Output-Only Modal Analysis and System Identification for Indirect Bridge Health Monitoring: Needs, Requirements, and Limitations

Output-only modal analysis and system identification for indirect bridge health monitoring: needs, requirements, and limitations

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Abstract. Vibration-Based Structural Health Monitoring (SHM) relies on analyzing the vibrational response of structures to identify damage-sensitive features, offering early warnings of potential structural anomalies. Widely adopted over the past decades, these methods typically utilize data from permanently installed sensing devices, enabling continuous and permanent dynamic monitoring under ambient excitation. Operational Modal Analysis (OMA) algorithms play a crucial role in extracting damage-sensitive modal parameters, such as natural frequencies and associated mode shapes.

Despite the success of this traditional framework, challenges arise when applied to extensive road networks, such as the Italian highway system, characterized by a multitude of bridges and viaducts spanning over 3,000 km. Consequently, there has been a notable surge in interest in recent years in drive-by or indirect Bridge SHM (iBSHM), where data is collected by a moving sensing vehicle. However, characterizing bridge dynamics solely based on output recorded during vehicle movement or while stationary presents a complex undertaking.

This paper aims to provide a comprehensive overview of the primary theoretical and practical challenges in the realm of drive-by or indirect SHM. Additionally, it explores the necessary enabling technologies to effectively address these challenges, shedding light on the evolving landscape of structural health monitoring in extensive infrastructure networks.

Keywords: Indirect Structural Health Monitoring · Drive-by Structural Health Monitoring · Modal Analysis · Moving Sensing Vehicle · Bridge network

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1 Introduction

In the field of civil engineering, ensuring the reliability of infrastructure is of paramount importance. Addressing this concern, Structural Health Monitoring (SHM) has emerged as a steadily growing research focus. One of the primary objectives of SHM is to detect damage that could lead to catastrophic events, underscoring its critical role in enhancing the resilience and longevity of civil structures.

Traditional bridge SHM strategies employ sensors mounted on the monitored structure (direct SHM). Although this is a proven practice, the implementation and maintenance of permanently installed SHM systems are expensive. Moreover, the vast number of bridges and viaducts in transportation networks makes the planning of a complete monitoring system unrealistic and anti-economical when applied on a network scale.

In this context, Indirect Bridge Structural Health Monitoring (iBSHM) which is based on exploiting sensors mounted on a moving vehicle offers an interesting alternative to direct SHM. These are combined with algorithms to evaluate the health conditions of bridges without the need for costly physical inspections or permanently installed sensor networks. In principle, iBSHM answers the need to monitor a large number of bridges and viaducts, optimizing time and costs. The fundamental advantage of the indirect method lies in the possibility of monitoring multiple structures using one or more instrumented vehicles, which play the role of moving sensors. The main disadvantage of iBSHM is that the measured data are influenced by (i) the movement of the vehicle, and therefore of the sensors, (ii) the dynamic properties of the vehicle itself, and (iii) the road pavement roughness. Table 1 briefly summarises the main advantages and disadvantages of direct and indirect bridge SHM.

Singh, Mittal, and Sadhu [1] underscores that among over 200 papers on iBSHM, the majority concentrate on numerical and analytical investigations, including scaled experiments. On the other hand, the number of articles presenting the results of comprehensive full-scale tests involving a prototype of an instrumented vehicle is surprisingly lower [2]. The Authors of this paper found 22.

This article examines the 22 mentioned full-scale tests and the most relevant studies from the published literature aimed at the development of such a vehicle. However, differently from other review papers, the insight gained from the preexisting works is here directed toward the definition of the prototype's optimized technical specifications.

The information reported here has been gathered by the *AMBROSE* team, in the framework of the *Alta Scuola Politecnica* (ASP). ASP is a multidisciplinary two-year-long honours programme that runs parallel to the Master of Science degree, jointly held by Politecnico di Torino and Politecnico di Milano. Among the goals set by the *AMBROSE* team lies the realization of a sensor vehicle prototype for systematic iBSHM in Italy, in collaboration with the industrial partner *Movyon*.

Table 1. Comparison between direct and indirect bridge health monitoring.

