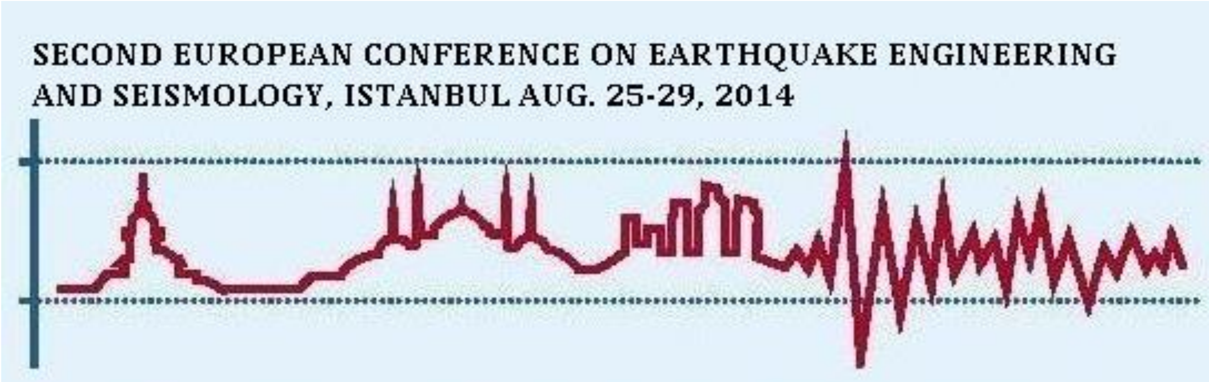

RELIABILITY OF USING SMART PHONES SENSORS AS AN EXPERIMENTAL INSTRUMENT ON STEEL BRIDGE

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ABSTRACT

Accelerometers in smart phones and “apps” that use them have a potential to determine dynamic characteristics of civil engineering structures. Damping ratio, which is a key quantity needed to design a structure, can only be identified by conducting experiments on similar structures. However smart phones have not been used as an experimental measuring tool for civil engineering structures. In this study, LIS331DLH ultra low-power high performance three axes linear nano MEMS internal accelerometer of smart phone sensor is tested with high-end expensive seismometer for deriving damping ratio of a pedestrian model steel bridge using snap-back method. Eight experiments have been conducted with various initial displacement imposed at the mid span of bridge. Measured amplitude of acceleration time histories together with numerically calculated displacement waveforms are compared in time and frequency domains. Furthermore wavelet analysis is employed to time histories to capture instant frequency changes on the vibration of structure. Finally correlation between applied initial displacement and the value of damping ratios are derived for each acceleration and displacement waveforms. Although smart sensors could not catch high frequency signals and amplitude levels as obtained from reference sensor, measured fundamental frequencies are derived similarly. The analysis carried out proves that smart phones can determine damping ratio in close proximity compared with quality accelerometers. With some drawbacks, smart phone sensors can be utilized in determining damping ratio of model steel bridge.

INTRODUCTION

There is a growing trend on the use of smart phone sensors in seismology and civil engineering. In recent years, many apps made available to use acceleration of phone sensors from earthquake detection to structural health monitoring (Naito et al., 2013). Researchers use mobile phone apps to collect, share or process data for technical, scientific as well as educational purposes. Although challenges are substantial such as unknown goodness and robustness of data, smart phones have the potential to transform real-time seismology into structural health monitoring. Currently, advanced traditional seismic networks only have stations every 10 km covering limited areas. Contribution of smart phones sensors has the potential to provide much higher resolution in urban areas for variety of purposes (Cochran et al. 2009, D’Alessandro and D’Anna 2013). For example; one of the projects,

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iShake developed by civil engineering department of UC Berkeley, uses personal devices to deliver rapid semi-qualitative earthquake shaking information (Dashti et al 2011, 2013).

