The 2016 World Congress on
The 2016 Structures Congress (Structures16)
Jeju Island, Korea, August 28-September 1, 2016

Measurements of Pedestrian's load Using Smartphones

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ABSTRACT

This paper explores the application of smartphones for human-induced loads measurements. Preliminary tests were carried out to select proper smartphones and data acquisition software. Shaking table tests were then conducted on selected smartphones to measure sinusoidal waves of various frequencies, sinusoidal sweep waves and earthquake waves. Comparison between the smartphones' measurements and real inputs showed that the smartphones used in this study gave reliable measurements for harmonic waves in both time and frequency domains. For complex wave, however, the smartphones' measurements should be used with caution. Subsequently, the motion capture technology was employed to explore two key technical issues for the application of smartphones for human-induced loads measurements. Experimental results on individual's jumping, walking and bouncing activity demonstrated that the installation manner and angel correction had a significant effect on the measurement accuracy of smartphone. When the phones were securely fastened and the original data was corrected to right angles, the smartphones' measurements agreed well the references. Encouraged by the above experimental validation results, the smartphones were attached to a moving person to measure the acceleration near the center-of-mass of his/her body. The human-induced loads were then reconstructed by the acceleration measurements in conjunction with a biomechanical model. Satisfactory agreements between the reconstructed forces and that measured by force plate were observed for jumping and bouncing load, clearly demonstrating the capability of the smartphones for human-induced loads measurements.

INTRODUCTION

People walk, jump and bounce in pop concerts or large sports events when they feel excited. These kinds of human activities will probably cause structural vibration. Violent vibration threatens the structural serviceability and even their safety. Recently, with more construction of large-span structures, like foot bridges, bleachers and flexible floor slab, engineers and structure designers have paid more attentions to structural vibration serviceability.

The dynamic properties of human-induced loads are essential for the structural vibration analysis, and the massive reliable measured data should be collected to build

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human load model. There are three measurements to get human load data: the first method utilizes force plates to record the ground reaction forces that has high-precision results but cannot catch every step of walking load because of the number the plate is limited. The second method and the third method respectively utilize the treadmill and the insole to measure the human load ground reaction that seems similar with the first method. The last two measurements can record every step continuously, but some unreliable data are usually mixed. All those three methods are difficult to record the human load naturally, thus making the study on human-induced load have some pivotal problems.

Ministry of Industry and Information Technology of the People’s Republic of China said that until December 2015, 13.06 hundred million smartphones have been used in China, which means every hundred people have had 95.5 smartphones. Smartphone and other similar portable devices like iPod and smart band have gradually changed people’s lifestyle. The development of the mobile phone hardware and software can provide people with more convenience and cool user experience. Based on MEMS (Micro-Electro-Mechanical Systems) technology, the sensor-embedded smartphones can catch the device’s motion trail, which provide a new train of thought to use the smartphone in the field of engineering or the vibration measurement.

SMARTPHONE’S WORKING PRINCIPLE

Synopsis of the Smartphone’s Embedded Sensors

The acceleration sensor and gyroscope sensor which are based on MEMS technology are regarded as MIMU (Micro Inertial Measurement Unit), which integrates six-dimension inertia parameters together in a micro electronical unit to record tri-axial accelerations and tri-axial angular velocity. According to the statement above, it is possible to ensure the object’s movement precisely and apply these parameters to further research.

MEMS gyroscope plays an important role in smartphone’s measurement precision. Factors that affect the accuracy of gyroscope include scale factor, zero-bias stability, measurement range, output noise, bandwidth, and resolution ratio. Normally, the main motion trial can be directly recorded by acceleration sensor. Take iPhone for example, and the Linear Acceleration Sensor is able to provide a series of acceleration data in three dimensions without gravity effect.

Relevant Information about the Embedded Sensors

The following introduction about measurement principle is based on iPhone6. The unit of the output acceleration is gravitational acceleration (shorthand for g), and the positive direction is in accordance with the red arrows in Figure 1. Gyroscope sensor can record three-dimension angular velocity data with the same sample frequency of the acceleration sensor. The positive directions of these angular velocities meet right-hand rule, which means the thumb points at the positive direction of acceleration coordinate axis and the other four fingers curves to the positive direction of angular velocities. We us SensorLog (Figure 2) as the data acquisition software in the test.

