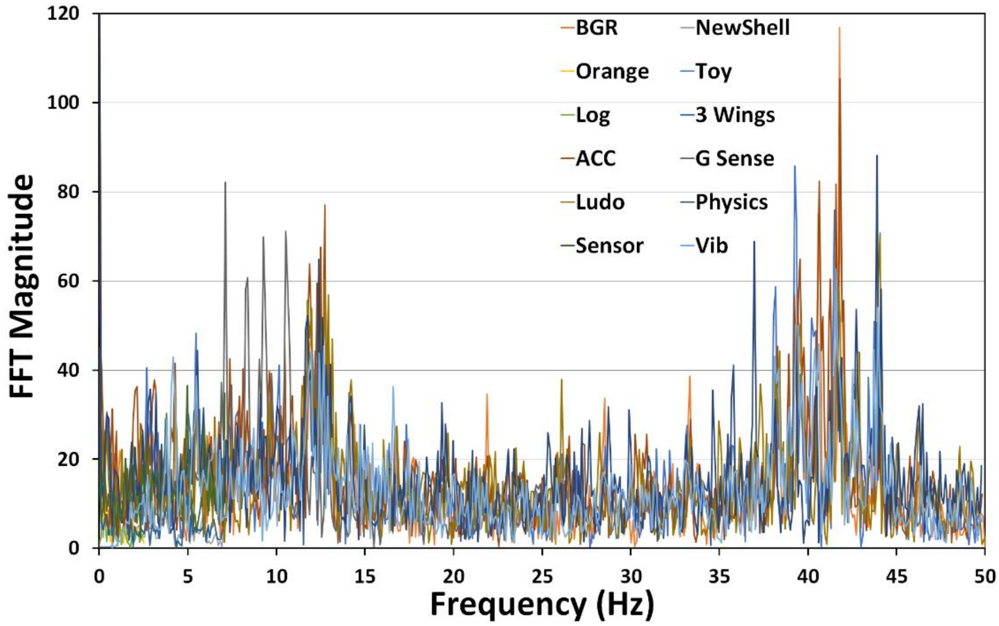

Fig. 9 Mean differences between individual App measurements and baseline accelerometer for TGV bridge passage

with the Orange app having the best agreement at 10Hz with μ = 0.048m/s^2 from the actual reference value (Fig. 6). A summary of the mean difference and standard error obtained for each app for the four excitation frequencies is given in Table 2.

Table 3 Mean differences and standard error for selected apps for TGV bridge passage

Application	Mean Difference (m/s²)	Standard Error (m/s²)
BGR	0.00255	0.02066
NewShell	-0.03498	0.03715
Orange	0.15581	0.11670
Toy	0.01284	0.02194
Log	0.1266	0.10417
3 Wings	-0.05602	0.04165
ACC	-0.01688	0.02453
G Sense	0.04424	0.04259
Ludo	-0.01753	0.02181
Physics	-0.00083	0.02304
Sensor	-0.00459	0.10911
Vib	0.14572	0.02217

The acceleration response of each app for the simulated train passage over a bridge was obtained experimentally and was compared against the measured response of the baseline accelerometer (Fig. 7). For a natural frequency of 12.83Hz for the model bridge, it was found that the apps registered peaks between the range of 12.40Hz and 12.73Hz, with the ACC app recording a frequency closest to the natural frequency of the bridge (Fig. 8).

A Tukey Kramer Multiple Comparisons procedure for the TGV case study found that significant differences in means existed between the Vib, Log and Orange apps and that of the baseline measurement, with $\mu = 0.146 m/s^2$, $0.127 m/s^2$ and $0.156 m/s^2$ being obtained respectively. A boxplot of the mean differences between baseline measurements and app measurements (Fig. 9) indicate that the Physics app had the best agreement for the TGV profile with $\mu = 0.001 m/s^2$ from the actual reference value, followed by the BGR app with $\mu = 0.003 m/s^2$. A summary of the performance of all apps is presented in Table 3.

4. Conclusions

While the performance of smartphone accelerometers has been considered and compared for different phones, experimental studies on variability levels of different apps are not available. This paper assesses such variability, while keeping the phone and related hardware issues unchanged as much as possible. An initial screening led to the choice of 12 apps and the selected apps were subsequently investigated to compare their performance during laboratory-based testing. Utilising a vibration shaking table and a permanent magnet shaker, the apps were assessed first for single frequency. The ability of the apps to accurately measure the amplitude of such loadings was analysed through analysis of variance (ANOVA). Following this, the vibrational response of a bridge during train passage was applied to each app utilising the shaker unit. While each app investigated has the ability to accurately measure frequency of both loadings and the host structure, measurements pertaining to the amplitude unreliable and no one app outperformed its counterpart consistently. However, this study indicates that the apps may be useful when investigating a phenomenon or a dynamic response of interest below 5Hz for the typical range for various civil structural responses in their operational condition. The representation of frequency content for the accelerometer apps are repeatable and more consistent for various apps and they may be used for tests for a range of different scales in the laboratory or for full-scale deployment. The levels of variation of the measurement errors of each app are similar independent of the test. This study provides the need for appropriate calibration or checks in relation to variations of measurement by different apps, along with their limitations when deploying a smartphone for the monitoring or assessment of dynamic structures. The work also provides a first estimate of the levels of such variation within the typical frequency zone of interest for monitoring a range of civil structures.