The first question need to be answered is how reliable they are and possibility of using their MEMS sensors (LIS331DLH ultra low-power high performance three axes linear nano MEMS) as a replacement to high-quality expensive seismometers. Potential of smart phones is endless but can they be used to analyse dynamic characteristic of structures such as damping ratio of a system? One of the important parameters of structures, damping ratio is a quantity of energy dissipation of a structure that is very difficult to obtain numerically (Kawashima et al, 1993). Thus generally it is derived from experimental studies. Basically, there are three experimental approach to identify damping of a system; a) ambient excitation (Nagayama, 2005), b) forced vibration test (Abazarsa et al., 2013, Soyoz et al., 2013) and c) snap-back method where each has its own advantages and disadvantages. Although many experiment conducted with the first two methods, there is only a few experiment with snap-back method (Butterworth, et al., 2004). Snap-back is based on simply imposing an initial displacement and releasing structure to oscillate (Tamura and Yoshida, 2008).

In this study, we have tested internal accelerometer of smart phone sensor with high-quality expensive seismometer on deriving damping ratio of a pedestrian model steel bridge using snap-back method. Eight experiments have been conducted with various initial displacement and acceleration time histories are measured. These accelerations and numerically calculated displacement waveforms are then compared in time and frequency domains. Wavelet analysis is employed to time histories to capture instant frequency changes in time. We derived correlation between imposed initial displacements. Finally, the value of damping ratios are derived from both acceleration and displacement waveforms.

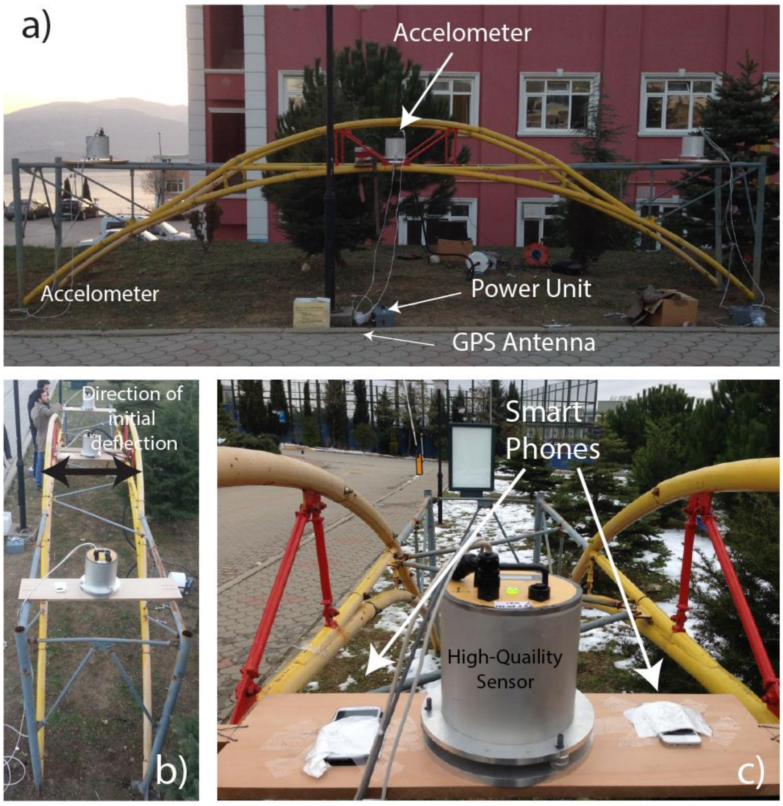

Figure 1. a) Experimental setup of scaled steel frame bridge b) direction of initial deflection c) location of smart phone and reference sensor

Experimental Setup

We have applied initial displacement by controlled human power in the middle of bridge. Displacements are applied by pulling and releasing with a rope. First we have placed high-quality

Capacitive Force Micromachined accelerometer, which has 32-bit high resolution and has 120 dB dynamic range at the mid-span of the bridge. This accelerometer has separate GPS antenna and a power unit that allows us to operate it without any electricity (Figure 1a-c). A smart phone also is located next to reference accelerometer and it is pinned securely to wooden holder. Recorded accelerations are accurately time stamped for quality seismometer. On the other hand smart phone has a built in GPS but records are not time stamped. For comparison, we pre-process two records manually and initiation of waveforms are synchronized.

Initial motion is imposed in transverse direction (Figure 1b) of bridge and waveform of acceleration (one component) is recorded 100 sample per seconds for both sensors which allow us to analyse up to 50 Hz. Then both raw records are base-line corrected, trends are removed and filtered with Butterworth band pass between 1 Hz to 5 Hz. With the help of numerical integration velocity and displacement records are calculated for each experiment. After applying signal processing techniques we employed Fast Fourier Transform to get frequency content of signals, namely frequency of the oscillation of bridge. Furthermore, records from both sensors are analysed with wavelet transform which allowed us to track change of frequency of bridge in time. With wavelet, we could closely looked how two sensor catch the vibration on the system.