	Direct bridge health monitoring	Indirect bridge health monitoring
Advantages	– Sensors are either in direct contact with the structure or embedded within it. – Direct measurement (relatively low noise) – Possibility of real-time monitoring	– Fast monitoring of multiple bridges – Data collected at every point of the deck in the longitudinal direction (more spatial information) – Sensors and data acquisition systems are easily powered – Highly adaptable system
Disadvantages	– Elevated initial and maintenance costs – Sensors' nominal life is shorter than the bridge's – Need for continuous power supply – Sensors are sensible to climatic conditions, especially in aggressive environments	– Data influenced by the movement and dynamic properties of the vehicle – Vehicle's velocity must be low – High influence of noise from pavement roughness and other external sources

This paper discusses the vehicle's requirements in Section 2, concentrating on the type of vehicle and its characteristics. Section 3 analyzes the conditions in which to acquire measurements, while Section 4 argues about the needed instrumentation. A summary of the post-processing approaches is finally presented in Section 5. All the topics on which this research focuses are outlined in Figure 1 where they are represented as sketches.

2 Vehicle Specifications

In collaboration with Movyon, Autostrade per l'Italia S.p.A., the AMBROSE team has assessed numerous optimal vehicle features for iBSHM implementation.

2.1 Vehicle type

According to the full-scale test references present in the literature, it is possible to notice that the majority of the vehicles used are minivans or Multi-Purpose Vehicles (MPVs). A peculiar case is posed by Lin and Yang [3], Kong, Cai, and Kong [4], and Yang et al. [5], where the vehicle chosen was a trailer, linked to the towing vehicle by flexible joints. The vehicles used by the considered full-scale tests are summarized in Figure 2.

Fig. 1. Overview of the dealt issues.

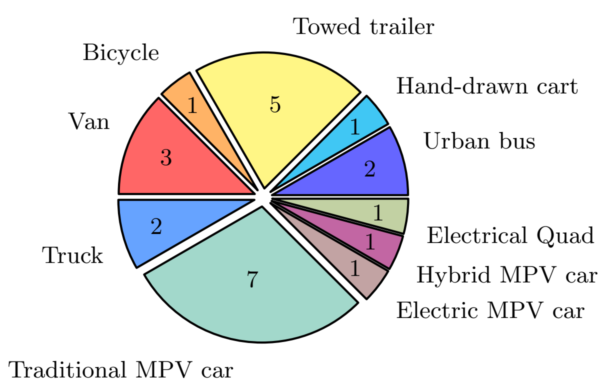

Fig. 2. Full-scale tests from literature collected by type of instrumented vehicle used. The sum is 24 since two papers tested multiple vehicles [6, 7].

2.2 Modal parameters

Minivans and MPVs exhibit complex dynamic behaviour with peak frequencies between 1 Hz and 50 Hz, influenced by suspensions, steering and engine [8]. Trailers present higher frequencies but face pitch effects and the influence of many parameters, such as the connection with the towing vehicle. Furthermore, they suffer from joint effects and are limited to low travelling speeds.

Studies on heavy vehicles, such as city buses [9, 10], reveal that the higher filtering effect, given by the high mass, yields remarkable results in the estimation of the first natural frequency. Since the mechanical filtering effect grows with decreasing stiffness or increasing vehicle mass, the suspension system must be tuned for even short-span bridge measurements.

A notable example of suspension tuning is represented by Urushadze and Jong-Dar [11]. The dynamic behaviour of the sensing vehicle is changed properly acting on the suspension stiffness and variable additional masses. This approach can be broadened also to bigger vehicles, adopting variable-geometry or active suspensions.

A full modal analysis of the vehicle can be used to differentiate its resonance from the bridge response. This can be performed in workshops with high accuracy and low costs. However, to the best of the Authors' knowledge, no example of full-scale experimental application of this type of procedure can be found in the reviewed literature.

2.3 Mean of propulsion and engine choice

The choice of vehicle propulsion and sizing is influenced by vehicle autonomy and measurement noise. Internal combustion engines cause collateral vibration [8], negatively impacting data quality. Switching to electrical propulsion, such as hybrid [12] or electric vehicles [8], can overcome this issue. However, commercial hybrid vehicles cannot switch to electric propulsion at will. Although electric vehicles have limited autonomy, longer-lasting batteries could be developed in the foreseeable future [13].

3 Operating Conditions

Many papers concentrate on the optimal operating conditions to extract significant results. This section collects considerations on speed, position in the lane, number of crossings and bridge excitation force.

Speed The appropriate speed to obtain reliable results has been extensively investigated (see Figure 3), with many suggesting a speed between 10 km/h and 40 km/h, and some investigating speeds lower than 8 km/h or higher than 50 km/h. In conclusion, although speed influences the measurements' quality, it seems to be a non-limiting factor. On the other hand, damage localization relies on a constant velocity during data acquisition [14], which is why a cruise control system is recommended.

