Monitoring Infrastructure Vibrations with a Vehicle Platform: Mobile Sensing versus Conventional Accelerometers

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Abstract. This contribution presents an experimental study investigating the potential of mobile-sensing strategies for vibration-based identification (VBI) of infrastructures. The work focuses on the use of a small-scale vehicle as a mobile sensing unit, instrumented with both conventional accelerometers and a commercial smartphone, with the aim of assessing the feasibility of low-cost and easily deployable monitoring solutions versus professional sensing equipment. The proposed approach relies on vehicle–structure interaction: the instrumented vehicle is driven at controlled speeds over selected infrastructures in the urban area of Palermo (Italy), enabling the acquisition of dynamic response data associated with both the vehicle and the underlying structure. The accelerations recorded by piezoelectric sensors, considered as reference measurements, are complemented by those collected through the embedded sensors of the smartphone. This dual-sensing configuration allows for a systematic evaluation of sensitivity, noise performance, and the capability of extracting key vibration-based features. While the accelerometer-equipped setup demonstrates clear potential for identifying structural dynamic characteristics, the performance of the smartphone presents a more nuanced outcome. Issues related to noise, sampling stability, and environmental interference are considered, with the aim of understanding the limitations and possible preprocessing strategies required for reliable modal identification. The analysis highlights the conditions under which smartphone measurements may approach acceptable accuracy, as well as scenarios where their performance remains insufficient without additional filtering or calibration. While demonstrated on a scaled vehicle platform, the methodology is applicable to other structures and mobile sensing scenarios. Despite these open challenges, the study reinforces the promise of mobile-sensing techniques as scalable and cost-effective tools for structural diagnostics. The results contribute to the ongoing development of practical methodologies for vibration-based assessment that could, in the future, support widespread, rapid, and user-friendly structural monitoring campaigns in transportation networks.

Keywords: Mobile-Sensing, Vibration-Based Identification, Smartphone sensors, Scaled Vehicle, Structural Monitoring.

Introduction

The assessment of bridges and transport infrastructure is increasingly important as many structures operate under progressive ageing, repeated service loading, environmental degradation, and occasional extreme events. Within this scenario, Structural Health Monitoring (SHM) has become a

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central framework for condition assessment, early warning, and maintenance planning [1-3]. Among vibration-based techniques, Operational Modal Analysis (OMA) is one of the most established tools because it enables the estimation of natural frequencies, damping ratios, and mode shapes from measurements collected under operating conditions. OMA methods may be formulated in the time domain, for example through the Natural Excitation Technique (NExT) and Stochastic Subspace Identification (SSI), or in the frequency domain through procedures such as Peak Picking and Frequency Domain Decomposition (FDD) [4-6]. Despite OMA reliability, its practical implementation, however, often requires several sensors installed on the structure, dedicated acquisition hardware, power supply, and a non-negligible setup effort, which limits frequent or network-scale applications. [7-8].

For this reason, indirect monitoring strategies based on Vehicle–Bridge Interaction (VBI) have attracted growing interest [9]. In this framework, bridge dynamic properties are inferred from the response of an instrumented vehicle crossing the structure, thereby reducing the need for fixed sensors on the bridge itself. Foundational studies demonstrated that bridge frequencies can be extracted from the dynamic response of a passing vehicle, establishing the theoretical basis of this approach [10-11]. Subsequent investigations confirmed its potential, while also highlighting critical factors such as pavement roughness, vehicle-related frequencies, and signal-processing choices [12-15]. In parallel, the diffusion of smartphones equipped with embedded micro-electro-mechanical systems (MEMS) accelerometers has opened the possibility of extremely accessible mobile sensing solutions. Their portability, accessibility, and ease of deployment make them particularly attractive for scalable and potentially crowd-sensing-oriented monitoring frameworks [16]. Within the VBI context, smartphone-assisted measurements are especially appealing because they may significantly reduce instrumentation costs while enabling rapid and repeatable data collection. However, the available experimental evidence is still limited, and further validation is required to assess the reliability of smartphone MEMS accelerometers with respect to conventional piezoelectric sensors, particularly when modal identification is pursued under realistic operating conditions. In this regard, recent experimental work has shown that smartphone-based VBI measurements can provide meaningful estimates of bridge frequencies and that the agreement with conventional accelerometers may be satisfactory under controlled crossing conditions and suitably low vehicle speeds [17]. At the same time, the literature also indicates that the accuracy of indirect identification is strongly influenced by vehicle motion conditions and by the characteristics of the mobile sensing platform [17-18].