In a series of eight experiments, filtered damped free vibration records are recorded and displacements are calculated for initial displacement of 0.113 cm, 0.249 cm, 0.411 cm, 0.500 cm, 0.606 cm, 0.797 cm, 1.002 cm, 1.213 cm which are applied at the mid-span. Experiments are conducted on a scaled pedestrian bridge whose span and width is 6.84 m and 0.90 m, respectively (Figure 1a). All the members are connected with bolts and the bridge is simply supported to the soil.

Calculating damping ratios

Damping ratio of a structure can be calculated with the amplitudes of filtered damped free vibration record for both acceleration and deflection time histories. One of the simple but effective method to compute the equivalent viscous damping ratio, (ξ) is using log-decrement equation given below (Chopra, 2012);

$$x = \frac{1}{2p} \ln \frac{u_i}{u_{i+1}} \tag{1}$$

where, u_i and u_{i+1} are two successive peak deflections. However, in most dynamic analysis experiments, displacements are not directly recorded, but they are obtained by numerical integrations of accelerations wavefroms. Thus, damping ratio can also be calculated by using two successive peak accelerations, $\ddot{u}_i$ and $\ddot{u}_{i+1}$;

$$x = \frac{1}{2p} \ln \frac{\ddot{u}_i}{\ddot{u}_{i+1}} \tag{2}$$

In this study, we prefer to use the equation given below to derive damping ration for a period of time as;

$$\xi = \frac{1}{2\pi} \frac{1}{\mathrm{n}} \sum_{1}^{\mathrm{n}} \ln \frac{\Delta_{Tn}}{\Delta_{Tn+1}} \tag{3}$$

where n the number of cycle for the analyzed time span, Δ_{Tn} is the corresponding amplitude of acceleration or displacement of the cycle.

RESULTS AND DISCUSSION

Comparison of recorded waveforms

For assessment of two sensors, unfiltered acceleration records and displacements waveforms (after filtered and numerically integrated) with their FFT are shown for three cases; first experiment with minimum initial displacement of 0.113 cm (Figure 2), fifth experiment with initial displacement of 0.606 cm (Figure 3) and last experiment with the maximum initial displacement of 1.213 cm (Figure 4). Y-axis is not normalized and peak accelerations are reached up to 120, 580 and 680 cm/s/s.

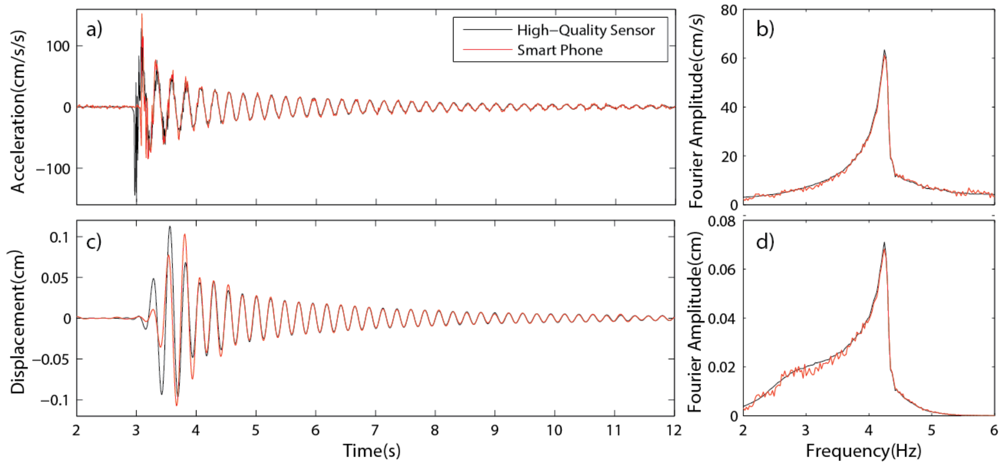

Figure 2. Comparison of High-quality sensor with smart phone sensor for initial displacement of 0.113 cm recorded in the middle of investigated steel bridge a) Acceleration record b) FFT of acceleration record c) displacement records and d) FFT of displacement record