Figure 1 The positive direction of acceleration sensor

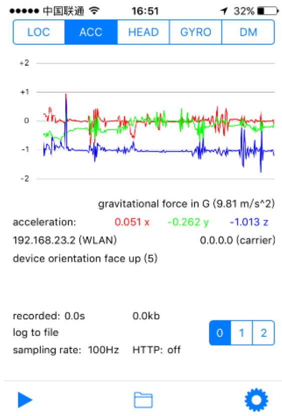

Figure 2 SensorLog user interface

The details about acceleration sensor are as follows: in the static condition, the smartphone will have a very small acceleration record under 577mg, which doesn't make big sense about the acceleration data. When the smartphone have randomly motion trail in the three-dimension space, these three-dimension in every step equals gravitational acceleration, which means the accelerations in three dimension meet parallelogram law. The iOS system adopts Sensor Fusion algorithm to filter most gravitational acceleration, but still maintain marginal linear acceleration term.

The smartphone still has acceleration deviation caused by residual gravitational acceleration after being flitted by Sensor Fusion algorithm. Specially, when the smartphone is located on the ground where the z axis consistent with the direction of the gravitational acceleration, the Sensor Fusion algorithm doesn't work well. In order to reduce the impact of the residual gravitational acceleration, the 4 order 0.25Hz Butterworth high-pass filter is suggested to suppress the useless acceleration term.

Using the Data to Analyze the Kinstate of the Smartphone

No matter how the smartphone waves in the three-dimension space, the motion condition of the smartphone could be resolved into two kind of kinstates: translation and rotation

Here, we define these three-dimension angular velocity as $\vartheta_x, \vartheta_y, \vartheta_z$ with the unit of $\mathrm{rad/s}$. It is supposed that the original acceleration coordinate is $[\vec{x}(0), \vec{y}(0), \vec{z}(0)]$, and the coordinate at time instant *t* is $[\vec{x}(t), \vec{y}(t), \vec{z}(t)]$ where the acceleration coordinate is $[a_1(t), a_2(t), a_3(t)]$.

Obviously, at time instant *t*, the angular is $[\alpha_t, \beta_t, \gamma_t]$ which are represented by Equation(1), (2) and(3).

$$\alpha_t = \sum_1^n \vartheta_x \Delta t \tag{1}$$

$$\beta_t = \sum_1^n \vartheta_y \Delta t \tag{2}$$

$$\gamma_t = \sum_1^n \vartheta_z \Delta t \tag{3}$$

where, *n* stands for sample count that can be expressed by:

$$\mathrm{n} = \frac{t}{\Delta t}$$

where, Δt represents sample interval. In this article, all the smartphones in the experiment have been set with 100Hz to sample in order to get more sampling points as much as possible.

To get the relation between the original acceleration and the acceleration of the t moment, the following equation simplify the computing method.

$$\left[a_x, a_y, a_z\right]^T = \mathbf{H}\left[a_1, a_2, a_3\right]^T \tag{4}$$

where, $\mathbf{H}$ stands for the correction matrix with the introduction the concept of Eulerian Angle, and the superscript T stands for matrix transpose.

When the smartphone move randomly, this kind of kinstate can be regarded as translation of translation and rotation. Smartphone rotation seems extremely complex, but on the base of the concept of Eulerian Angle, we can resolve this arbitrary rotation into three simple rotation around each coordinate axis.

The picture below show the resolving process in the order of zxy (Figure 3).The rotational angle at certain moment is (φ, θ, η), the coordinate transformation matrix can be deduced as follow, where R, Z, N, Z' ,as shown in Equation(5), (6), (7) and (8), stand for operators which are used for the transformation between original coordinate and arbitrary coordinate.

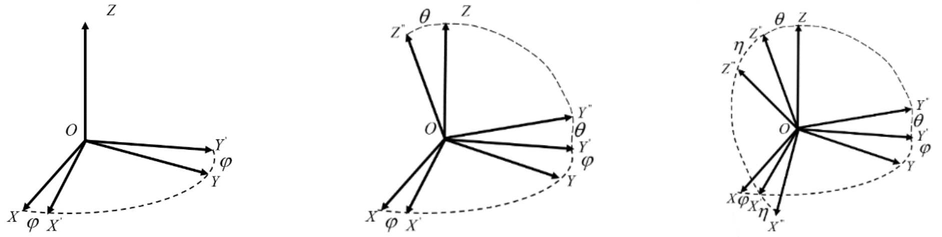

Figure 3 The resolving the smartphone's kinstate in the three-dimension space

$$Z'(\varphi)=\begin{pmatrix}\cos\varphi & \sin\varphi & 0\\ -\sin\varphi & \cos\varphi & 0\\ 0 & 0 & 1\end{pmatrix} \tag{5}$$

