Structural Monitoring and Maintenance, *Vol. 9, No. 4 (2022) 305-321*
https://doi.org/10.12989/smm.2022.9.4.305

Identification of bridge bending frequencies through drive-by monitoring compensating vehicle pitch detrimental effect

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(*Received September 28, 2022, Revised December 2, 2022, Accepted December 8, 2022*)

Abstract. Bridge structural health monitoring with the aim of continuously assessing structural safety and reliability represents a topic of major importance for worldwide infrastructure managers. In the last two decades, due to their potential economic and operational advantages, drive-by approaches experienced growing consideration from researcher and engineers. This work addresses two technical topics regarding indirect frequency estimation methods: bridge and vehicle dynamics overlapping, and bridge expansion joints impact. The experimental campaign was conducted on a mixed multi-span bridge located in Lombardy using a Ford Galaxy instrumented with a mesh of wireless accelerometers. The onboard time series were acquired for a number of 10 passages over the bridge, performed at a travelling speed of 30 km/h, with no limitations imposed to traffic. Exploiting an ad-hoc sensors positioning, pitch vehicle motion was compensated, allowing to estimate the first two bridge bending frequencies from PSD functions; moreover, the herein adopted approach proved to be insensitive to joints disturbance. Conclusively, a sensitivity study has been conducted to trace the relationship between estimation accuracy and number of trips considered in the analysis. Promising results were found, pointing out a clear positive correlation especially for the first bending frequency.

Keywords: bridges; drive-by monitoring; expansion joint; indirect frequency estimation; structural health monitoring; vehicle pitch compensation

1. Introduction

Infrastructural networks metaphorically represent the veins and arteries of a country. They allow the flux of people and goods, essential for the flourishing of culture and economics. To give an idea of today's importance of infrastructural networks, it is worth reporting two data referred to the European context: in 2019, land transportation accounted for more than 80% of passenger transport and 64% of freight transport (European Commission 2020). Within the framework of infrastructural networks, bridges represent a key player. The golden era of bridge construction started during the second world war economic boom in the United States, followed by most countries in Europe and Asia. According to the design criteria of that time, the minimum target service life of such structures was 50 years (Jeong *et al.* 2018), and they were not designed for the heavy freight traffic of today. In the US, 42% of bridges are at least 50 years old, and 7.5% are considered structurally deficient (American Society of Civil Engineering 2021). The situation is similar in the European panorama,

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http://www.techno-press.org/?journal=smm&subpage=7 ISSN: 2288-6605 (Print), 2288-6613 (Online)

with UK (Thousands of UK bridges at risk of collapse, warns RAC 2017), Germany (Germany tries to close infrastructure backlog 2018), French, and Italy (Bridges across Europe are in a dangerous state, warn experts 2018) disclosing concerning data in regard. Focusing on the far East, in Japan, the number of aged bridges will constitute half of all road bridges by the year 2025 (Fujino *et al.* 2009), while Korea and China, albeit starting later, are now facing extraordinary growth in terms of number of bridges built on their territory (Jeong *et al.* 2018). The main problem related to bridge ageing is the lack of time and money needed to stick to the guidelines ruling monitoring and maintenance. Last year, the Federal Highway Administration disclosed a backlog of bridge repair needs of $125 billion. A similar situation affects Europe as well (After Italy Collapse, Europe Asks: How Safe Are Our Bridges? 2018). This shortage of resources forces us to rethink the way the monitoring of infrastructural networks is performed, striving for a change of rationale from time-based to condition-based maintenance (Ahmad and Kamaruddin 2012). As the word suggests, the establishment of this new paradigm can be possible only by expanding our current knowledge about the conditions of bridges, collecting data in a fast and economically feasible way. This need is driving the research for new techniques to support decision-making and prioritization of interventions.

Among them, indirect methods represent a promising idea. Proposed for the first time by Yang *et al.* (2004), according to this type of monitoring the structural behaviour is indirectly captured by sensors installed onboard a diagnostic vehicle which behaves as a signal carrier while crossing the structure. For this reason, indirect structural health monitoring is also known as drive-by monitoring. Since 2004 this paradigm has received increasing attention from researchers, as witnessed by literature reviews by Malekjafarian *et al.* (2015), Yang and Yang (2018), and Shokravi *et al.* (2020). Even though indirect sensing techniques share a common principle, they can be differentiated depending on the measured quantities and the monitoring objectives. An important dividing line can be traced between modal and non-modal-based approaches. The former links the structural health to modal parameters: most studies focused on the extraction of natural frequencies, either numerically (Sitton *et al.* 2020, Yang and Chang 2009b, McGetrick *et al.* 2009) or including experimental verification (Matarazzo *et al.* 2018, Matarazzo *et al.* 2020, Singh and Sadhu 2022); some others explored damping estimation exploiting Vehicle-Bridge Interaction (VBI) models (McGetrick *et al.* 2009, González *et al.* 2012, González *et al.* 2010); conclusively, mode shapes are studied too, mostly relying on numerical simulations (Zhang *et al.* 2012, Obrien and Malekjafarian 2016). Conversely, non-modal-based studies rely on other quantities to assess the structural health: Martínez *et al.* (2016) and Elhattab *et al.* (2016) focused on bridge displacement; Malekjafarian *et al.* (2018) used a Laser Doppler Vibrometer to evaluate the curvature of the deck; Mcgetrick and Kim (2013) applied the Morlet wavelet to identify and locate possible damage; OBrien *et al.* (2017) proposed a hybrid methodology, relying on the frequency domain, but not considering the bridge natural frequencies. Fig. 1 (Gkoumas *et al.* 2021) provides a portrait of the current literature on indirect structural health monitoring, highlighting also the type of study

