Monitoring Bridge Vibrations via Pedestrians and Mobile Sensing

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Abstract
Mobile and smart sensors in structural health monitoring (SHM) applications is getting more and more widespread. A unique combination of these sensors refer to smartphone technology which poses a futuristic SHM potential if citizen engagement difficulties can be tackled. This paper presents two bridge monitoring strategies utilizing smartphone accelerometer data carried by pedestrians. These strategies utilize smartphone-based vibration measurements from walking and standing pedestrians and use it for pedestrian-induced load estimation and bridge modal identification. Comparing theoretical walk-induced forces with smartphone-based measurements of a walking pedestrian, efficiency of the former strategy is validated. The strategy associated with standing pedestrian determines vibration features of pedestrian biomechanical system, and uses it as a transfer function to isolate bridge features from the pedestrian biomechanics. With the proposed method, biomechanical effects can be eliminated from smartphone user measurements and bridge-only frequency spectra can be generated.

Keywords: structural health monitoring (SHM), mobile sensing, smartphone sensors, pedestrian bridges, biomechanical systems

1. Introduction

Understanding bridge vibrations with measurement instrumentation is one of the fundamental ways of bridge condition assessment. SHM systems developed in the last four decades show significant advances in this field [1], however, mostly require advanced equipment and extensive labour work. Mobile and smart sensing technologies emerged to solve the majority of the practical problems [2-5]. With the advent of smartphones, citizen power has become an innovative source for SHM applications [6].

Most of the smartphones are equipped with sensors such as accelerometer, gyroscope, magnetic compass, and more. Following proper crowdsourcing strategies, smartphone users can serve as SHM operators which causes no burden to system administrators and infrastructure owners [7]. If the spatiotemporal uncertainty or orientation distortion problems are resolved, it is possible to establish a smart monitoring framework for citizen engagement into the SHM process [8-9]. For example, pedestrians equipped with smartphones can measure vibrations with their phones while they are on a bridge [10].

In this paper, two major pedestrian features are investigated and two bridge monitoring solutions are proposed. The first method relies on smartphone accelerometer measurements of a moving pedestrian to estimate walk-induced forces. The second method processes standing pedestrian data to remove pedestrian biomechanical features from bridge features to illustrate bridge spectral properties. Section 2.1-2.3 introduces the theory behind the moving and stationary scenarios. Section 2.4-2.5 presents a real pedestrian and bridge experiment and the findings. Section 3 draws conclusions from this study.

2. Materials and Methods

2.1 Biomechanical Models

Biomechanical models are widely used in automotive industry, aircraft engineering, and medical studies to identify how human body interacts with vibrating environments. Adopting a similar perspective, biomechanics can be helpful to understand the relationship between pedestrians and bridges. In general, pedestrians can take numerous forms while performing any action on a bridge. Figure 1 symbolizes a number of common scenarios which can be performed by human beings.

Figure 1: Depiction of typical human activities

To mathematically and physically represent human body, numerous biomechanical models are developed by researchers. These models vary in modelling details which depends on the purpose of the model. Depending on the model detail, human body can be represented with few or many numbers of masses and springs. Figure 2 shows four different human biomechanical models with different levels of abstraction and accordingly different degree-of-freedom numbers [11-14].