$$N(\theta)=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta & \sin\theta\\ 0 & -\sin\theta & \cos\theta\end{pmatrix} \tag{6}$$

$$Z(\psi)=\begin{pmatrix}\cos\psi & \sin\xi & 0\\ -\sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{pmatrix} \tag{7}$$

$$\begin{aligned}R(\psi,\theta,\varphi)&=\begin{pmatrix}\cos\psi\cos\varphi-\sin\psi\sin\varphi\cos\theta & \sin\psi\cos\theta+\cos\psi\sin\varphi\cos\theta & \sin\varphi\sin\theta\\ -\cos\psi\sin\varphi-\sin\psi\cos\varphi\cos\theta & -\sin\psi\sin\varphi+\cos\psi\cos\theta & \cos\varphi\sin\theta\\ \sin\psi\sin\theta & -\cos\psi\sin\theta & \cos\theta\end{pmatrix}\\ &=\begin{pmatrix}\cos(x',x) & \cos(x',y) & \cos(x',z)\\ \cos(y',x) & \cos(y',y) & \cos(y',z)\\ \cos(z',x) & \cos(z',y) & \cos(z',z)\end{pmatrix}\end{aligned} \tag{8}$$

Finally, using the transformation operator based on the concept of Eulerian Angle, the original acceleration $[a_1(t),a_2(t),a_3(t)]$ and the acceleration $a_x(t),a_y(t),a_z(t)$ at moment of t can be easily transformed mutually.

$$a_x(t)=a_1(t)\cos(a_x(t),a_1(t))+a_2(t)\cos(a_x(t),a_2(t))+a_3(t)\cos(a_x(t),a_3(t)) \tag{9}$$

$$a_y(t)=a_1(t)\cos(a_y(t),a_1(t))+a_2(t)\cos(a_y(t),a_2(t))+a_3(t)\cos(a_y(t),a_3(t)) \tag{10}$$

$$a_z(t)=a_1(t)\cos(a_z(t),a_1(t))+a_2(t)\cos(a_z(t),a_2(t))+a_3(t)\cos(a_z(t),a_3(t)) \tag{11}$$

Moreover, the original condition can be decided by researchers on the basis of experimental needs, and our group make a simple vertical equipment to accord smartphone's y axis with the direction of gravitational gravity. Because in the following part of the human-induced load measurement experiments, it should be get the vertical acceleration of the walking, jumping and bouncing, and the coordinate transformation make big sense of this purpose.

SHAKING TABLE CALIBRATION TEST

In this experiment, Quanser one-way shaking table that is used for dynamic structural test plays important role. The object of these experiments is to verify the precision of the smartphone while inputting different kinds of waves, like periodic acceleration wave and probabilistic earthquake acceleration wave. We fix the smartphone on the shaking table (Figure 4).

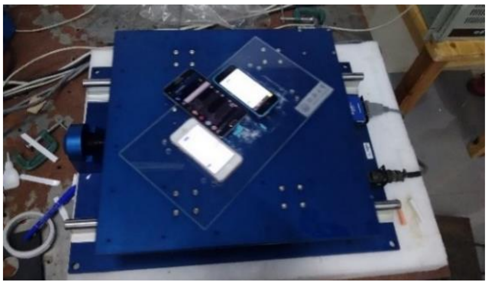

Figure 4 Installation of smartphone on the shaking table

First of all, we input 7 sine wave into the shaking table system, and the frequency covers from 1.2Hz to 3.4Hz, which also covers the normal frequencies of human-induced loads. The acceleration time history and Fourier amplitude spectrum of the 1.6Hz wording condition have been represented below. As the result, the acceleration time history and Fourier amplitude spectrum of the smartphone are extremely close to the output of the shaking table, and other cases is very similar to the example showed in Figure 5 and Figure 6.

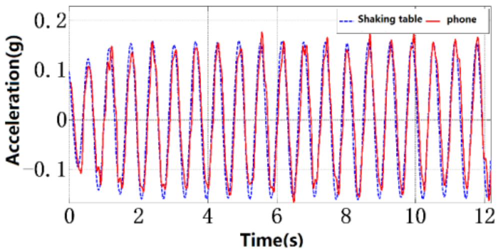

Figure 5 Time history of 1.6Hz sine wave

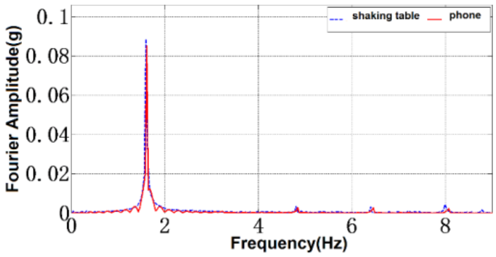

Figure 6 Fourier amplitude spectrum of 1.6Hz sine wave

Furthermore, more experiments are recommended to carry on in order to examine the smartphone’s precision in complex vibration, like sweep acceleration (1.2-3.6Hz) and earthquake acceleration (EL-Centro, Northbridge, Kobe and Mendocino earthquake). Figure 7 shows us the 1s Running Root-Mean-Square (1sRMS) between the acceleration time history of shaking table and smartphone, and mean relative error of the corresponding sampling points is 18.88%, but the frequency-domain characteristic almost the same with each other.