Although smartphone sensor reaches as the same peak acceleration with reference sensor, records are not as similar as the given vibration. For the raw acceleration records of all the experiments, we found that the very beginning of the records are not similar when compared with the rest of the records. It seems that smart phone sensor could not catch the initial acceleration. For example the negative amplitude of the accelerations at the beginning (Figure 2a, 3a, 4a) are missing for smart phone (red line) records. This loss causes a variation in the displacement records in the numerical integration process (Figure 2c, 3c, 4c). However, after a few cycles, the amplitudes are very similar for both records. This similarity disappears with higher initial displacements (Figure 4c).

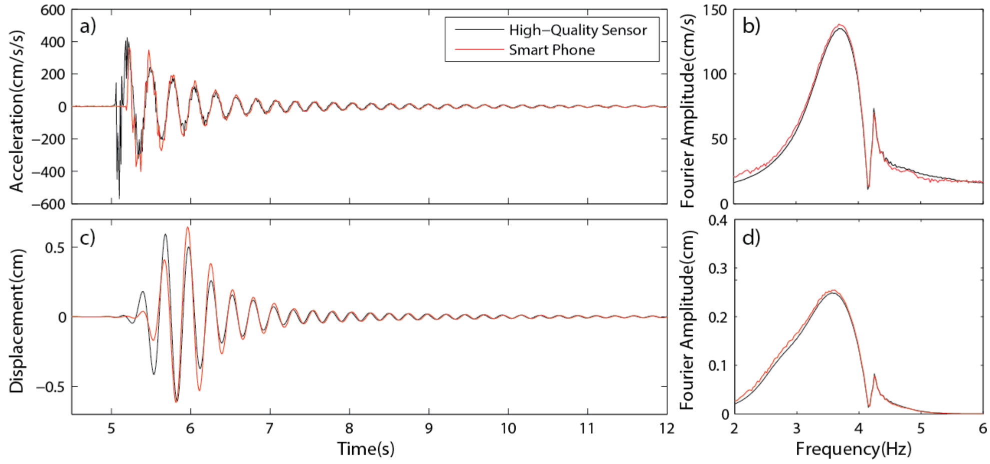

Figure 3. Comparison of High-quality sensor with smart phone sensor for initial displacement of 0.606 cm recorded in the middle of investigated steel bridge a) Acceleration record b) FFT of acceleration record c) displacement records and d) FFT of displacement record

Although discrepancies on amplitude, we found frequency content of vibration is very similar for both sensors when FFT results are checked. Difference in Fourier amplitudes is very small and it increases with higher initial displacements (Figure 4b and 4d). Variation on noise levels is clearer for small amplitudes as in the first experiment (Figure 2b and 2d). However, the importance of this variation is not critical because the dominant frequency of the bridge is accurately determined by smart phone as the high-quality sensor.

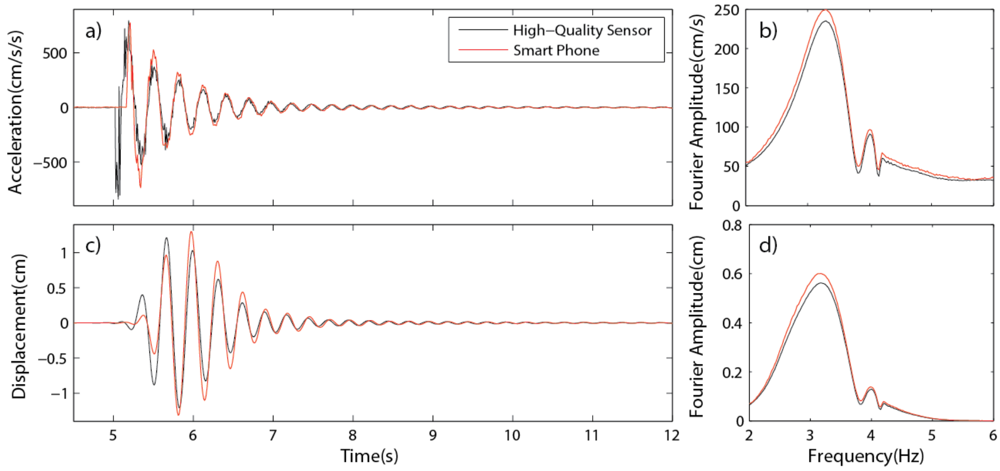

Figure 4. Comparison of High-quality sensor with smart phone sensor for initial displacement of 1.213 cm recorded in the middle of investigated steel bridge a) Acceleration record b) FFT of acceleration record c) displacement records and d) FFT of displacement record