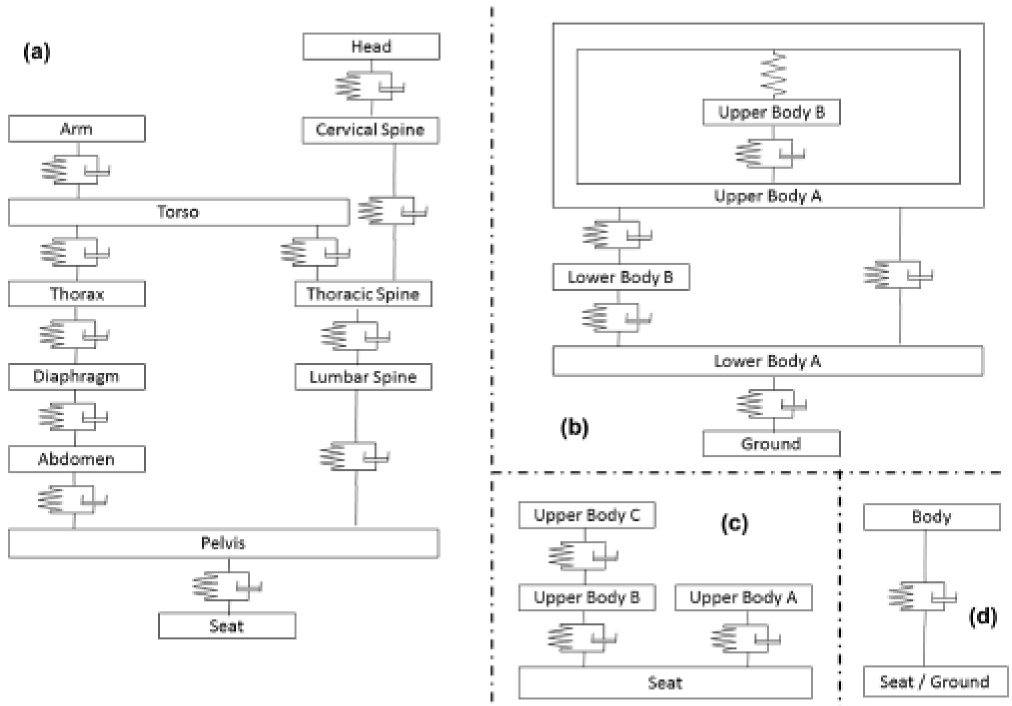

Figure 2: Exemplary biomechanical models existing in the literature [11-14]

2.2 Walk-Induced Vibrations

Considering a pedestrian as a mechanical system, dynamic forces are imposed on a bridge depending on pedestrian activity. A pedestrian moving on a bridge (e.g. walking or running) exerts harmonic forces on the bridge. Following a theoretical model given in [15] and using physical parameters such as human body weight and activity rate, these motions resemble the time history and spectral features given in Figure 3. Considering the problem in inverse direction, human body motion can be captured by smartphone accelerometer carried by the pedestrian.

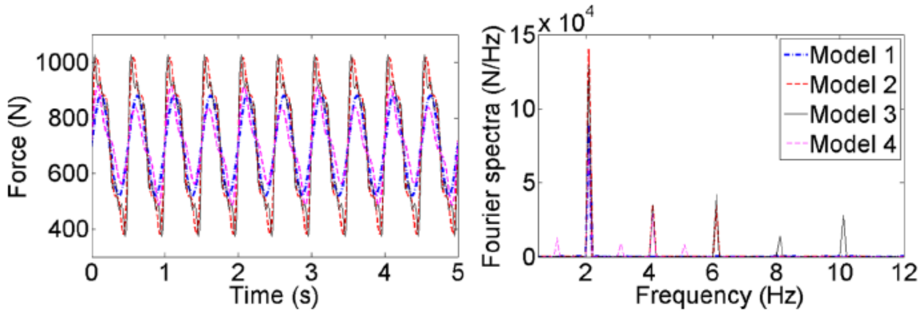

Figure 3: Time history and frequency spectra of walk-induced pedestrian forces

2.3 Standing Pedestrian Transfer Functions

Similar to walking cases, stationary pedestrian body can be represented with mathematical expressions. Considering pedestrian as a mechanical system, dynamic parameters can be determined in terms of mass, damping and stiffness. These parameters can be used to describe pedestrian body's features in the frequency domain with the help of transfer functions. Figure 4 demonstrates a variety of theoretical transfer functions representing different pedestrian bodies.

