Smartphone-Based Dynamic Testing of a Rehabilitated Pedestrian Bridge: A Comparative Study with Traditional Accelerometers

SUZANA EREIZ, MARIA PINA LIMONGELLI
ABDOLLAH MALEKJAFARIAN, IVAN DUVNJAK
and JURICA PAJAN

ABSTRACT

The structural health monitoring (SHM) of bridges plays a vital role in ensuring the safety and longevity of aging infrastructure. Recent advances in sensor and mobile technologies have enabled low-cost, scalable, and portable alternatives to conventional monitoring systems. This study presents the development and validation of a cloud-integrated methodology for dynamic testing using smartphones, with a focus on modal identification of bridge structures subjected to ambient vibrations. A rehabilitated pedestrian bridge in Zagreb, Croatia served as the case study. Operational modal analysis (OMA) was performed using both conventional piezoelectric accelerometers and embedded MEMS accelerometers within smartphones. Data were collected in parallel and processed using Artemis Modal Pro software. The results demonstrated a strong correlation between the two measurement systems, confirming the capability of smartphone-based sensing to accurately capture key dynamic characteristics. The proposed approach offers a viable and accessible alternative for SHM, reducing cost and logistical complexity while maintaining sufficient precision for practical engineering applications. Moreover, the integration of mobile technology with automated data processing workflows opens new possibilities for rapid deployment and broader implementation in infrastructure diagnostics. This work contributes to the growing field of smart monitoring solutions, emphasizing the practicality of smartphone-based systems in both research and real-world engineering contexts.

INTRODUCTION

Monitoring the structural health of bridges, including changes induced by environmental conditions and traffic loads, is essential for the early detection of potential damage or deterioration. It also informs maintenance and rehabilitation decisions. Over the past decades, advances in sensor technology [1] and communication systems [2] have enabled the development of sophisticated structural health monitoring (SHM) systems that allow continuous tracking of essential bridge parameters [3]. Analysis of these parameters over time provides insight into the bridge's life-cycle stage, identifies potential structural problems, and predicts future performance [4].

Many bridges are now approaching or have exceeded their intended service life [5], resulting in escalating maintenance and rehabilitation costs. This trend emphasizes the need for efficient, accurate, and cost-effective monitoring systems. Traditional visual inspections, although widely used, present limitations. They require traffic closures, expose inspectors to risks, and are subjective, depending on the inspector's experience and judgment [6]. Hidden or evolving deficiencies can often be missed. Sensor-based monitoring systems, particularly those employing wired sensors such as accelerometers and strain gauges, offer greater precision and objectivity. However, their installation is labor-intensive and costly, requiring drilling into structures, which can introduce minor damage [7]. Wired systems also involve high costs related to data acquisition infrastructure, environmental protection, and ongoing maintenance.

To overcome these challenges, wireless sensor networks (WSNs) have been introduced, offering simpler and faster deployment [8]. Nonetheless, WSNs face their own difficulties, including signal loss, interference, synchronization issues, and battery limitations, especially during dynamic testing. Smartphones have recently emerged as a promising low-cost alternative for structural monitoring [9]. Modern smartphones are equipped with sensitive MEMS accelerometers, gyroscopes, and GPS modules, along with advanced processing and wireless communication capabilities. Various monitoring approaches using smartphones have been proposed, either with stationary devices mounted on structures [10] or through smartphones carried by pedestrians [11] and vehicles [12]. Smartphone sensors can capture key parameters such as natural frequencies of bridges [13] and cables [14], static displacements [15], and surface roughness [16], among others [17]. Prior research has shown that, with appropriate data processing, smartphone-based measurements can achieve remarkable accuracy, providing a low-cost, scalable, and portable SHM solution.

This paper investigates the application of smartphones for dynamic testing of a rehabilitated pedestrian bridge subjected to ambient vibrations. Data collected via smartphones are compared to measurements from conventional accelerometers to assess reliability and accuracy. A custom-developed algorithm was created to enable parallel data acquisition from multiple smartphones through an Online Matlab environment, integrated with automated operational modal analysis using Artemis software. The methodology was validated through a comparative experimental campaign on a rehabilitated pedestrian bridge. The remainder of the paper is structured as follows: Section 2 discusses smartphone-based monitoring concepts; Section 3 describes the case study, including the bridge description, instrumentation, and data acquisition procedures; Section 4 evaluates the feasibility of the smartphone-based methodology. The paper concludes with a summary of key findings and recommendations for future research.