Comparison of recorded waveforms with wavelet analysis

Wavelet analysis of the eight experiments are conducted for both sensors type up to 50 Hz. Comparison of experiment 1, 5 and 8 are shown in Figure 5, 6, and 7, respectively. These figures allow us to analyse changes of frequencies (y-axis) with time (x-axis). For example, high-quality sensor has recorded higher frequencies of the environmental noise on the top of the bridge (Figure 5a). Although frequencies in this high range is not needed to determine dynamic properties of the most structures, analysis based on ambient vibration cannot be conducted by smart phones probably due to self-noise of devices because they cannot catch high frequency content of vibration..

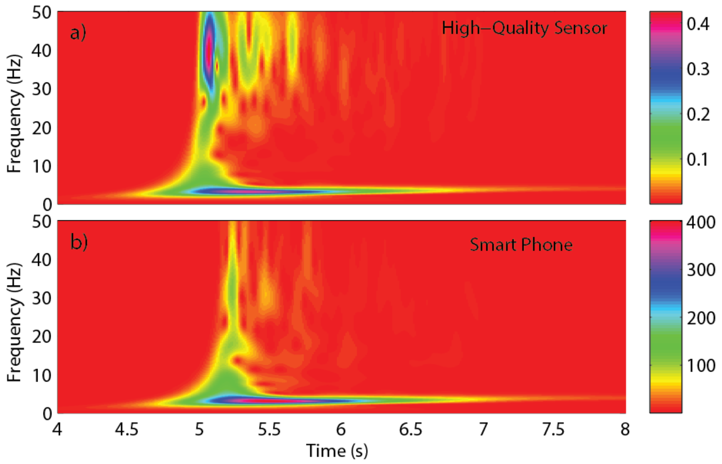

Figure 5. Wavelet analysis of acceleration records from a) high-quality sensor and b) smart phone for experiment one

Although the amplitude of colours are different (Figure 5, 6, 7 a-b) the fundamental frequencies around 3-4 are detectable by eye for each individual tests. As expected, the oscillation continues (fundamental frequency) for experiment eight as in experiment one. Smart phone sensors successively detected dominant frequency of bridge like expensive accelerometers for all eight experiments.

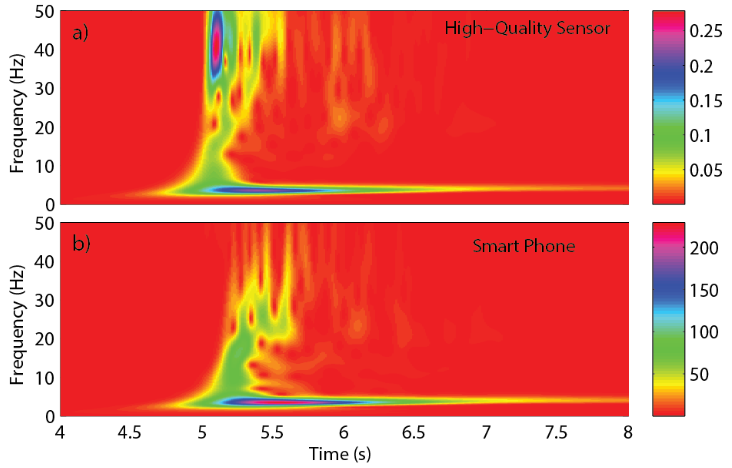

Figure 6. Wavelet analysis of acceleration records from a) high-quality sensor and b) smart phone for experiment five