In this framework, full-scale experiments represent a minority, and their results rarely match the findings claimed by numerical and laboratory studies (González *et al.* 2008). With the aim of bridging this gap, the work presented herein is entirely based on an experimental campaign on an existing bridge. The idea is to prove the effectiveness of the technique notwithstanding all the factors that behave as sources of disturbance when it comes to real-world application. Among them, vehicle dynamics, travelling speed, external traffic, and asphalt conditions are recognized as the most relevant ones. Inserted in the framework of modal-based techniques, the present work focuses on the problem of the coupling of bridge and vehicle dynamics. Due to Vehicle-Bridge Interaction, the

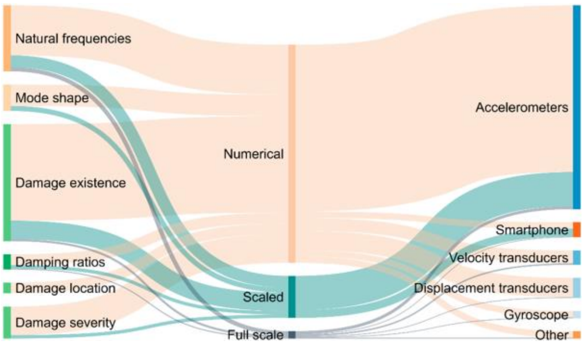

Fig. 1 Breakdown of the current literature on indirect structural health monitoring according to scope of the work, type of study, and sensing unit

diagnostic vehicle acts as a filter between the sensors and the bridge object of monitoring (Cebon 1999), thus being extremely impactful on the results of the identification campaign. Contrary to what the first paper from Yang *et al.* (2004) affirmed, successive studies demonstrated that having bridge and vehicle resonances close to each other represents a problem (Yang and Chang 2009a, Yang and Chang 2009b). Indeed, if the car and the bridge are featured by similar natural frequencies it is hard to distinguish the two contributions in the frequency domain. For this reason, Siringoringo and Fujino (2012) highlighted the importance of conducting modal tests on the vehicle to be able to distinguish its natural frequency from the other peaks in the spectrum. They also report the detrimental effect of bridge joints as exciters of bouncing and pitching modes of the car. The latter is a main contributor to vertical vehicle dynamics. The presence of intense asphalt roughness, road irregularities, and structural elements such as bridge joints usually favours the excitation of this mode. As a result, the indirect identification of first bridge frequencies may be undermined. Such an event is more likely to happen in the case of short-to-medium span structures for two reasons: first, their first natural frequencies usually belong to a bandwidth close to the one typical of car dynamics; second, the shorter the span, the lower the time to sense bridge vibrations after car dynamics transient is damped out. Acknowledging the negative effect of bridge and car dynamics coupling, a recent study from Yang *et al.* (2022) proposed the design of a frequency-free cart to perform drive-by monitoring. Other works demonstrated the effectiveness of using a special configuration of vehicles to remove some detrimental effects such as vehicle vibrations (Lin and Yang 2005) and road roughness (Kim *et al.* 2016). However, despite being successful, such methods foresee the design of an ad hoc experimental configuration to perform drive-by monitoring. This harms a big benefit of the technique, which resides in the possibility of collecting data from any vehicle spontaneously crossing a bridge.

To save this powerful characteristic, this paper proposes a new method to compensate for the effect of car pitch motion, preventing it from masking the first natural frequencies of the bridge. Moreover, the effect of expansion joints is studied, evaluating their impact on the quality of the identification. Conclusively, the application on a large scale of drive-by monitoring is considered. As a decision-making tool, the accuracy and repeatability of its results must be guaranteed, thus a statistical analysis is conducted to trace the relationship between the frequency estimation error and the number of trips travelled across the bridge. The goal is to understand the trade-off between the speed and the trustworthiness of the method, to optimize its large-scale deployment.