SMARTPHONE BASED STRUCTURAL HEALTH MONITORING

Modal identification of parameters such as natural frequencies, damping ratios, and mode shapes remains fundamental to structural health monitoring (SHM). These dynamic properties describe a structure's behavior under operational conditions and are essential for early damage detection and monitoring degradation. Traditionally, identifying them requires high-precision instruments, complex cabling, and expensive data systems. Recent advances in mobile technology, however, have enabled low-cost and accessible alternatives, particularly through smartphones with MEMS accelerometers. Recent studies have explored the use of smartphones for SHM in both drive-by and stationary configurations. Matarazzo et al. [18–20] showed that smartphones mounted in vehicles could successfully capture modal properties of long-span bridges, accounting for sensor variability and vehicle dynamics. Other researchers have applied methods such as inverse filtering [21], wavelet transforms [22], and matrix completion [23] to improve signal quality and enable modal parameter extraction from noisy, asynchronous datasets. Beyond vehicular applications, stationary smartphones placed directly on structures have also effectively recorded ambient and operational vibrations, allowing for the detection of natural frequencies and mode shapes [24–26]. Advanced processing techniques like Variational Mode Decomposition, Random Decrement Technique [27], and Second Order Blind Identification [28], have further enhanced measurement data reliability. The scalability of this approach has enabled large-scale SHM initiatives, such as the study by Castellanos-Toro et al. [29] who successfully performed modal identification across 450 bridges within an urban network.

The main contribution of this study is the development and experimental validation of an integrated, cloud-based framework for smartphone-enabled modal identification. Unlike previous approaches, the proposed methodology unifies data acquisition, synchronization, and processing into a single streamlined workflow. As shown in Figure 1, the process includes: (1) data acquisition—placing multiple smartphones at predefined bridge locations to collect real-time acceleration data via MATLAB Mobile; (2) cloud synchronization and preprocessing—automatic upload and signal alignment using custom scripts; and (3) modal analysis—importing processed data into Artemis Modal Pro for extracting key dynamic parameters.

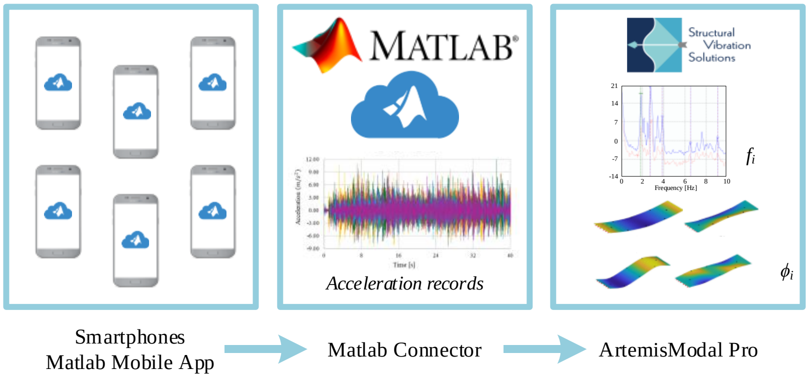


Figure 1. Methodology for dynamic testing using smartphones: (1) Synchronized data collection via MATLAB Mobile; (2) Cloud upload to MATLAB; (3) Modal analysis in Artemis Modal Pro.

This system provides a cost-effective, portable, and scalable alternative to traditional SHM techniques, reducing reliance on expensive equipment and complex logistics. Its effectiveness was confirmed through a field test on a rehabilitated pedestrian bridge in Zagreb, Croatia. The results demonstrate that smartphone-based dynamic testing, combined with cloud processing, can deliver accurate and reliable diagnostics under real-world conditions, highlighting its potential for broader application in smart infrastructure monitoring.