Within this context, the present study investigates a smartphone-assisted dynamic identification strategy based on a scaled instrumented vehicle equipped with both professional accelerometers and a low-cost smartphone sensor, and experimentally assessed on a pedestrian footbridge located in Palermo, Italy. The investigation is structured around a preliminary validation of the sensing system and a field application in which the dynamic properties of the monitored span are identified indirectly through the vehicle–bridge interaction mechanism, and then compared with reference frequencies independently obtained through a conventional OMA campaign.

To this end, the study adopts a simplified stop-and-go procedure, in which the instrumented vehicle is sequentially moved to predefined locations along the deck and temporarily held stationary during each acquisition stage. This strategy is intended not only to improve the observability of the structural contribution in the recorded response, by reducing the influence of continuous vehicle motion and enabling the analysis of short quasi-stationary intervals, but also to reproduce realistic traffic situations in which vehicles may intermittently stop because of congestion or regulated traffic flow. In this way, the proposed approach moves beyond idealized constant-speed crossing conditions and explores a traffic-oriented operational setting that remains compatible with low-cost sensing and simplified instrumentation.

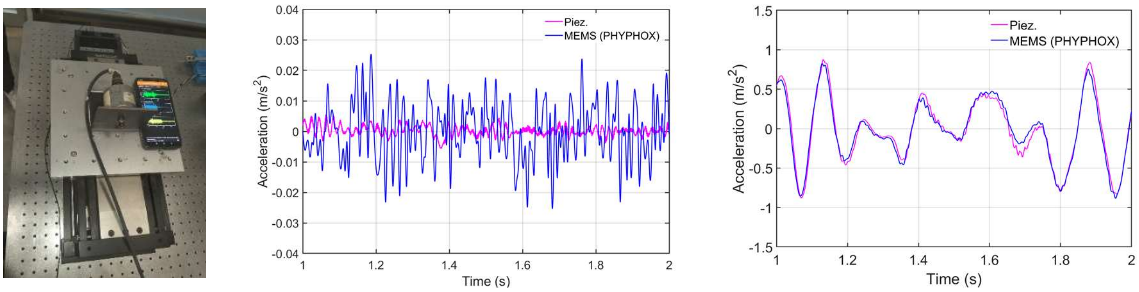
The proposed framework is therefore intended to contribute to the development of low-cost, easily deployable, and experimentally robust procedures for the vibration-based assessment of transportation infrastructure. More specifically, the study aims to clarify the extent to which smartphone MEMS measurements can support indirect dynamic identification when compared with conventional accelerometers, while also assessing whether a reduced and operationally simple stop-and-go setup can still provide reliable estimates of the main structural frequencies. In this sense, the work lies at the intersection of indirect bridge monitoring, mobile sensing, and traffic-informed testing conditions, with the broader goal of supporting more accessible strategies for the continuous assessment of urban infrastructure networks.

1. Preliminary tests

Before the footbridge tests, a preliminary experimental phase was carried out to verify the suitability of the sensing setup and to support the interpretation of the subsequent indirect measurements. The activity addressed two main aspects. First, the response of the smartphone MEMS accelerometer was compared with that of a reference seismic sensor in order to assess the reliability of the low-cost acquisition chain. Second, the dynamic behaviour of the vehicle platform was examined under operating conditions representative of those later adopted in the bridge campaign. These preliminary investigations were therefore not intended as a stand-alone study of the vehicle, but as a necessary step to validate the measurement strategy and to distinguish vehicle-related contributions from bridge-induced response in the VBI tests.