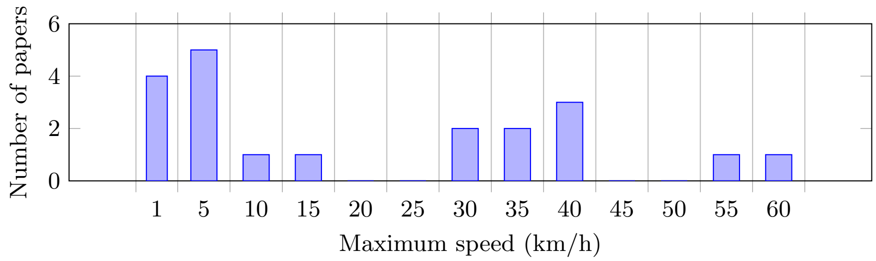

Fig. 3. Total number of papers detailing a tested vehicle speed.

Position in the lane The vehicle's position in the transverse direction on the deck is important only when the torsional motion of the bridge is of interest. If this is not the case, it is advisable to drive the vehicle above the bridge's centre [5] or in an arbitrary position depending on the measurement's goal.

Number of crossings Different studies have suggested different numbers of crossings. This aspect is strictly linked to the techniques used to collect and extract the bridge's modal parameters — i.e., whether one or multiple scanning vehicles are employed and the specific algorithm adopted. The aim is to obtain more reliable results by combining numerous trips over the bridge of interest [15]. In the case of an inspection vehicle, the minimum recommended number of crossings was individuated as three [3]; while in the case of crowd-sensing the number of total trips goes from thirty to over one hundred [7, 16].

Bridge excitation Vehicular traffic has repeatedly been proven sufficient to excite bridges into vibrating. iBSHM offers the theoretical possibility of operating without traffic restrictions [17], modelling traffic as a white noise component in accelerations. Relying on external factors like traffic flows increases data amplitude and reliability [16].

4 Instrumentation Specifications

This section investigates nuisance vehicle vibrations and the optimal choice of implementable sensors.

4.1 Collateral measure of other motions of the vehicle

To understand a bridge's dynamic behaviour, measuring the vertical motion of the vehicle and suspension assembly is crucial. However, these measurements can be corrupted by other vehicle motions, particularly pitch and roll. To minimize the effect of undesired vibrations, several post-processing techniques have been employed. The strategic placement of sensors, near the rotation axis of the aforementioned movements, is a noteworthy example [18]. In future works, the empirical assessment of the centre of mass of the vehicle could be of utmost importance.

4.2 Sensor choice and positioning

As mentioned above, very few performed full-size tests, and even fewer concentrated on the implemented sensors. Among those who did, Fiandaca et al. [8] and Di Matteo, Fiandaca, and Pirrotta [12] adopted piezoelectric sensors, which offer many advantages compared to other technologies, such as precision and low noise. On the other hand, Nagayama et al. [6], Di Matteo, Fiandaca, and Pirrotta [12], Matarazzo et al. [15], and Benedetti et al. [18] used micro-electromechanical system (MEMS) accelerometers, which offer a compact and low-cost solution.

Moreover, Di Matteo, Fiandaca, and Pirrotta [12] compared the two technologies' performance, obtaining very similar results. This leads to the conclusion that sensor performance is not the limiting factor in iBSHM. Table 2 compares two high-performance commercial piezoelectric and MEMS accelerometers.

Table 2. Comparison between high performance piezoelectric (PCB Piezotronics 393B04 [19]) and MEMS (STMicroelectronics LIS3DHH [20]) accelerometers.

	Piezoelectric	MEMS
Full Scale Range $[g]$	± 5	± 2.5
Bandwidth $[Hz]$	0.06 – 450	0 – 440
Noise PSD $\left[\mu g/\sqrt{Hz}\right]$	0.04 – 0.30	45
Temperature range $[°C]$	-26 – +80	-40 – +85
Axes	1	3

Intuitively, a higher number of sensors leads to a better result. However, several experimental studies [6, 8, 12, 21] implemented a single accelerometer, while Benedetti et al. [18] installed a network of eight MEMS sensors. Moreover, Wang et al. [21] investigated how placing accelerometers one in front of the other can efficiently remove correlated noise given by road surface roughness.

To detect when the vehicle is crossing a bridge, one or more localization sensors are suggested, such as GPS or inertial measurement units [15]. A temperature sensor can prove effective in foreseeing changes in stiffness and frequency due to temperature [22].