CASED STUDY

This chapter describes the bridge, instrumentation setup, measurement procedures, and comparative analysis of the results. Measurements using both smartphones and conventional accelerometers enabled evaluation of the accuracy and reliability of each method

Description of structure

The Old Sava Bridge in Zagreb, Croatia (Figure 2.), also known as the Blue Bridge, was originally constructed in 1939 based on a design by Milivoj Frković. The current superstructure is a combination of steel girders and a reinforced concrete deck, resting on a masonry substructure dating back to 1892. The bridge consists of four spans of approximately 55 meters each, with a total length of 219 meters and a width of 9 meters, including cantilevered sidewalks.

Figure 2. The pedestrian bridge over the Sava River – the Old Sava Bridge ("Blue Bridge") in Zagreb

Originally built for vehicular traffic, the bridge now primarily serves pedestrians and cyclists after the construction of the nearby Adriatic Bridge. The 1939 construction introduced advanced welding techniques and reinforced concrete wind bracing, with partial composite action between the deck and steel girders confirmed by later testing. In 2019, major rehabilitation was undertaken due to damage and heritage status: the concrete deck was replaced, while the steel superstructure remained intact. The main structural issue was the poor seismic performance and age-related deterioration of the masonry substructure, particularly the central pier, which was addressed by installing shock transmission units (STUs) to redistribute seismic forces and control displacements without restricting thermal movement

Traditional operational modal analysis

To evaluate the proposed smartphone-based methodology for structural health monitoring (SHM), a comparative test using conventional accelerometers was conducted on one of the central spans—selected for its geometric and structural symmetry and assumed to be representative of the entire bridge—with measurement points placed at quarter-span locations, approximately 13.8 meters apart. (Figure 3).

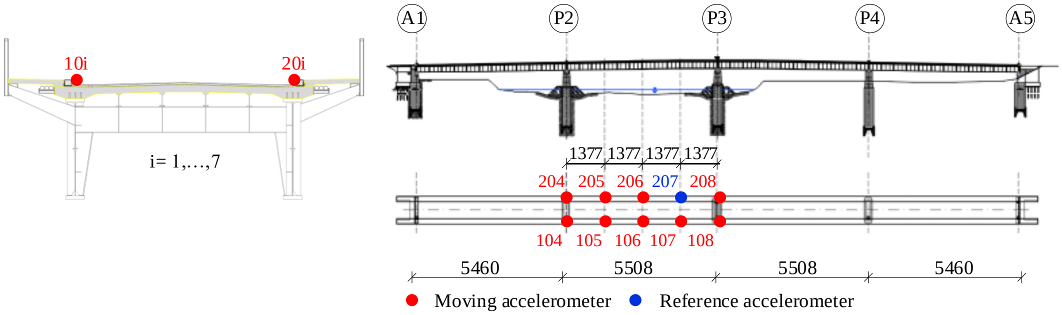
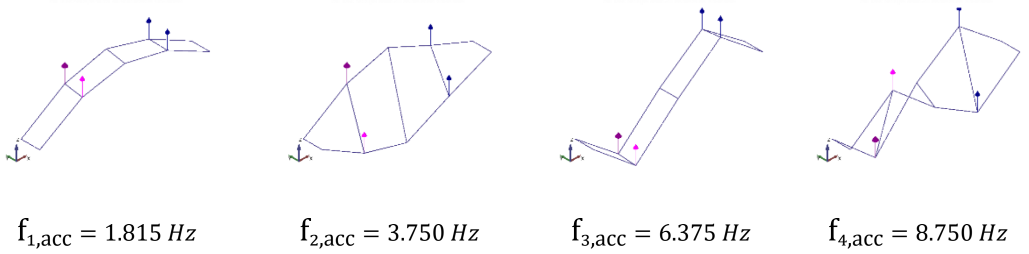


Figure 3. Schematic view of sensor locations: cross-section (left) showing edge positions and longitudinal section (right) with reference and measurement points spaced approx. 13.8 m apart

Sensors were placed at the cross-section edges to better capture torsional vibration modes. Measurements were performed using Brüel & Kjær piezoelectric accelerometers (1000 mV/g sensitivity) and a 3560C data acquisition system. Data was recorded at 128 Hz over 256 seconds and processed in Artemis Modal Pro to extract natural frequencies and mode shapes. Due to limited sensors and channels, a multi-setup approach was used, with one fixed reference point while others were repositioned to capture all degrees of freedom (x, y, z) (Figure 3). Modal analysis results are shown in Figure 4. and Figure 5.