1.1 Comparison between smartphone and reference accelerometer

A preliminary laboratory test was first performed to compare the acceleration signals acquired by the smartphone through the Phyphox application with those measured by a reference seismic accelerometer connected to a National Instruments NI PXIe-1082 acquisition system. The comparison focused on the acceleration component along the direction of shaking-table excitation. Two sensors were mounted on the upper plate of the shaking table: a seismic accelerometer (PCB 393B31), adopted as reference sensor for its high sensitivity and low noise, and the MEMS accelerometer embedded in a Xiaomi Redmi Note 13 smartphone (Fig. 1). The two devices were therefore subjected to the same imposed motion, allowing a direct comparison of their outputs under controlled excitation conditions. The tests were carried out under three input conditions: harmonic excitation at constant frequency, chirp-sine excitation, and broadband noise. For each case, the acceleration time histories recorded by the smartphone and by the seismic sensor were processed in MATLAB. To make the two datasets comparable, the MEMS signal was first detrended in order to remove possible offsets and the constant gravity component. The signals were then temporally aligned to compensate for possible delays between the two acquisition systems. Finally, the smartphone data were interpolated to match the time resolution of the PXIe recordings, thus enabling a consistent comparison in the time domain. For brevity, only the results obtained under broadband excitation are presented here, as this input better reflects the operating conditions considered in the subsequent experimental campaign while also providing a more informative assessment of sensor performance over a wider frequency range [19]. In particular, the comparison was performed for two acceleration levels, approximately 0.025 m/s^2 (Fig.1(b)) and 1 m/s^2 (Fig.1(c)). The results show that the agreement between the MEMS sensor and the reference accelerometer is satisfactory at the higher amplitude level, whereas more evident discrepancies arise at lower amplitudes. This behaviour is reasonably attributed to the lower sensitivity and limited resolution of the embedded MEMS sensor, whose influence becomes more significant when the measured response approaches the sensor noise floor. Despite these limitations, the results suggest that smartphone-based MEMS sensors can be effectively employed provided that the vibration levels are sufficiently high compared withthe sensor noise floor. In this perspective, a preliminary evaluation of the response amplitudes expected under ambient excitation appears advisable in order to assess whether the sensing system can deliver sufficiently reliable measurements.

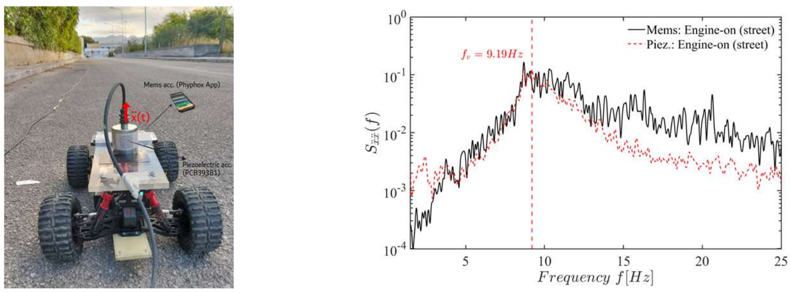


(a) (b) (c)

Fig. 1. Preliminary shaking-table test: (a) experimental setup; (b)-(c) comparison between seismic and smartphone-based acceleration signals under broadband excitation, at approximately (b) 0.025 m/s² and (c) 1 m/s².

1.2 Dynamic characterization of the vehicle platform

The mobile platform used in the preliminary tests, and later in the bridge campaign, was an electric 1:10 scale radio-controlled vehicle with four-wheel drive manufactured by Radio Kontrol (RK). A scaled platform of this type is attractive for VBI applications because it is inexpensive, easy to instrument, highly repeatable in laboratory conditions, and suitable even for infrastructures that cannot be crossed by full-scale vehicles, such as pedestrian bridges. Vehicle accelerations were measured through a conventional seismic piezoelectric accelerometer (PCB 393B31), connected to a Digital ICP USB Signal Conditioner (model 485B39) and managed through a custom LabVIEW acquisition interface with sampling frequency equal to 1000 Hz. In parallel, a Redmi Note 13 Pro 5G smartphone was fixed to the vehicle to record accelerations through its embedded MEMS sensor using the Phyphox application. In the present work, only the vertical component was retained. For the adopted smartphone, the average sampling frequency was approximately 105 Hz. To examine the vehicle behaviour under conditions closer to those later encountered during the bridge tests, measurements were carried out on asphalt pavement with the vehicle travelling at approximately constant speed (Fig. 2(a)). The recorded signals were processed in MATLAB, and the corresponding Power Spectral Density (PSD) functions were computed for both the piezoelectric and smartphone-based measurements. In both datasets, a distinct dominant peak was identified at approximately 9.19 Hz (Fig. 2(b)). This frequency was therefore assumed as the representative vehicle-related reference for the interpretation of the subsequent VBI campaign.



(a) (b)

Fig. 2. On-road characterization: (a) asphalt test layout; (b) PSD comparison between piezoelectric and MEMS measurements.