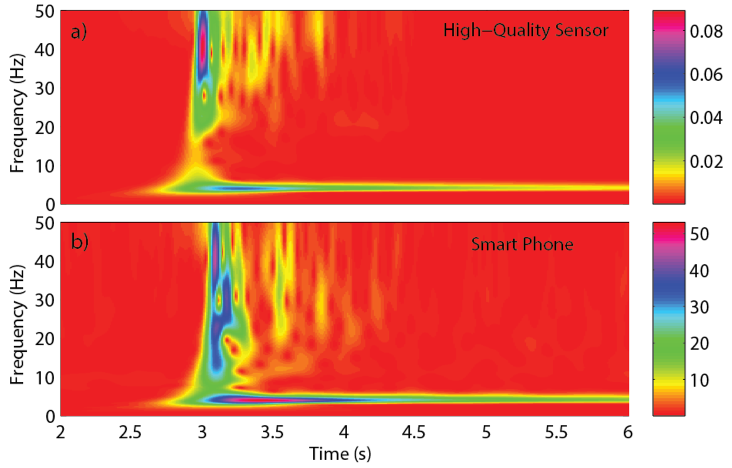

Figure 7. Wavelet analysis of acceleration records from a) high-quality sensor and b) smart phone for experiment eight

Comparison of damping ratios

Log-decrement equations are used in filtered damped free vibration records of eight experiments. For experiment one, peak amplitudes of free vibration acceleration waveforms are shown as red circles in Figure 8a and 8b for both sensors. Corresponding results from displacement records are also calculated and shown in Figure 8c and 8d. Damping ratio is calculated by using each two successive amplitude pair for acceleration and displacement waveform. Each damping ratio from pairs changes with time (Figure 8e and 8f). We observed ratios are high for the first cycles and decrease in time.

Values of damping ratio saturate after within ten seconds clearly for reference sensor (black circles) however, deviation is much higher for smart phone sensors (black squares). Although standard deviation seems to be high, the mean of the damping ratio over 10 seconds is found to be very close (black line in Figure 8e and 8f). For experiment one, damping ratios are derived as1.2% and 1.3% from acceleration record for each sensor. Difference for the displacement waveform is 0.1%.