Fig. 2 The Bressana bridge. Top left: aerial view and localization of the bridge; top right: view of the three spans over the riverbed; bottom: panoramic lateral view from the railway access road

2. The Bressana bridge

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The Bressana Bridge, also called Ponte di Mezzana Corti, is a mixed road and rail bridge, which crosses the Po river between the villages of Mezzana Corti and Bottarone, Pavia Province. The bridge, designed by Alfredo Cottrau, was originally built in 1866: the superstructure was made up of fine mesh reticular beams while the piers were made of masonry. During the Second World War the bridge was bombed causing the collapse of the central main beams. As a result, the original superstructure was completely replaced with a metal truss structure, and construction work ended in 1951. The first three spans towards Voghera are in the riverbed, the remaining over the floodplain besides. The bridge, shown in Fig. 2, is featured by 10 spans with a double-deck structure, 75 m pin-to-pin length each, all well decoupled and separated through expansion joints (Ferrovie dello Stato 1949).

The choice of this bridge depends on the following reasons:

- Being part of Regione Lombardia project (Regione Lombardia - Politecnico di Milano 2019), we already know its modal characteristics. In particular, the first bending mode shape has a frequency of 2.5 Hz, close to typical pitch frequency of cars (Mastinu and Ploechl 2014);
- The spans are featured by a common structural scheme, good to use as a case study, and have joints, whose effect on the results of the campaign are deemed worth to study;
- From a functionality perspective, the traffic on the bridge is intense - estimated average daily traffic value of 15000 vehicles/day (Regione Lombardia 2020) -, which means that there is good excitation, but also many possible sources of noise. Moreover, the presence of traffic allows to test the impact of the experimental campaign on the road service.

Let us now report the modal properties of interest from the knowledge acquired within the Regione Lombardia project. Being all the spans featured by the same structural characteristics, their modal parameters resulted to be very similar, as theoretically expected and confirmed by literature (Bernardini *et al.* 2021). For this reason, and considered that the goal of this work is not an Operational Modal Analysis of the bridge, the frequencies to which compare the results of the drive-

Table 1 Natural frequencies of the first two bending modes extracted from a fixed sensor networkalready present on the bridge. The frequencies are reported in terms of mean value and standard deviation, statistically aggregating the results of the single span

Mode order	Type of mode	Frequency
1^{st}	Bending	2.49 ± 0.01 Hz
2^{nd}	Bending	5.83 ±0.1 Hz

Table 2 Main structural features and picture of the diagnostic vehicle

Dimensions	Picture
Wheelbase 2850 mm Length 4853 mm Width 1916 mm Height 1811 mm Curb weight 1978 kg	

by campaign are not reported span-wise, but statistically aggregated in terms of mean value and standard deviation. Table 1 reports the natural frequencies associated to the bridge first two bending modes, whose indirect estimation is target of this study.

3. Experimental campaign

The experimental campaign involved a two-stage data collection. First, a preliminary test was conducted to extract information about the dynamics of the diagnostic vehicle and validate the design of the measurement grid. Then, the focus of the experimental campaign was moved to the bridge to perform the drive-by tests, keeping the same sensors setup. The following subsections, reported in chronological order, aim to provide the reader with more details regarding the experimental data collection.

3.1 Vehicle dynamics

When dealing with drive-by monitoring, a preliminary knowledge of the diagnostic vehicle dynamics is essential to properly design the sensors mesh distribution and be able to distinguish between car and bridge frequency contents inside onboard time histories (Siringoringo and Fujino 2012). Hence, as mentioned before, the purpose of the first campaign conducted was the definition of the vehicle natural frequencies of interest. The vehicle used for the campaign is a Ford Galaxy, belonging to Politecnico's Department of Mechanical Engineering. Table 2 reports some relevant structural characteristics and a picture of the vehicle. To excite the vehicle with a broad random spectrum input, a free driving road test has been conducted. The car was driven for an hour within

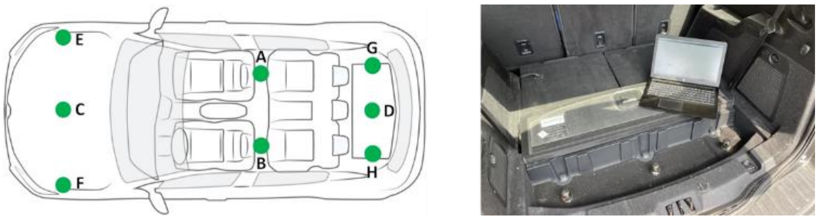

Fig. 3 On the left: schematic representation of the sensor network deployed on the diagnostic vehicle. The letters refer to the list above; on the right: placement of the three sensors inside the car trunk

the city of Milan during normal traffic condition, thus attaining different speeds and experiencing different pavement conditions, which translate into a wide range of excitation conditions for the vehicle. The car was equipped with 8 wireless triaxial MEMS accelerometers (G-Link-200) positioned as schematically represented in Fig. 3.

The explanation behind the presented sensors mesh can be summarized in the following points:

- To place a couple of sensors on theoretical pitch neutral axis (A, B);
- To place a couple of sensors on theoretical roll neutral axis (C, D);
- To place a sensor in correspondence to each wheel (E, F, G, H).