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References

Cahill, P., Hazra, B., Karoumi, R., Mathewson, A. and Pakrashi, V. (2018), "Vibration energy harvesting based monitoring of a bridge undergoing forced vibrations", *Mech. Syst. Signal Pr.,* **106**, 265-283.

Cahill, P., Nuallain, N.A.N., Jackson, N., Mathewson, A., Karoumi, R. and Pakrashi, V. (2014), "Energy harvesting from train-induced response in bridges", *ASCE J. Bridge Eng.*, **19**(9), 04014034.

Daponte, P., De Vito, L., Picariello, F. and Riccio, M. (2013), "State of the art and future developments of measurement applications on smartphones", *Measurement*, **46**(9), 3291-3307.

Dashti, S., Bray, J.D., Reilly, J., Glaser, S., Bayen, A. and Mari, E. (2014), "Evaluating the reliability of phones as seismic monitoring instruments", *Earthq. Spectra*, **30**(2), 721-742.

Feng, M., Fukuda, Y., Mizuta, M. and Ozer, E. (2015), "Citizen sensors for SHM: Use of accelerometer data from smartphones", *Sensors*, **15**(2), 2980-2998.

Gartner (2015), Gartner Says Smartphone Sales Surpassed One Billion Units in 2014; Gartner, Stamford, U.S.A. http://www.gartner.com/newsroom/id/2996817.

Giardini, M.E., Livingstone, I.A.T., Jordan, S., Bolster, N.M., Peto, T., Burton, M. and Bastawrous, A. (2014), "A smartphone based ophthalmoscope", *Proceedings of 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society,* Chicago, U.S.A., August.

Guido, G., Vitale, A., Astarita, V., Saccomanno, F., Giofre, V.P. and Gallelli, V. (2012), "Estimation of safety performance measures from smartphone sensors", *Procedia Soc. Behav. Sci.,* **54**, 1095-1103

Haberman, Z.C., Jahn, R.T., Bose, R., Tun, H., Shinbane, J.S., Doshi, R.N., Chang, R.M. and Saxon, L.A. (2015), "Wireless smartphone ECG enables large-scale screening in diverse populations", *J. Cardiovasc. Electrophysiol.,* **26**(5), 520-526.

Hemminki, S., Nurmi, P. and Tarkoma, S. (2013), "Accelerometer-based transportation mode detection on smartphones", *Proceedings of 11th ACM Conference on Embedded Networked Sensor Systems,* Rome, Italy, November.

Höpfner, H., Morgenthal, G., Schirmer, M., Naujoks, M. and Halang, C. (2013), "On measuring mechanical oscillations using smartphone sensors: Possibilities and limitation", *ACM SIGMOBILE Mobile Comput. Commun. Rev.*, **17**(4), 29-41.

Kardous, C.A. and Shaw, P.B. (2014), "Evaluation of smartphone sound measurement applications", *J.*

Acoust. Soc. Am., **135**(4), 186-192.

Kronbauer, A.H., Santos, C.A.S. and Vieira, V. (2012), "Smartphone applications usability evaluation: A hybrid model and its implementation", *Proceedings of 4th International Conference on Human-Centered Software Engineering,* Toulouse, France, October.

Lane, N.D., Miluzzo, E., Lu, H., Peebles, D., Choudhury, T. and Campbell, A.T. (2010), "A survey of mobile phone sensing", *IEEE Commun. Mag.*, **48**(9), 140-150.

Liu, M. (2013), "A study of mobile sensing using smartphones", *In. J. Distrib. Sens. N.,* **9**(3), 272916.

Le, V. and Yu, T. (2015), "Mass and stiffness estimation using mobile devices for structural health monitoring", *Structural Health Monitoring and Inspection of Advanced Materials, Aerospace, and Civil Infrastructure 2015,* **9437**, 94371B.

Morgenthal, G. (2012), "The application of smartphones in bridge inspection and monitoring", *IABSE Congress Report*, **18**(23), 610-618.