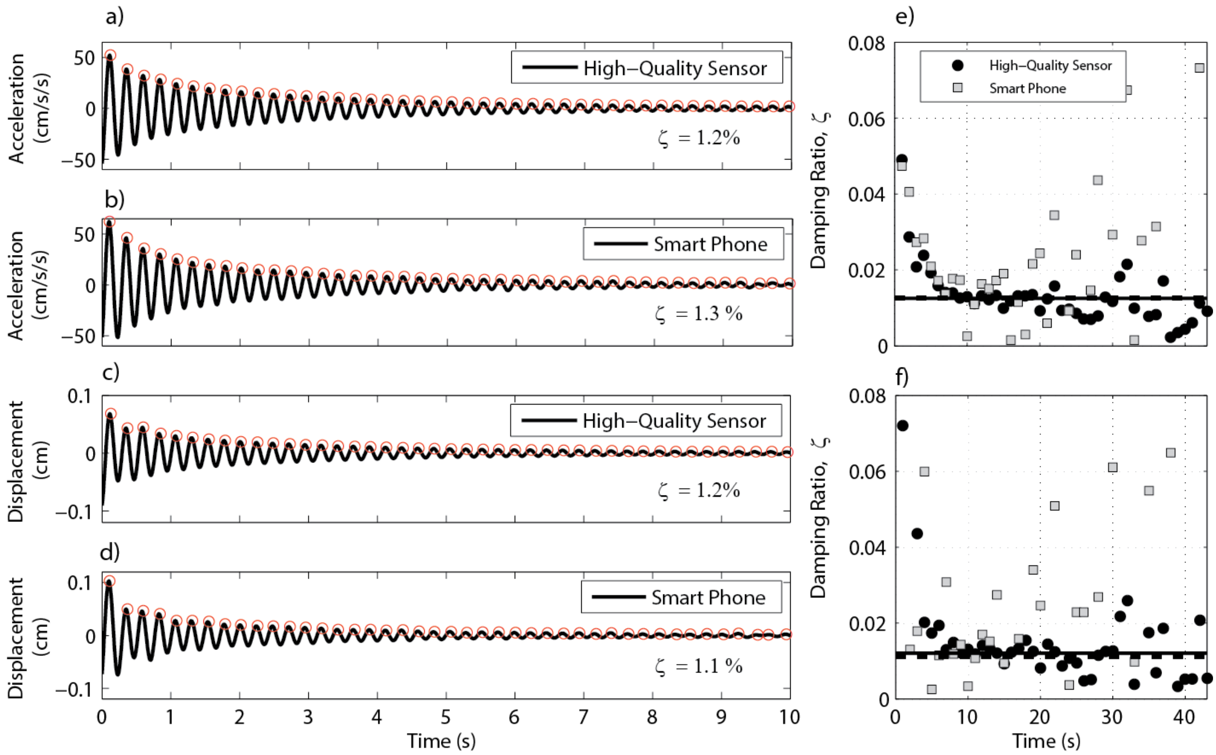

Figure 8. Comparison of decrement amplitudes for experiment one. Acceleration time histories of a) high-quality sensor b) smart phone. Displacement time histories of c) high-quality sensor, d) smart phone. Calculated damping ratios from e) acceleration and f) displacement for each pair

Results obtained for damping ratio from all the tests are plotted in Figure 9. This figure shows the correlation between applied initial displacement and the value of damping ratios derived from acceleration (Figure 9a) and displacement waveforms (Figure 9b). Damping ratios are very similar for both sensors where we found slightly over estimation with smart phone (red triangles) compared to reference sensor. Estimated ratios are comparable from both waveforms up to initial displacement of 6 mm corresponding to the first five test. For higher initial displacement however, value of damping ratios from displacement are higher than acceleration record.

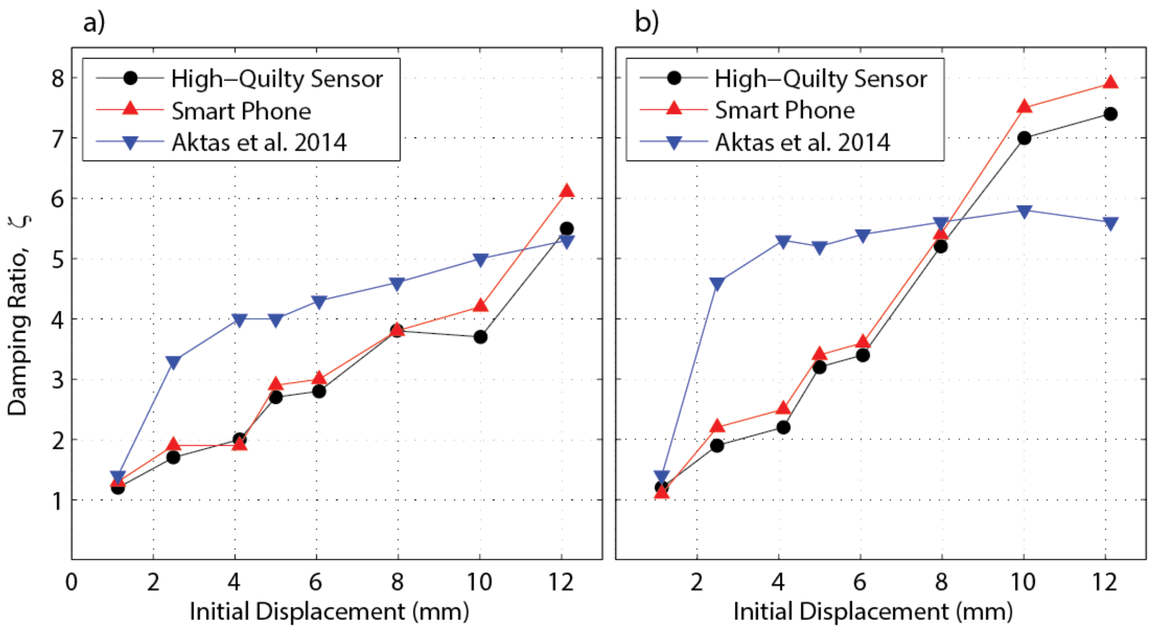

Figure 9 Correlation between damping ratio and initial displacement for a) acceleration b) displacement records

Aktas et al, (2014) conducted similar test for the same model bridge. Their results from direct log-decrement are slightly different from this study. This might be due to difference of time interval which affect the number of successive peak pairs. Furthermore, they have used curve fitting methods to exponential envelope curves to identify damping ratios (blue upside triangles in Figure 9). Damping ratio from Aktas et al, (2014) and calculated log-decrement equation in this study has divergence. The under estimation of our results might be due to longer time span we selected to use.