The positioning also took into account the reachability of the measuring points and the feasibility of attaching the sensors exploiting their magnetic base for a rigid connection. More specifically, sensors A and B were placed inside the car, on the ground in front of the rear seats; sensors C, E, and F were attached on top of the car hood; sensors D, G, and H were placed in the car trunk, the closest possible to the rear end. The acceleration signals have been acquired by means of a base station (LORD Microstrain WSDA-2000) responsible for the network management and sensors synchronization. The sampling frequency was set equal to 128 Hz.

3.2 Drive-by campaign

The drive-by campaign consisted of 10 complete crossings of the structure, 5 per direction of travel. The test took place in the late morning, therefore off-peak hours, without imposing any traffic limitation. The car was driven without any stops throughout the test, exploiting two roundabouts close to the bridge ends to change the direction of travel. When on the structure, the travelling speed was kept constant and equal to 30 km/h. It was decided to keep a constant travelling speed because this parameter was not the objective of the analysis. The value of 30 km/h was chosen because it is close to the highest speed at which some successful experimental results from drive-by monitoring are reported in literature (Siringoringo and Fujino 2012, Lin and Yang 2005). The cruise speed was pushed towards the upper limit thinking of the real application of this technique on a large scale, where extremely low speed might disrupt the traffic. To be coherent with the preliminary test on vehicle dynamics, the measurement grid and the sampling parameters have been kept the same reported in subsection 3.1. In particular, the presented sensors mesh made the authors able to investigate the effect of car frequencies on the success of indirect monitoring and test methods to overcome the problem of car and bridge dynamics coupling. Once performed the campaign, the acquired signals were divided into different data sets, each specific for a certain kind of analysis.

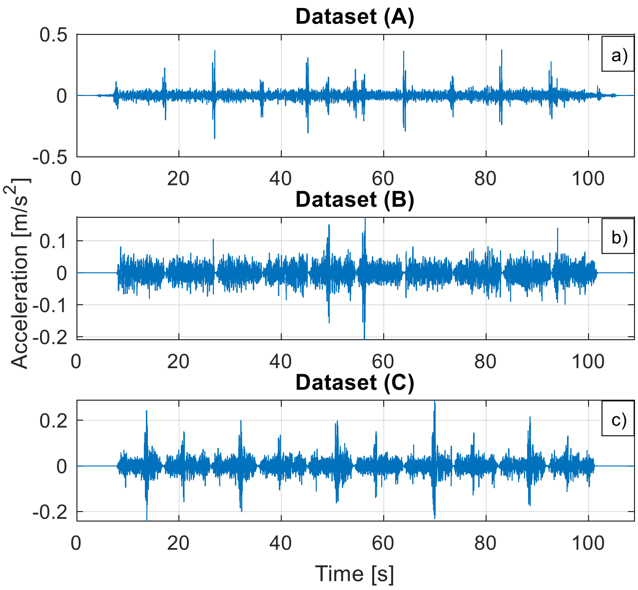

Fig. 4 An extract of each dataset obtained by preprocessing the raw data. (a) Dataset (A), (b) Dataset (B) and (c) Dataset (C)

A premise is necessary at this point: the effect of the connection joints between the various spans, being similar to that of an impulse, was considered unfavourable for the subsequent frequency analysis of the time signals, since it would have been a disturbance on all frequencies, and a strategy was therefore implemented to try to contain the detrimental effect associated with these joints. What follows is a description of each dataset, detailing the pre-processing to obtain it, starting from the raw acquisitions:

- Dataset (A) was obtained appending 10 time histories, one per crossing, filtering the joints at bridge ends. The filtering took place in the time domain, and the intensity on the joints has been attenuated windowing each passage with a Tukey window (Tukey (tapered cosine) window);
- Dataset (B) was obtained appending 100 time histories, one per span per crossing, filtering the joints at every span ends. This time each joint present on the bridge (11 joints for 10 spans) has been identified in the acceleration signal, and using the same approach as previously, each span has been windowed with a Tukey window to remove the influence of the intra-spans joints;
- Dataset (C) is constituted of 10 groups (one per span) of 10 time histories (one per crossing) obtained appending the data collected on each span during the 10 crossings, also in this case windowed to remove the intra-spans joints influence. This dataset is basically realized through a span-wise reorganization of the single time histories constituting dataset B.

Fig. 4 shows an extract of each dataset. In particular, 4a is the time history of one bridge crossing, 4b is the same time history but having filtered out the joints, and 4c is a signal obtained appending the ten bridge crossings on the sixth span.