$f_{1,acc} = 1.815\ Hz$ $f_{2,acc} = 3.750\ Hz$ $f_{3,acc} = 6.375\ Hz$ $f_{4,acc} = 8.750\ Hz$

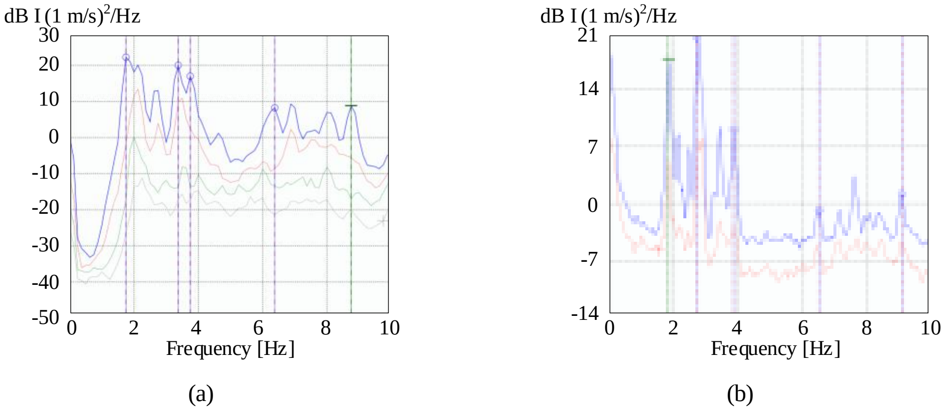
Figure 4. Numerical natural frequencies $\left(f_{i,acc}\right)$ and mode shapes $\left(\Phi_{i,acc}\right)$ obtained from the initial FEM of the laboratory footbridge for *i = 1, …,4.*

Smartphone-based operational modal analysis

To assess the potential of smartphones for low-cost structural health monitoring, ambient vibration measurements were conducted using four Android-based smartphones from the Samsung Galaxy series. Each device was equipped with the MATLAB Mobile application and configured to acquire acceleration data at the maximum available sampling frequency of 100 Hz. All smartphones were connected to the same local wireless network as the control computer, from which the data acquisition process was initiated. The measurements were carried out concurrently with the conventional accelerometer testing, and each smartphone recorded tri-axial acceleration (X, Y, Z) over a duration of approximately 256 seconds, matching the acquisition time used for the reference system. Due to the limited number of available smartphones, a multi-setup measurement approach was employed. The same number and configuration of measurement points were used as in the conventional setup. At each configuration step, one point was designated as the fixed reference location, while the smartphones were repositioned to cover all intended measurement locations. Although time synchronization between devices was not explicitly implemented, identical sampling frequencies and synchronized measurement start ensured comparability of the collected data. The smartphones were placed directly on the bridge deck surface. Prior to placement, the surface was cleaned to minimize irregularities and improve smartphone stability during recording. No additional mounting hardware was used. The collected data were processed using Artemis Modal Pro software. Operational Modal Analysis (OMA) techniques were applied to extract key dynamic characteristics of the structure, including natural frequencies (Figure *5*. (b)) and mode shapes. These results were then compared (Table *1*.) with those obtained from conventional piezoelectric accelerometers to evaluate the reliability and performance of smartphone-based measurements.