Mourcou, Q., Fleury, A., Franco, C., Klopcic, F. and Vuillerme, N. (2015), "Performance evaluation of smartphone inertial sensors measurement for range of motion", *Sensors*, **15**(9), 23168-23187.

O'Donnell, D., Srbinovsky, B., Murphy, J., Popovici, E. and Pakrashi, V. (2015), "Sensor measurement strategies for monitoring offshore wind and wave energy devices", *J. Physics, Conf. Ser.*, **628**(1), 012117.

O'Donnell, D., Wright, R., O'Byrne, M., Sadhu, A., Murphy, E., Cahill, P., Kelliher, D., Ghosh, B., Schoefs, F., Mathewson, A., Popovici, E. and Pakrashi, V. (2017), "Modelling and testing of a historical steel suspension footbridge in Ireland", *Proc. Inst. Civ. Eng. Bridge Eng.*, **170**(2), 116-132.

Pakrashi, V., Fitzgerald, P., O'Leary, M., Jaksic, V., Ryan, K. and Basu, B. (2018), "Assessment of structural nonlinearities employing extremes of dynamic responses", *J. Vib. Control*, **24**(1), 137-152.

Reilly, J., Dashti, S., Ervasti, M., Bray, J.D., Glaser, S.D. and Bayen, A.M. (2013), "Mobile phones as seismologic sensors: Automating data extraction for the iShake system", *IEEE Trans. Autom. Sci. Eng.,* **10**(2), 242-251.

Sharma, A. and Gupta, D. (2014), "Smartphone as a real-time and participatory data collection tool for civil engineers", *Int. J. Modrn. Comput. Sci.,* **2**(5), 22-27.

Song, Y., Chee, Y., Oh, J. and Lee, S. (2014), "Development of android based chest compression feedback application using the accelerometer in smartphone", *Proceedings of the International Conference on Biomedical Engineering and Systems,* Prague, Czech Republic, August.

Srbinovski, B., Magno, M., Edwards-Murphy, F., Pakrashi, V. and Popovici, E. (2016), "An energy aware adaptive sampling algorithm for energy harvesting WSN with energy hungry sensor", *Sensors,* **16**(4), 448, 1-19.

Steinhubl, S.R., Muse, E.D. and Topol, E.J. (2015), "The emerging field of mobile health", *Sci. Transl. Med.,* **7**(283), 283rv3.

Stiros, S. (2008), "Errors in velocities and displacements deduced from accelerographs: An approach based on the theory of error propagation", *Soil dynam. Earthq. Eng.,* **28**(5), 415-420.

Thompson, C., White, J., Dougherty, B., Albright, A. and Schmidt, D.C. (2010), "Using smartphones to detect car accidents and provide situational awareness to emergency responders", *International Conference on Mobile Wireless Middleware, Operating Systems, and Applications,* Springer, Berlin Heidelberg, Germany.

Yu, Y., Han, R., Zhao, X., Mao, X., Hu, W., Jiao, D., Li, M. and Ou, J. (2015a), "Initial validation of mobile-structural health monitoring method using smartphones", *Int. J. Distrib. Sens.*, 1-14.

Yu, Y., Zhao, X., Han, R. and Ou, J. (2015b), "Design and initial validation of external sensors board of smart phones for mobile structural health monitoring system", *Proceedings of the 7th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII'15)*, Torino, Italy, July.

Yu, Y., Zhao, X. and Ou, J. (2012), "A new idea: Mobile structural health monitoring using Smart phones", *Proceedings of the 3rd International Conference on Intelligent Control and Information Processing (ICICIP),* Dalian, China, July.

Znidaric, A., Pakrashi, V., O'Connor, A. and O' Brien, E. (2011), "A review of road structure data in six european countries", *Urban Design Planning*, **164**(4), 225-232

Zhao, X., Han, R., Ding, Y., Yu, Y., Guan, Q., Hu, W., Li, M. and Ou, J. (2015a), "Portable and convenient cable force measurement using smartphone", *J. Civil Struct. Health Monitor.*, **5**(4), 481-491.

Zhao, X., Yu, Y., Hu, W., Jiao, D., Han, R., Mao, X., Li, M. and Ou, J. (2015b), "Cable force monitoring system of cable stayed bridges using accelerometers inside mobile smart phone", *SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring,* 94351H-94351H7.

Zhao, X., Yu, Y., Li, M. and Ou, J. (2015c), "Research on Cloud-SHM and its applications", *Proceedings of the 7th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII'15),* Torino, Italy, July.

Zhao, X., Ri, K., Han, R., Yu, Y., Li, M. and Ou, J. (2016), "Experimental research on quick structural health monitoring technique for bridges using smartphone", *Adv. Mater. Sci. Eng.*, 1871230.

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