To understand the choice of showing the time histories on this particular span the reader is invited to look at the signal in 1a, that points out a strong acceleration peak in correspondence of the sixth span. Focusing on such a span, 1c is able to highlight the repeatability of the measures, showing the

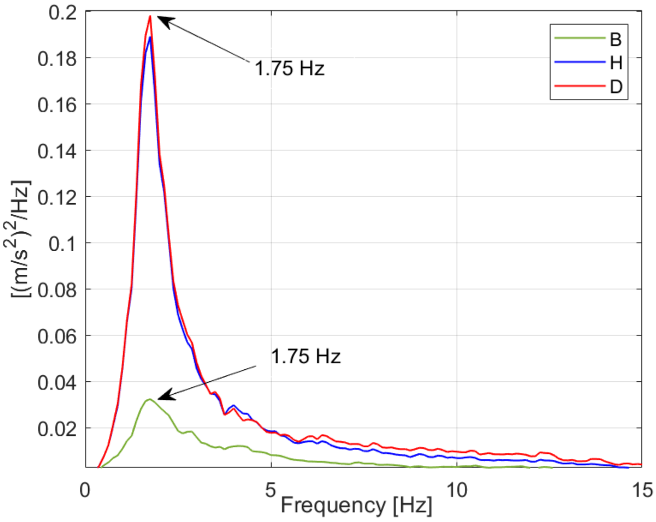

Fig. 5 PSD functions computed from sensor B (on pitch axis), D (on roll axis) and H (above wheel). Pitch and bounce peaks are highlighted

above mentioned acceleration peak is present in all the 10 crossings, with different intensity and location according to the travel direction. This visualization helps to notice the difference between dataset B and C: the time histories collected on the same span - dataset C - are much more similar to each other.

4. Results and discussion

4.1 Vehicle dynamics

The goal of the preliminary study of vehicle dynamics is the identification of the modal parameters of the car. The data collected during the test described in subsection 3.1 were analysed with Matlab® (MATLAB R2022a). According to the scope, the frequency bandwidth was limited to 0.8 Hz to 8 Hz, applying a bandpass filter featured by such cutoff frequencies. In particular, referring to Fig. 3, the authors report the analyses performed on the vertical channels of three sensors, namely B, D and H. These sensor positions were chosen since B approximately lies on the pitch neutral axis and D is mounted about the roll neutral axis instead. In addition, position H was taken into account, since this sensor is not lying on any motion neutral axis, and, theoretically, it should contain bounce, roll and pitch contributions. Fig. 5 illustrates the PSDs resulting from the vertical accelerations acquired at B, D an H positions, and then processed by means of the *pwelch* function of Matlab® : in particular, it is possible to observe that both H and D PSDs show a remarkable pitch component at 1.75 Hz. Also the bounce motion stands at the same frequency, as demonstrated by the PSD computed from sensor B, meaning that pitch and bounce motions are coupled. Sensor H does not show any other appreciable peaks other than the pitch one. This result can be explained by the fact that exciting roll motion when the car is running a normal service is more difficult than exciting pitch and bounce motion.

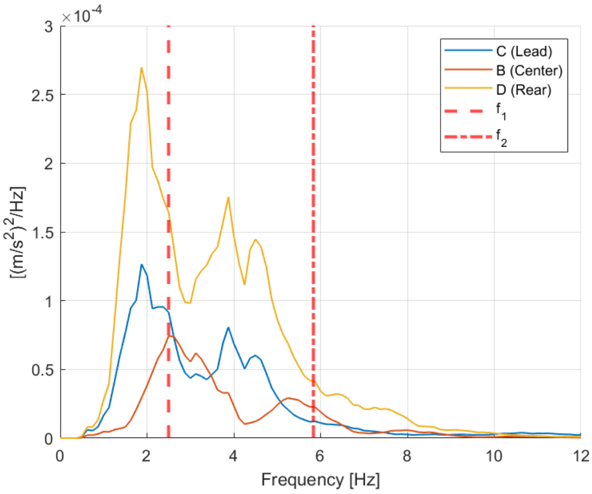

Fig. 6 PSD functions computed from sensors B, C, and D. The dashed lines highlight the first two bending frequencies of the bridge. Refer to Fig. 3 for the positioning of the sensors

Given the significant amplitude associated to its frequency, as demonstrated by Fig. 5 and the ease with which its motion is excited during normal service, pitch motion is particularly critical in terms of its capability to hide bridge information contained inside onboard measurements. The obtained pitch frequency is in line with literature findings (Yang *et al.* 2004) and near to the first bending frequency of the bridge, as desired to test the methodology of this work.

4.2 Drive-by campaign

Let us now present the results of the drive-by experimental campaign. Exploiting the data sets described above, we addressed different research questions, each of which specifically treated in the following subsection. Before going through them, the goals of the study are summarized:

- Leveraging the sensors placement and data processing, find a way to correctly identify the first natural frequencies of the bridge even though superimposed to the pitch motion of the vehicle;
- To study the impact of bridge joints on the identification performances of the technique;
- Bearing in mind the upscaling of the method, trace the relationship between number of passes and accuracy of the results.