2 Dynamic investigation of a pedestrian footbridge through OMA and smartphone-assisted VBI

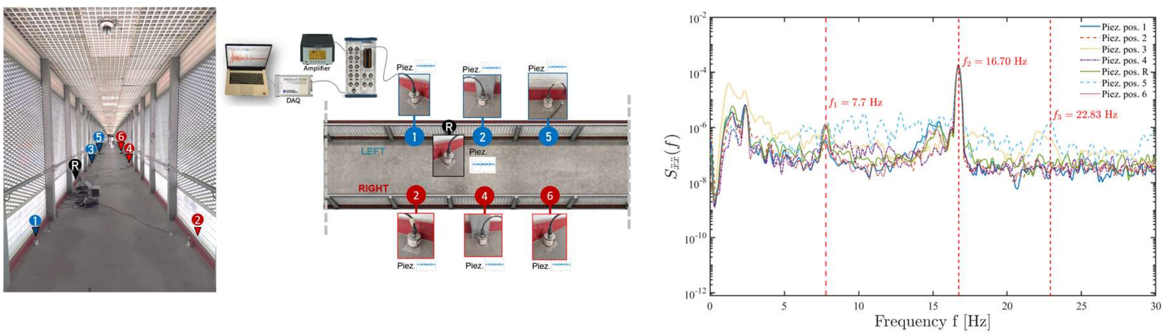
The experimental campaign was carried out on the Via Emiri pedestrian footbridge in Palermo, Italy, shown in Fig. 3. The structure spans Viale Regione Siciliana, one of the city's main urban traffic arteries, and provides a protected pedestrian crossing over a heavily trafficked roadway. From a structural viewpoint, the footbridge consists of a two-span steel system with truss-like main members supporting the deck, together with two access towers located at the opposite ends of the structure. In the present study, the analysis was restricted to one span only, between two supports, which was selected as the monitored segment for both the reference and indirect identification tests.

2.1 Reference identification through OMA

A conventional Operational Modal Analysis (OMA) campaign was first carried out in order to define a reference set of structural frequencies for the bridge. To this end, seven mono-axial piezoelectric accelerometers (PCB 393B31) were installed along the deck to measure vertical accelerations at locations selected so as to capture the expected modal response while limiting the influence of nodal regions. Four sensors were placed on the left side of the deck and three on the right, as shown in Fig. 4(a). One of these positions, denoted as R, was retained as a fixed reference point and was subsequently used as the bridge-mounted sensor during the indirect VBI tests. The sensing chain consisted of a laptop-based acquisition system connected to a National Instruments DAQCard-6036E, interfaced with an NI BNC-2110 terminal block. Since the piezoelectric accelerometers require signal conditioning, all sensors were connected to a NEXUS signal conditioner/amplifier, which provided the necessary power supply and signal amplification before data acquisition. The acceleration signals were then digitized and recorded on the PC at a sampling frequency of 1000 Hz. The analysis was based on five one-minute records processed in MATLAB. A Butterworth band-pass filter in the range 1–30 Hz was applied, and the PSDs were estimated using Welch's method with a Hanning window and 50% overlap. When the bridge was directly excited by pedestrian passage, three distinct frequencies emerged at approximately 7.7 Hz, 16.70 Hz, and 22.83 Hz (Fig. 4(b)). These values were therefore assumed as the reference natural frequencies of the structure for the subsequent comparison with the indirect measurements.

(a) (b)

Fig.3. Via Emiri pedestrian footbridge in Palermo: (a) external view; (b) internal view.

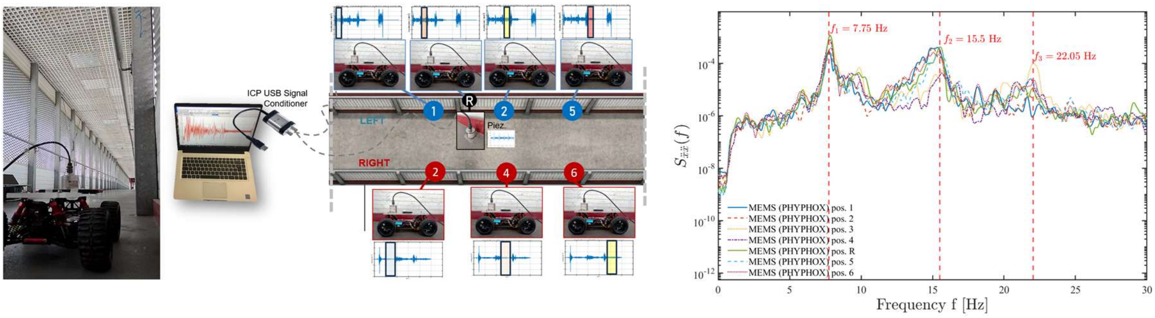


(a) (b)

Fig. 4. Reference OMA campaign: (a) sensor layout on the deck; (b) PSDs from the OMA campaign under ambient vibration.