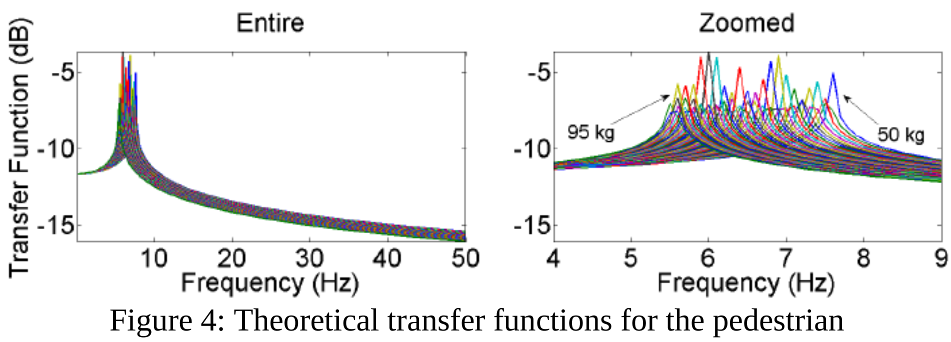

Figure 4: Theoretical transfer functions for the pedestrian

Considering standing pedestrian body as an intermediate mechanical system between the bridge and a mobile sensor, pedestrian transfer functions can be used as a tool to use indirect smartphone measurements for bridge response measurements. Sensor measurement carried by a pedestrian includes bridge vibration characteristics as well as pedestrian biomechanics. In order to isolate bridge features from pedestrian biomechanics, biomechanical system of the human body needs to be developed. Once the biomechanical system spectral features are determined, they can be removed from the smartphone data carried by the standing pedestrian can be converted into bridge-only spectral features. The entire transformation procedure of the vibration signal is depicted in Figure 5.

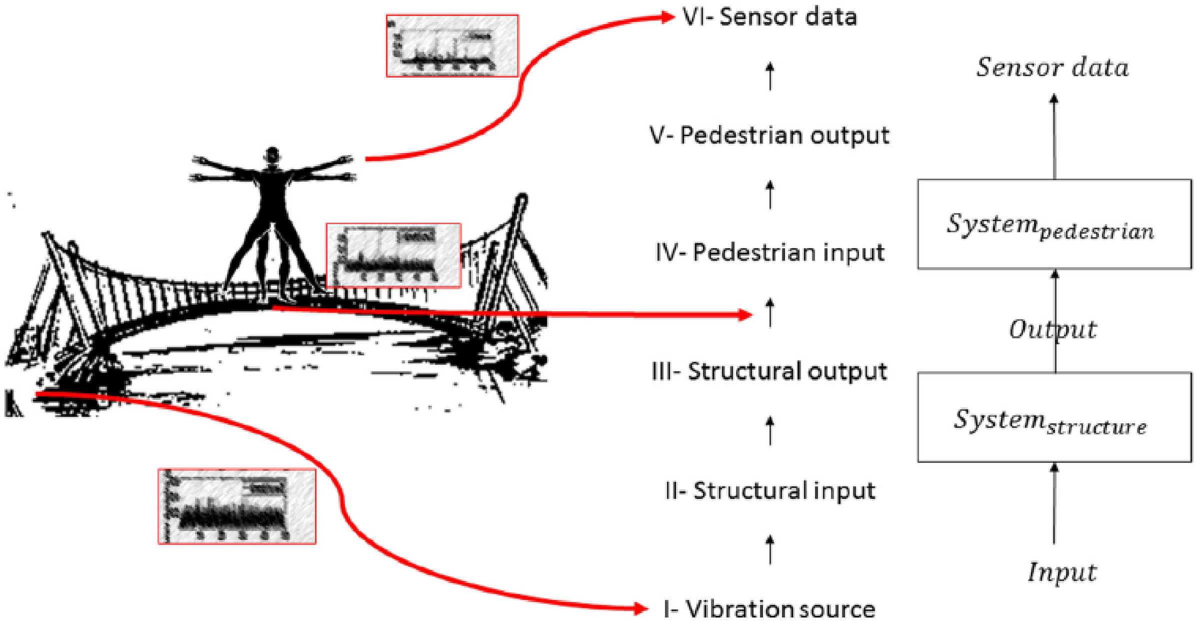

Figure 5: Transformation of the vibration signal from the source to the smartphone

2.4 Field Tests

In order to visualize the proposed methods with experimental data, eight different cases are defined. Case 1, 2, 5, 6, 7 corresponds to vibrations take from a pedestrian on a bridge, while Case 3, 4, and 8 reflects pedestrian standing on fixed ground. In Case 1 and 3, the accelerometer measurements are taken while the pedestrian is moving whereas the rest of the cases correspond to a standing pedestrian. Case 1-4 represents a smartphone carried in a backpack while Case 7 and 8 represents a smartphone carried in a pocket. Case 5 and 6 are the scenarios where there is no pedestrian intervention, and the phone is either in a backpack on the bridge, or directly coupled with the deck surface. Figure 6 shows typical conditions of the smartphone carried by the pedestrian and Figure 7 shows time histories and spectral characteristics of the smartphone measurements of each case.