4.2.1 Sensors placement

Being a complex mechanical system, the vehicle has been densely instrumented as described in 3.1. The same setup has been adopted during the drive-by tests to investigate the effect of positioning on the capability of correctly retrieving bridge frequencies. To explore this topic we exploit dataset A, the one featured by the least possible cleaning preprocessing. The results are presented in terms of Power Spectral Densities, obtained applying the *pwelch* algorithm (Welch's power spectral density estimate) to the time histories, previously bandpass filtered between 0.8 Hz and 8 Hz. First, Fig. 6 reports a comparison of the results obtained from three sensors placed on the roll neutral axis of the vehicle (i.e., centreline of the car in longitudinal direction). Sensor C is on the lead, sensor B

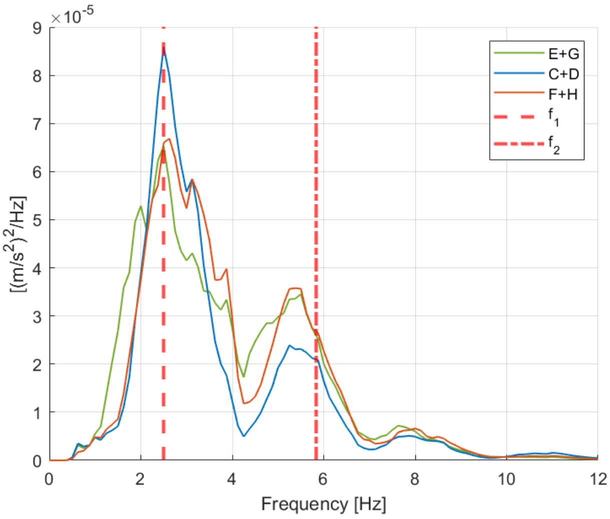

Fig. 7 PSD functions computed from three different signals, obtained summing the raw data from sensors E and G, C and D, and F and H respectively. This artifice allows to compensate the pitch motion of the car, highlighting the bridge dynamics. The red dashed lines highlight the first two bending frequencies of the bridge. Refer to Fig. 3 for the positioning of the sensors

is in the centre, inside the car, and sensor D is in the trunk. The PSDs from sensors C and D could not identify the first bending frequency of the bridge, due to the hiding effect exerted by pitch motion of the car. This result was anticipated by Fig. 5, that shows how sensor B is less sensitive to pitch motion thanks to its positioning in the measurement scheme. Sensor B managed to point out the correct bridge frequency – dashed line in Fig. 6 – while sensors C and D, featured by very similar dynamic content, show a main peak at 1.75 Hz, corresponding to car pitch mode. Regarding the two sensors inside car, despite giving better results, the shape of the two frequency peaks reveals that they registered more damped signals, which negatively affects the identification performances.

According to such results, we studied the nature of car pitch motion to get insights on how to minimize its effects on the identification technique. In the theoretical models of cars, the pitch motion acts with the same amplitude but opposite phase on the front and back of the vehicle. From this principle, we drew the idea of summing the raw data from couples of sensors one in front, one behind the car, so that the pitch effect could be reduced. Following this rationale, we produced three new time histories, one per couple of sensors, that we processed with same algorithm used before. Fig. 7 shows that the artifice we tested successfully removed the effect of the pitch: we are now able to correctly identify both bridge's first and second bending modes from all couples of sensors placed on the vehicle. In terms of accuracy, the first frequency is estimated with the minimum possible error, corresponding to the frequency resolution, while the second one is featured by an error of 5%. This result is deemed relevant since it overcomes a quite big flaw of drive-by monitoring without placing sensors in correspondence of pitch neutral axis, a position characterized by low reachability from the outside of the car, and high invasiveness and signal damping from the inside.

Once proven the effectiveness of leveraging sensors placement and ad hoc data processing to prevent pitch motion from hiding bridge dynamics, we investigated the effect of increasing the number of sensors.

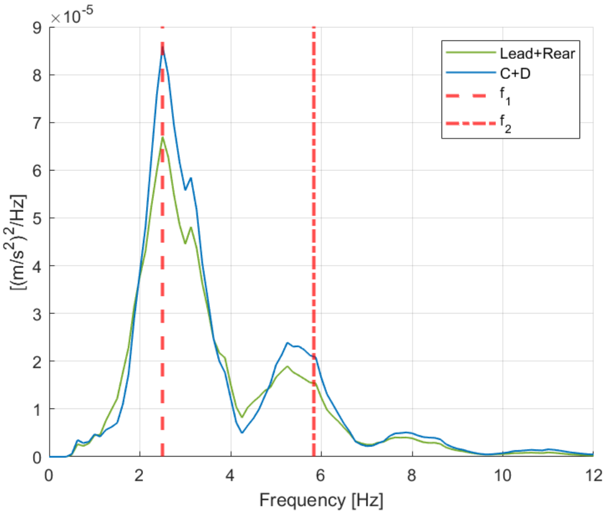

Fig. 8 Comparison of the PSD functions computed from two different signals: the green line refers to a signal obtained averaging the raw data from the sensors placed on the lead (C, E, F) and on the rear (D, G, H); the blue line refers to a signal obtained averaging the raw data from sensors C and D. The dashed lines highlight the first two bending frequencies of the bridge. Refer to Fig. 3 for the positioning of the sensors

To this end, we averaged the raw data from the two groups of sensors – behind and in front – before removing pitch with the technique explained above. In principle, the averaging operation could be useful to mitigate possible local effects, thus providing more accurate and stable results. Fig. 8 shows the outcomes of the identification comparing the use of a single couple of sensors with all the three available.