2.2. Indirect identification through stop-and-go VBI tests

Once the reference frequencies had been established through the OMA campaign, the proposed indirect identification procedure was assessed by means of a stop-and-go VBI configuration. Compared with the reference OMA setup, the instrumentation was reduced to a minimum (Fig. 5(a)) and consisted of one smartphone mounted on the vehicle, one piezoelectric accelerometer installed on the vehicle as a benchmark, and one piezoelectric accelerometer left on the bridge at the reference position R. In this arrangement, the vehicle-mounted piezoelectric sensor was used to evaluate the consistency of the smartphone measurements, whereas the bridge-mounted sensor provided a fixed structural reference during the tests. The vehicle was remotely driven to each of the seven deck locations previously considered in the OMA layout and then temporarily stopped, as illustrated in Fig. 5(a). These positions corresponded to the same points instrumented during the reference campaign, thus allowing a direct comparison between direct and indirect measurements. The adopted procedure was intended to reproduce a simplified stop-and-go operating condition, in which the vehicle response could be recorded during short quasi-stationary intervals rather than during uninterrupted motion. At each location, the vehicle remained at rest for approximately 20 s, while acceleration data were simultaneously acquired from the smartphone, the vehicle-mounted piezoelectric sensor, and the reference sensor on the bridge. The PSDs, depicted in Fig. 5(b), obtained from the smartphone measurements showed that the main structural frequencies previously identified through OMA could also be retrieved from the mobile sensing system. In particular, the corresponding peaks were detected at approximately 7.75 Hz, 15.5 Hz, and 22.05 Hz. As can be seen in Fig. 5(b), the PSDs obtained from the smartphone measurements still exhibit a limited contribution from the vehicle dynamics between the two main frequencies; however, this influence does not appear to substantially affect the identification of the dominant structural frequencies. As reported in Table 1, the agreement is particularly good for the first mode, for which the error is minimal, while the correspondence becomes less accurate for the higher-frequency components. Nevertheless, the overall comparison remains satisfactory, indicating that the proposed simplified setup can still provide a sufficiently reliable estimate of the main dynamic properties of the bridge.



(a) (b)

Fig. 5. Stop-and-go VBI tests: (a) experimental setup; (b) PSDs from piezoelectric and MEMS vehicle measurements.

Table 1. Comparison between frequencies identified through reference OMA and the stop-and-go VBI tests.

Frequencies	OMA	stop-and-go VBI	Discr. [%]
f_1 [Hz]	7.7	7.75	0.65
f_2 [Hz]	16.70	15.5	7.19
f_3 [Hz]	22.83	22.05	3.42

Frequencies	OMA	stop-and-go VBI	Discr. [%]
f_1 [Hz]	8.09	8.12	0.37
f_2 [Hz]	11.76	11.29	4.00
f_3 [Hz]	17.55	17.58	0.17

3. Concluding remarks

This study investigated a smartphone-assisted VBI strategy for the indirect dynamic identification of a pedestrian footbridge, combining a preliminary validation of the sensing system with a field application on a real case study for which the reference modal frequencies were independently obtained through OMA. The preliminary tests showed that the smartphone-based MEMS sensor, although less accurate than the reference piezoelectric instrumentation at very low response levels, can still provide sufficiently consistent measurements when vibration amplitudes remain adequately above the sensor noise floor. The same preliminary phase also allowed the dominant vehicle-related frequency to be identified under operating conditions, representative of the subsequent bridge tests, thus providing a useful reference for the interpretation of the indirect measurements.
In this context, the present work adopts a stop-and-go procedure in which the instrumented vehicle is sequentially moved to predefined locations along the deck and temporarily held stationary during each acquisition stage. This strategy was introduced to improve the observability of the structural contribution in the recorded response, by limiting the influence of continuous vehicle motion and allowing the signal to be analysed over short quasi-stationary intervals, while also reflecting realistic traffic scenarios in which vehicles may temporarily stop due to traffic flow conditions. The bridge application confirmed that this approach can retrieve the main structural frequencies of the monitored span with overall satisfactory agreement with the reference OMA results. In particular, the agreement was very good for the first mode, for which the discrepancy was minimal, whereas the correspondence for the higher modes was less accurate, though still acceptable, suggesting that the proposed setup can provide a sufficiently reliable estimate of the principal dynamic properties of the structure while relying on a low-cost and operationally simple sensing scheme.
At the same time, the results confirm that the quality of the identification remains dependent on excitation level, sensor resolution, and measurement strategy. Future developments will therefore focus on improving MEMS-oriented signal processing, refining the experimental protocol, and extending the approach toward more advanced output targets, such as modal-shape estimation and broader in-service monitoring applications.

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