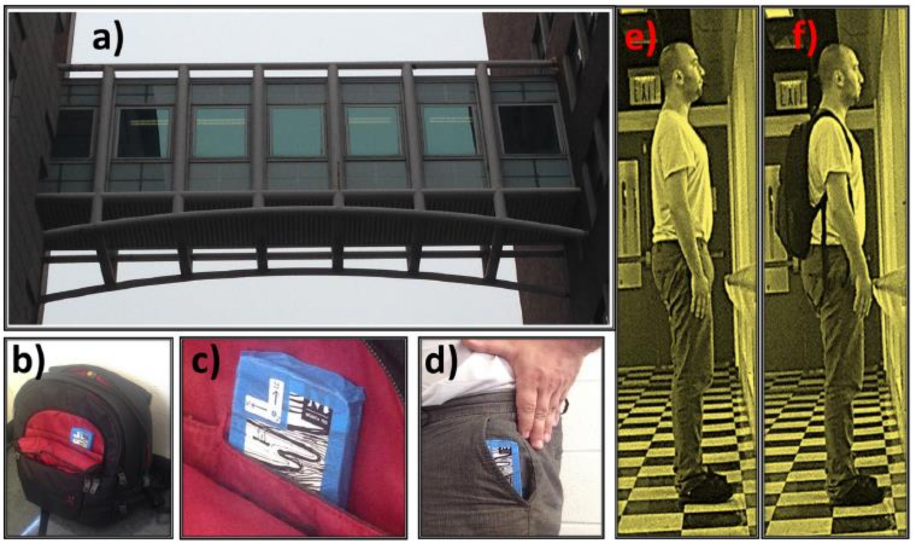

Figure 5: Test-bed bridge and smartphone configuration carried by the pedestrian

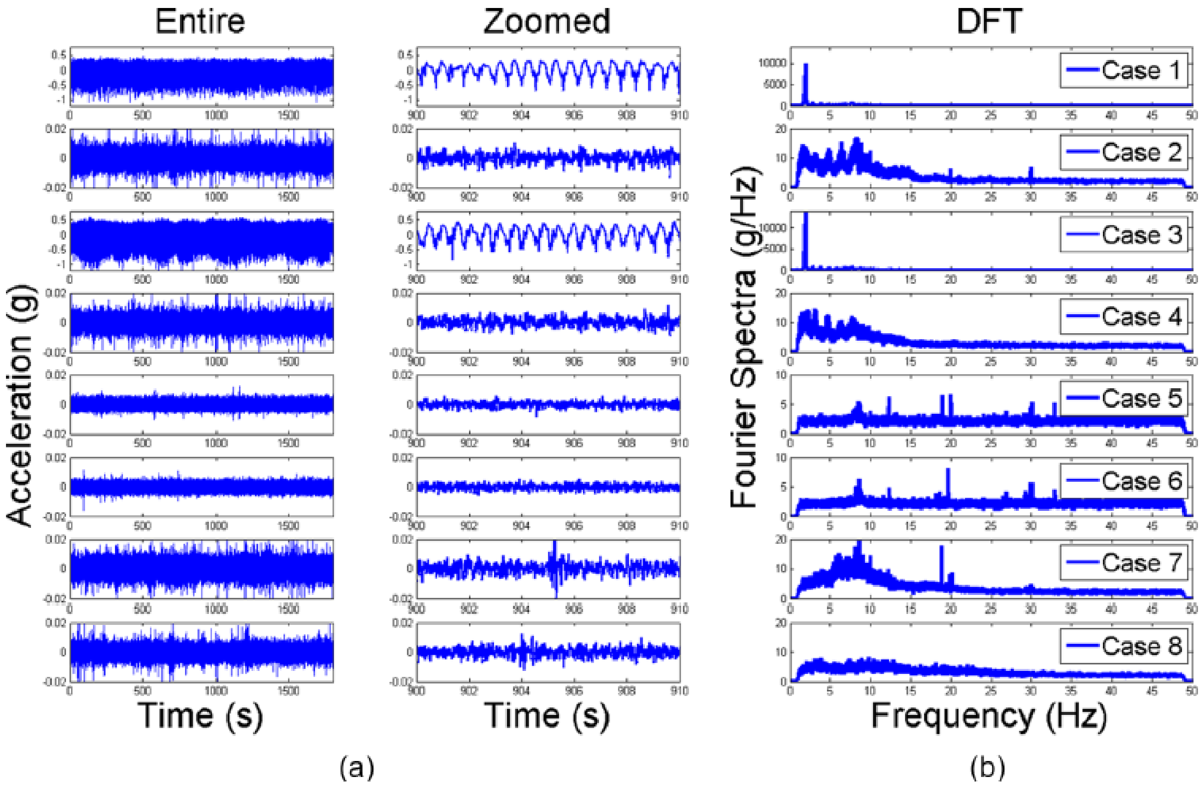

Figure 6: Time histories and spectral characteristics of pedestrian measurements

2.5 Results and Discussion

In summary, 8 cases considering different pedestrian and smartphone mobility conditions are tested. Using these cases, two main scenarios are utilized for a bridge monitoring framework. These frameworks correspond to walk-induced force estimation for the moving pedestrian scenario and modal identification isolating human biomechanical effects for the standing pedestrian scenario.

One of these cases, Case 1 corresponds to the pedestrian walking on the bridge. Modifying accelerometer data in the vertical direction with pedestrian weight, acceleration is converted into walk-induced force which is shown in Figure 7. Looking at the time history and the Fourier spectra of the estimated forces, there is a similar pattern with those obtained from the theoretical models.

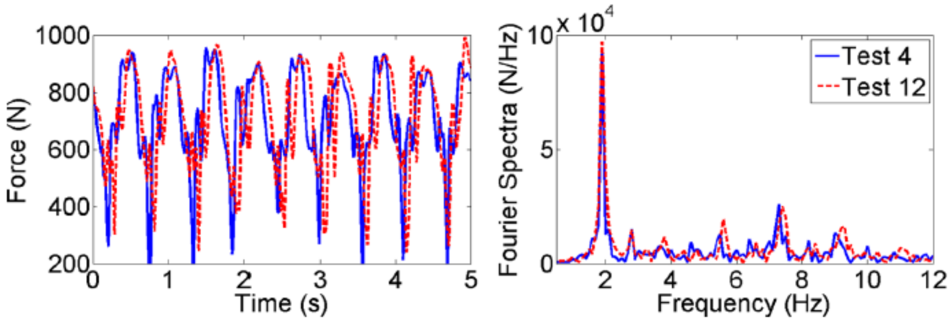

Figure 7: Time history and spectral characteristics of walking pedestrian force estimated by smartphone accelerometer

For the standing pedestrian cases, Case 2 and 7, the pedestrian stands on the bridge whereas for the Case 4 and 8, pedestrian stands on a rigid surface. Case 4 and 8 are processed to develop the biomechanical transfer function of the pedestrian. Afterwards, these transfer functions are used to remove human content from the accelerometer data carried by a standing pedestrian on the bridge. In other words, removing human biomechanical features from the indirect vibration signal, one can obtain bridge-only spectral properties and therefore, identify modal parameters. Figure 8 shows the transformation scheme and Figure 9 shows development of bridge-only spectra from the smartphone accelerometer carried by the pedestrian. Finally, Figure 10 shows results from ideal conditions where smartphone is either directly in contact with the bridge or there is no intermediate biomechanical effects even if there is no direct coupling between the sensor and the structure.

Looking at the results, it can be seen that the transformation significantly removes human-induced vibration content from the indirect signals, and represent bridge dynamics to a much better extent. However, this accuracy is higher for the high frequencies such as 20 and 30 Hz, whereas, the first mode falls within 8.5 Hz range and is still distorted by the biomechanical content up to a certain level.