In the experiment of earthquake testing, the acceleration of the smartphones can basically reflect the macroscopic characteristics of the earthquake signals, like the waveform and the number of the amplitude, but unfortunately the details of the signals between the two kinds of measurements still exist relatively large differences. The smartphone is not very recommended to be used in the earthquake test directly.

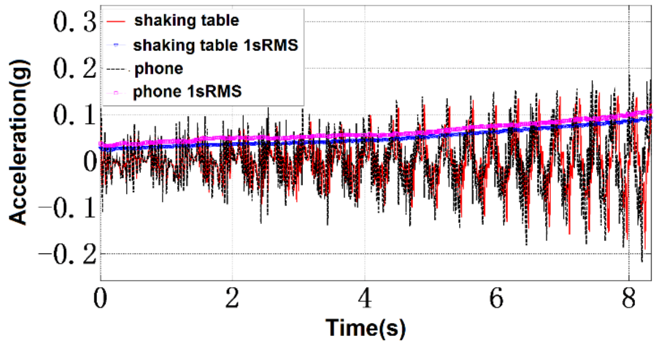

Figure 7 The comparison of shaking table data and smart phone sensor data under sweep acceleration

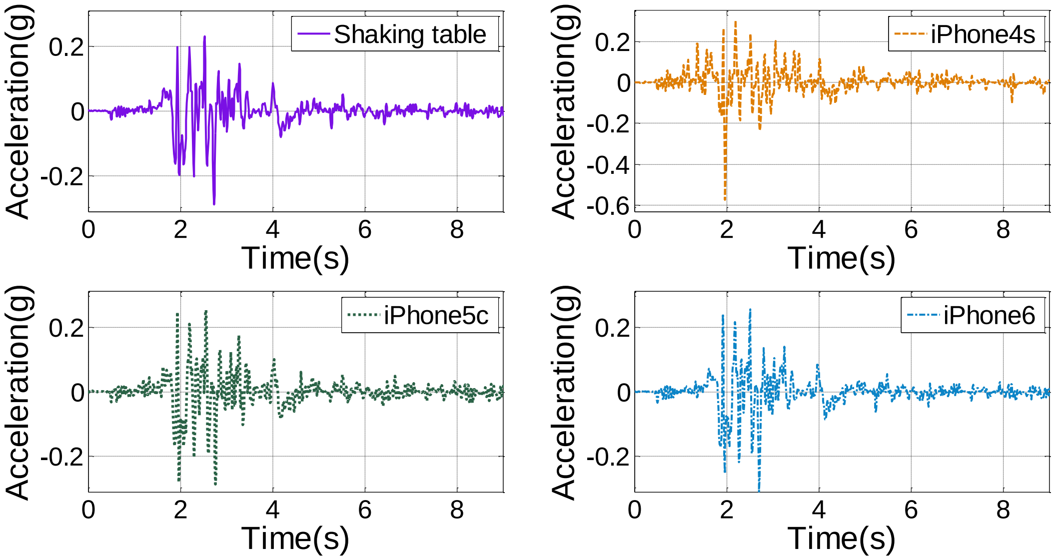

Figure 8 The comparison of the recording time history under El-Centro earthquake vibration between shaking table and smart phones with different types

USING SMARTPHONE TO MEASURE PEDESTRIAN'S LOAD

The smartphone fixed steadily on the human's waist where the trajectory of this part could stand for the whole body's movement. It is possible to use smartphone to record the data of body's movement and consequently get the acceleration $\tilde{a}(t)$ of body's vertical activity. Moreover, taking bounce activity for example and based on biomechanics, if the acceleration of the vertical activity is efficient, the single rigid-body model is suitable to be introduced. Based on the statement above, the conversion formula from acceleration of smartphone to the ground reaction force of bounce activity is given below.

$$G(t) = mg + mR\tilde{a}(t) \qquad (12)$$

where, $G(t)$ is defined as the ground reaction force that could stand for the bounce load; m stands for body mass; g is gravitational acceleration (m/s^2); R stands for vibration participation coefficient of body mass.