Looking at the plot, the response obtained averaging the signals from the two trios of sensors is dominated by the contribution from sensors C and D (refer to Fig. 3 for the sensors nomenclature), which determine the shape of the green curve. This result seems to suggest that there is no evident advantage in equipping the vehicle with more than two sensors, which is good outcome from the perspective of deploying drive-by monitoring on a large scale. Given the outcomes of this first study, the couple formed by sensors C and D, placed on the roll neutral axis, is deemed to be the best performing one. Thus, from now on all the research questions will be addressed analysing data collected by sensors C and D, henceforth named "best configuration".

4.2.2 Joints effect

According to the literature, joints may represent a problem for drive-by sensing since they act as a strong excitation source on the car (Siringoringo and Fujino 2012). The Bressana bridge presents a series of joints that offer the possibility to study their effect on the technique. This is deemed an interesting topic to investigate for a twofold reason: first, most multi-span bridges present expansion joints; second, from the acceleration signal point of view, joints impact on the car similarly to a local strong road irregularity, thus could be studied as a good approximation of common road defects such as big asphalt cracks or potholes. Hence, a deeper understanding of the impact of such morphological elements on drive-by monitoring is important to learn how to deal with possible noise brought by external factors frequently present on roads. To address this research question we

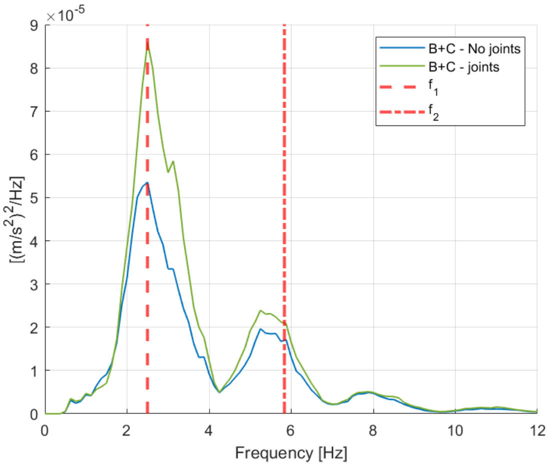

Fig. 9 Comparison of the PSD functions computed from two different signals: the green line refers to a signal obtained summing the raw data from sensors C and D; the blue line refers to a signal obtained summing the data from sensors C and D after removing the acceleration spikes in correspondence of the expansion joints (i.e., dataset B)

compared the identification results obtained analysing data sets A and B, the latter obtained removing the joints from the acceleration signals, as explained before in 3.2. From the point of view of the sensors, we only considered signals produced by the "best configuration", as defined in subsection 4.2.1. Fig. 9 depicts the results of the study. As one may notice, the presence of the joints had a strong impact on the magnitude of the signal, especially on the peak corresponding to the first mode, whose amplitude is almost doubled if joints are taken into account. Minor differences can be found with respect to the second natural frequency. Positively, not only did the herein proposed methodology prove to be resilient to joints effect, but rather a bigger vehicle-bridge interaction might have helped bridge dynamics to emerge. Notwithstanding, the experiment confirmed literature findings regarding the huge impact of expansion joints and similar irregularities on car dynamics, suggesting paying careful attention to the presence of these elements on the structure object of monitoring.

4.2.3 Trips number sensitivity

This analysis is not oriented to dig into drive-by monitoring technical aspects, but is significant to evaluate the burden of an extensive application of this methodology. As a tool for supporting decision-making in matters of social safety, proper accuracy of the results must be guaranteed. Considering the latter, this analysis investigates the relationship between the number of passes on the bridge and the quality of the identification results. Trivially, it is reasonable to presume that the more data are collected, the more precise the estimation, but the aim is to find an optimal trade-off that assures the required accuracy, avoiding unnecessary data collection. Such a topic is of irrelevant interest if a single bridge is considered, but inserted into the broader framework of a country's bridge system, it becomes a major issue to tackle. In fact, it is clear that a saving of 10 trips across a bridge does not impact a single monitoring campaign, but it means a huge save of time, money, and data when projected on thousands of bridges to be checked on a constant basis.