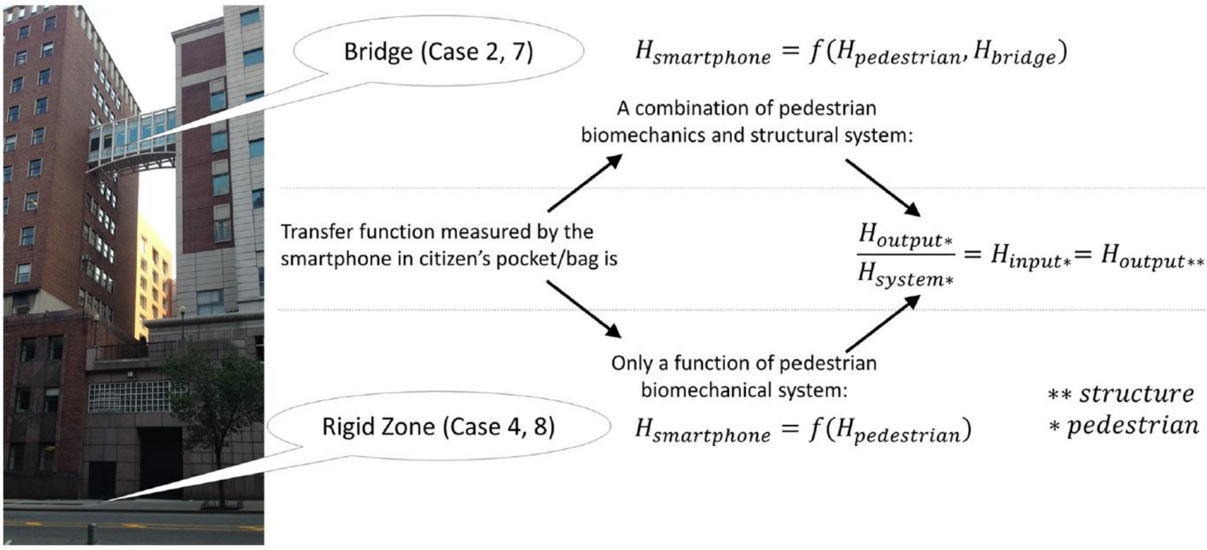

Figure 8: Vibration transfer scheme and development of pedestrian transfer function

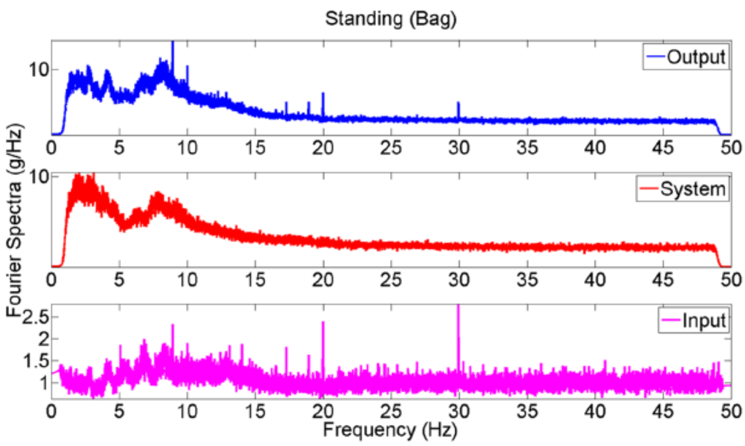

Figure 9: Conversion of smartphone-based pedestrian measurements into bridge spectral characteristics

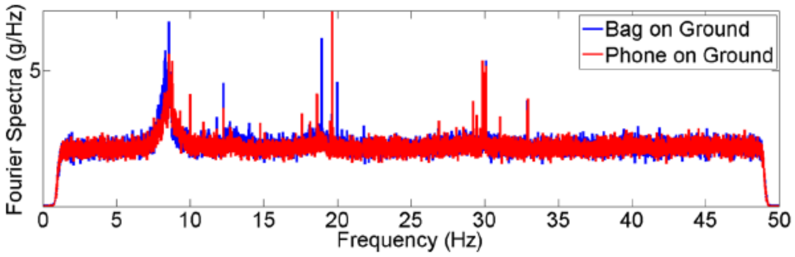

Figure 10: Reference bridge spectral characteristics without biomechanical intervention

3. Conclusion

In summary, this study presents a mobile sensing approach which utilizes pedestrian data for bridge monitoring. Using vibration data from walking pedestrians, one can estimate the dynamic load imposed on the bridge due to the human-induced activity. Using vibration data from standing pedestrians, it is possible to develop human biomechanical models with smartphone accelerometer, and use these models to eliminate biomechanical content from a sensor carried by a standing pedestrian. As a result, one can identify bridge modal characteristics using smartphone data even if there is no coupling between the sensor and the structure. The novel mobile sensing approach presented in this study can be used to understand bridge structural dynamic characteristics with a citizen-engaged and smartphone-based method. Such method can generate ubiquitous vibration datasets which is representative of city-scale bridge health monitoring applications.

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