During the experiment, 3D Motion Capture Technology (MCT) data has been used, and the comparison between the smartphone date and 3D device date will represent the viability of the usage of the smartphone measuring the human-induced load.

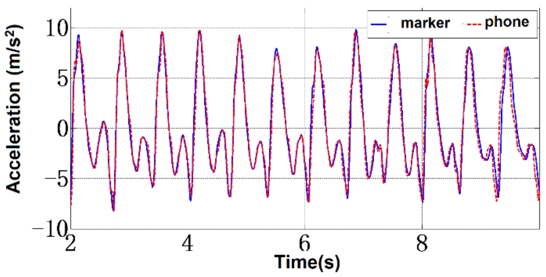

Figure 9 The comparison of acceleration bouncing 2.0Hz between smartphone sensor and Marker

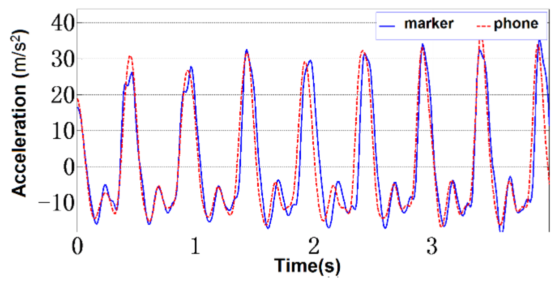

Figure 10 The comparison of acceleration jumping at 2.0Hz between smartphone sensor and Marker

The above comparison proves that the precision of the smartphone is almost similar with the marker's precision about human-induced load, so it is possible to apply smartphones in subsequent experiments.

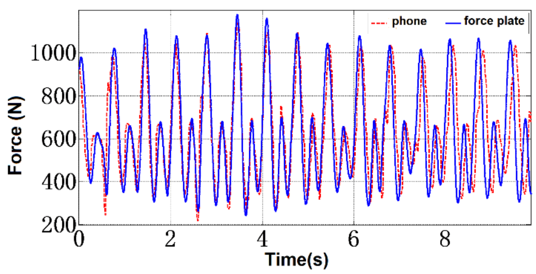

Figure 11 The comparison of force got by smart phone and force got by force plate under bounce load

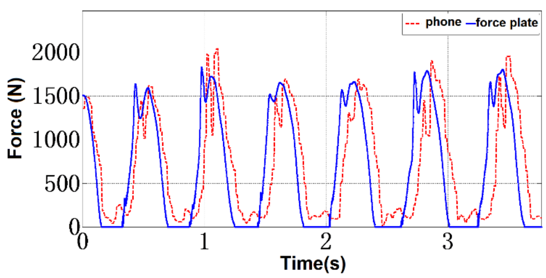

Figure 12 The comparison of force got by smart phone and force got by force plate under jumping load

Table 1 Other cases and parameters of bounce load

Case（Hz）	R	Amplitude error	RMS error
1.5Hz	0.75	3.06%	0.7%
2.0Hz	0.70	3.62%	0.74%
2.8Hz	0.60	0.90%	5.18%
3.5Hz	0.60	2.17%	3.23%

Table 2 Other cases and parameters of jumping load

Case（Hz）	R	Amplitude error	RMS error
1.5Hz	0.75	2.74%	7.34%
2.0Hz	0.75	1.24%	7.55%
2.8Hz	0.75	1.47%	9.67%
3.5Hz	0.60	3.17%	15.32%

According to Table 1 and Table 2, it can be speculated that if R is selected with the proper value, the force which is calculated by Equation (12) is very similar to the result of the real force plate measurement. Figure 11 and Figure 12 is the example of the comparison between the force plate and the model calculation result.

CONCLUSION

In order to verify the application of the smartphone measurement for human-induced load, this paper carried out the shaking table experiment and the pedestrian’s load experiment. In the shaking table experiment, the smartphone can record the sine wave acceleration accurately in time domain and frequency-domain. The time domain features of the sweep wave acceleration can also be obtained precisely. On the other hand, not all kinds of vibration signal can be gotten by the smartphone, like the earthquake acceleration, but some useful information can be found as well.

With the help of 3D MCT, it is verified that the smartphone used in this paper can be adopted in the real pedestrian’s load measurement. The model given in this paper provide us with a method to converse the vertical acceleration into the ground reaction force, but the precision of this model is based on the value of R, so the model optimization is the further research direction and make the measurement method better and reasonable.

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