5 Post-Processing Analysis

Full-scale tests on bridge modal identification primarily focus on natural frequency extraction, with conventional algorithms such as Fast Fourier Transform (FFT) and Power Spectral Density (PSD). Vehicle models like quarter-car and half-car are used to estimate the vehicle's response to vibration and excitation.

5.1 Modal parameters, vehicles, and algorithms

All the examined full-scale tests focus on structural modal identification, most of which focus on the extraction of natural frequencies, rather than on damage detection methods. Figure 4 illustrates, for each type of instrumented vehicle previously presented, the aim of the articles — i.e., the results obtained in terms of the extracted bridge modal parameters, and the relative algorithm and post-processing technique used on the collected acceleration data. In this context, it is noticeable how the majority of the authors have opted for rather conventional algorithms to retrieve the bridge's natural frequencies, such as peak picking using the FFT or the PSD of the signals, which was shown to be accurate. Just in one case [23] the Stochastic Subspace Identification algorithm (SSI) was implemented, while Quqa, Giordano, and Limongelli [16], in the perspective of crowd-sourcing, used the Hilbert Transform (HT) to obtain the mode shapes of the tested footbridge. More complex techniques [10, 15, 24] are unique within this field of application, requiring further experimental validations.

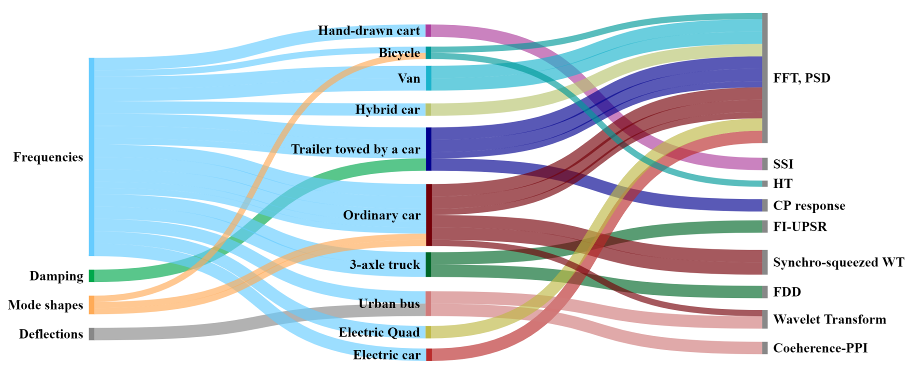

Fig. 4. Link between the results obtained (bridge modal parameters), the type of instrumented vehicle, and the algorithm used.

5.2 Vehicle dynamical model

In all the literature, several vehicle models are used to estimate the vehicle's response to the bridge's vibration and excitation. The most used models were the quarter-car model and the half-car model (see Figure 5). One notable exception is Yang and Yang [25], which adopted a full-car model.

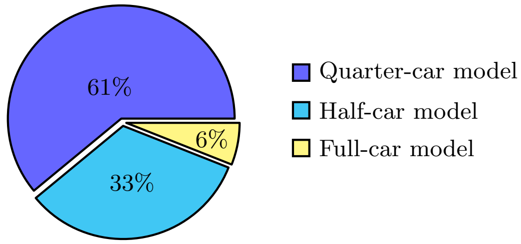

Fig. 5. Vehicle models chosen by other authors.

6 Conclusions

The paper discusses the growing interest in Indirect Bridge Structural Health Monitoring (iBSHM), highlighting the quite limited number of real-life applications, also due to the difficulty in designing the best moving platform. It aims to provide a state-of-the-art understanding of the topic, focusing on the technical details of an optimal prototype vehicle, to help researchers and practitioners alike to better understand and design the best moving platform. In this sense, the Authors envision the optimal choice to be an electric MPV car, with multiple piezoelectric accelerometers mounted on the axles, close to the wheels. The suggested speed should be lower than 40 km/h, performing multiple crossings in both directions.

The aim is to obtain a monitoring workflow with highly adaptable characteristics depending on the monitored bridge type. The great complexity of the problem will have to be faced by merging different technical backgrounds, from civil to ICT, electronic and mechanical engineering. Such a plurality of thoughts and multi-disciplinary approach are going to represent a key strong point of the *AMBROSE* team in the upcoming works.

Future research will consist of on-site testing on several bridges in northern Italy with a vehicle prototype provided by Movyon S.p.A. The acquired data will be used to search for the best algorithm for modal parameter identification and, in addition, to investigate an effective damage detection criterion.

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