Comparison of the traditional and smartphone-based OMA results

To evaluate the applicability and reliability of different types of accelerometers for Operational Modal Analysis (OMA), a comparative study was conducted using acceleration data obtained from two distinct sources. The first dataset was collected using conventional high-precision accelerometers, while the second dataset was acquired via embedded accelerometers in smartphones. Both datasets refer to the same structural object and were recorded under comparable environmental and operational conditions to ensure a consistent basis for comparison. The OMA was performed in Artemis Modal Pro software using the Frequency Domain Decomposition (FDD) method, which was applied consistently to both datasets to maintain methodological uniformity. Two separate projects were created within Artemis: Project 1 incorporated data from conventional accelerometers and Project 2 included data gathered using smartphone sensors. Upon completion of the modal analysis in each individual project, the results were compared using the Overlay Project Results functionality available in Artemis. This feature enables simultaneous visualization and comparison of modal parameters—specifically mode shapes and natural frequencies—identified in both projects. The comparison procedure focused on the identification of corresponding mode shapes between the two datasets and the examination of the consistency of the estimated natural frequencies. To support quantitative evaluation of the mode shape similarity, Modal Assurance Criterion (MAC) values were computed using built-in tools in Artemis. This structured methodology ensures that the comparison process is carried out under standardized conditions, enabling a reliable basis for evaluating potential discrepancies or equivalence in the identified modal parameters when using different types of sensing devices. The results obtained through this comparison are further discussed in the following section.



(a) (b)

Figure 5. Characteristic record of frequency domain decomposition (FDD) for the determination of natural frequencies of the pedestrian bridge using acceleration records from (a) high precision accelerometers (b) accelerometers embedded in smartphones

DISCUSSION

To evaluate the accuracy of using smartphones for the identification of modal parameters, the results of operational modal analysis based on data collected with smartphones were compared to those obtained from acceleration data recorded during ambient vibrations using conventional sensors. The comparison of natural frequencies revealed a close correspondence between the two datasets. The frequency values identified from the smartphone accelerometer data differed only slightly (max 3.3.%) from those obtained with conventional high-precision accelerometers, typically within a few percent (Table 1.). This level of deviation is generally considered acceptable in the context of operational modal analysis, especially given the lower measurement precision and limited frequency range of MEMS sensors integrated in mobile devices. In terms of mode shapes (Table 1.), all four compared modes exhibited a generally high degree of similarity, indicating that smartphone sensors can capture the structural dynamic behavior with sufficient fidelity. Minor discrepancies were observed in the higher-order modes, which can likely be attributed to differences in sensor sensitivity and signal-to-noise ratio. Nevertheless, these variations did not significantly affect the overall modal characteristics, and the dominant deformation patterns remained consistent across both datasets.

Table 1. Percentage differences between natural frequencies obtained using conventional accelerometers and smartphone sensors. Values are calculated relative to frequencies from conventional sensors.

Mode, i	$f_{i,acc}$ [Hz]	$f_{i,phone}$ [Hz]	Δf_i [%]	MAC $(\Phi_{i,acc}, \Phi_{i,\mathrm{phone}})$
1	1.825	1.845	1.1	0.995
2	3.750	3.875	3.3	0.991
3	6.325	6.345	0.3	0.985
4	8.750	8.785	0.4	0.982

These observations support the potential of using smartphone-based sensing systems in practical modal testing applications, especially for the identification of lower-frequency modes in structures.

CONCLUSION

This study presented an experimental investigation into the use of smartphones for dynamic testing of bridge structures through operational modal analysis (OMA) based on ambient vibrations. The research was conducted on a rehabilitated pedestrian bridge in Zagreb, utilizing both conventional piezoelectric accelerometers and modern smartphones equipped with MEMS sensors. An integrated methodology was developed, encompassing synchronized data acquisition via the MATLAB Mobile application, automated cloud-based signal processing, and modal analysis using the professional software package Artemis Modal Pro. The results demonstrated a high degree of consistency between the traditional and smartphone-based measurement systems. Natural frequencies identified using smartphone sensors deviated by less than

3.3% from reference values, while Modal Assurance Criterion (MAC) values for the compared mode shapes exceeded 0.98, confirming the reliability and accuracy of the proposed approach. These findings validate the feasibility of employing smartphones for low-cost, accessible, and efficient structural health monitoring, particularly in preliminary assessments, rapid diagnostics, and large-scale applications. Future research should focus on enhancing real-time synchronization between devices, optimizing data processing algorithms for larger sensor networks, and exploring long-term monitoring performance under real operational conditions. Additionally, the integration of participatory data collection approaches (e.g., through moving users) presents promising opportunities for advancing the field of smart infrastructure.

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