CONCLUSION

Damping ratio is a vital parameter in designing civil structures under dynamic loads. Damping ratio cannot be derived from other structural properties such as stiffness and mass. Thus experiments must be conducted. With this research, we tested smart phone sensors for whether they can be used as a replacement to high-end seismometers in the field test or not. Validity of the results is determined by comparing acceleration time histories and their frequency content observed from both devices. All the analysis carried out proves that smart phones can determine damping ratio in close proximity. Authors think that smart phones have the potential to change experimental measuring tools for civil structures. Further studies can be done to obtain other dynamic properties of structures in order to check reliability of smart phone sensors.

REFERENCES

Abazarsa F., Nateghi F., S. Ghahari F., and Taciroglu E., (2013) :Blind Modal Identification of Non-Classically Damped Systems from Free or Ambient Vibration Records: *Earthquake Spectra*: November 2013, Vol. 29, No. 4, pp. 1137-1157.

Aktas M, Kuyuk H.S. Yilmaz C, Agcakoca E, Celebi E, (2014) "Experimental study on determining damping ratio of steel bridges" *Second European Conference on Earthquake Engineering and Seismology*, Istanbul, Turkey

Butterworth J, Lee JH., Davidson B., (2004) "Experimental determination of modal damping from Full scale testing" *13th World Conference on Earthquake Engineering* Vancouver, B.C., Canada August 1-6,

D'Alessandro A and D'Anna G. (2013) "Suitability of Low-Cost Three-Axis MEMS Accelerometers in Strong-Motion Seismology: Tests on the LIS331DLH (iPhone) Accelerometer" *Bulletin of the Seismological Society of America*, Vol. 103, No. 5, pp. 2906–2913, October 2013, doi: 10.1785/0120120287

Cochran E.S., Jesse F. Lawrence, Carl Christensen, and Ravi S. Jakka (2009) "The Quake-Catcher Network: Citizen Science Expanding Seismic Horizons". *Seismological Research Letters*, v. 80, p. 26-30, doi:10.1785/gssrl.80.1.26

Dashti, S., Bray, J.D., Reilly, J., Glaser, S., Bayen, A., and Ervasti, M. (2013) "Evaluating the Reliability of Mobile Phones as Seismic Monitoring Instruments," *Earthquake Spectra Journal*, Earthquake Engineering Research Institute, (accepted and in press)

Dashti, S., Bray, J.D., Reilly, J., Glaser, S., Bayen, A., and Ervasti, M. (2011)."iShake: Using Personal Devices to Deliver Rapid Semi-Qualitative Earthquake Shaking Information." *GeoEngineering Report*, Depart. of Civil and Environ. Engineering, Univ. of California, Berkeley,

Kawashima, K., Unjoh, S., and Tunomoto, M. (1993). "Estimation of Damping Ratio of Cable-Stayed Bridges for Seismic Design." *J. Struct. Eng.*, 119(4), 1015–1031.

Nagayama, T., Abe, M., Fujino, Y., and Ikeda, K. (2005). "Structural Identification of a Nonproportionally Damped System and Its Application to a Full-Scale Suspension Bridge." *J. Struct. Eng.*, 131(10), 1536–1545.

Naito S,, Hiroki A.,, Shigeki S., Mutsuhiro Y., Hiromitsu N., Ken XH., Hiroyuki F., Yoshiharu H., Noboru Y., and Minoru Y., (2013) "Development and Testing of a Mobile Application for Recording and Analyzing Seismic Data" Journal of Disaster Research Vol.8 No.5

Tamura, Y. and Yoshida, A. (2008) "Amplitude Dependency of Damping in Buildings" *Structures Congress* pp. 1-10.doi: 10.1061/41000(315)39

Soyoz, S., Taciroglu, E., Orakcal, K., Nigbor, R., Skolnik, D., Lus, H., and Safak, E. (2013). "Ambient and Forced Vibration Testing of a Reinforced Concrete Building before and after Its Seismic Retrofitting." *J. Struct. Eng.* 139, SPECIAL ISSUE: Real-World Applications for Structural Identification and Health Monitoring Methodologies, 1741–1752.