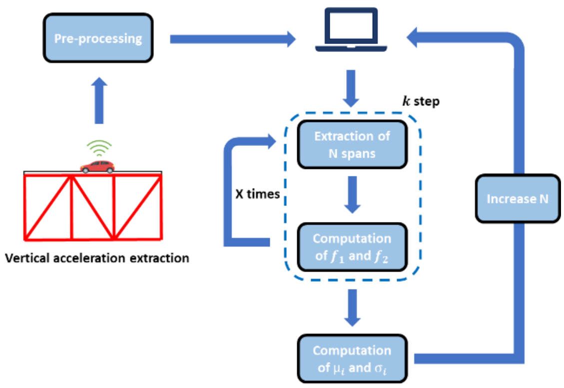

Fig. 10 Schematic description of the algorithm used for the study of the relationship between identification accuracy and number of trips taken into account while running the analysis

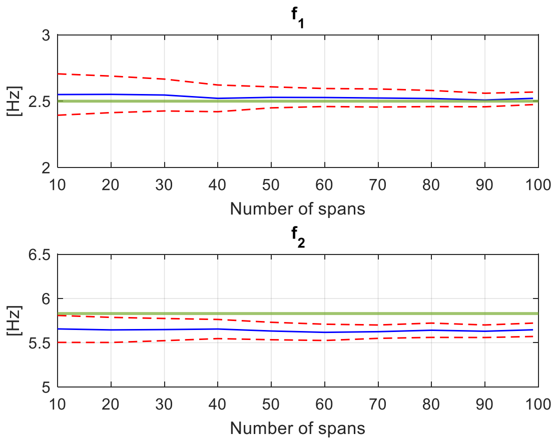

Fig. 11 Representation of mean value – blue line – and standard deviation – red dashed line – with respect to the number of crossed spans taken into account. The green line represents the target frequency. Above: 1st bending frequency; below: 2nd bending frequency

For this analysis, we selected multiple times sub-batches of different dimension from dataset B and tested the identification performances in terms of mean value and standard deviation. More in detail, the algorithm works according to the following steps:

- At step *k*, it is chosen a number N of spans, with N assuming discrete values from 10 to 100 with a pace of 10;
- Defined the number N, a sample of N spans is randomly extracted from the dataset B;
- The PSD function of interest is computed according to the pwelch function of MATLAB considering N spans;
- This operation is repeated X times, inside *k-th* step. For each iteration, peaks of the PSD around the frequency values are picked automatically;
- The mean and the corresponding standard deviation are then computed over a sample of X values for both first and second bending frequencies;

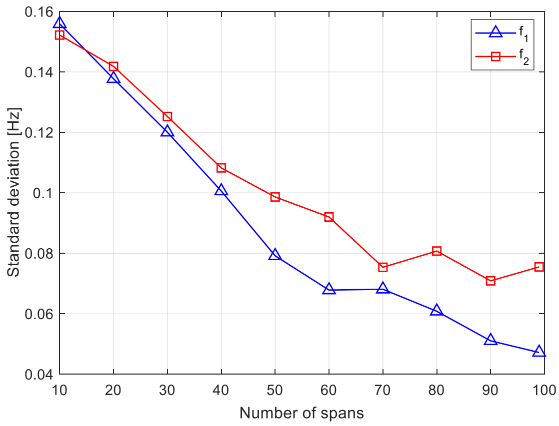

Fig. 12 Comparison of the standard deviation trends for the indirect estimation of the two natural frequencies of the bridge. On the abscissa, the number of crossed spans included in the analysis randomly extracted from data set B

- The algorithm proceeds to step $k+1$, and the procedure is repeated according to the previous points, with an increased number N of spans to be analysed.

The entire process, from raw data gathering and pre-processing to the extraction of frequency mean and standard deviation, is schematically depicted in Fig. 10.

In this way, it is possible to study and statistically quantify the influence of the number of spans considered in the indirect identification process on its performances. In particular, Fig. 11 reports the trend of the mean (blue solid line) and standard deviation (red dashed line) of the identified frequency plotted as a function of the considered number of spans. It is possible to observe that by increasing the number of spans, as expected, for both the two frequencies the standard deviation tends to decrease. Moreover, it is worth noticing that for the first bending frequency the mean value tends to the nominal one (green solid line in Fig. 11), while for the second bending frequency this is not observed.

The decrease of the standard deviation with increasing number of spans can be better visualized in Fig. 12.

The standard deviation curve associated to the second bending frequency seems to significantly change its trend from 70 spans onwards. Precisely, it is possible to observe a small oscillation around a horizontal asymptote, just below 0.08 Hz. Instead, even after 70 spans, the standard deviation regarding frequency still retains a clear decreasing trend. In other words, increasing the number of spans considered in the analyses leads to benefit for what concerns the accuracy in the identification of the first bending frequency, but not for the second one as well. A possible outlook of the study is then represented by the future investigation of the number of spans over which also the identification accuracy of the first bending frequency becomes insensitive to span increase.

According to the results of this sensitivity analysis, the standard deviation of the frequency estimation in case of a dataset of ten spans only is deemed too high to provide reliable results. For this reason, dataset C has not been taken into consideration for identification purposes. Nevertheless, the similarity of the time histories collected on the same span during different crosses is considered promising for the investigation of very local phenomena, such as asphalt defects and marked road irregularities.

5. Conclusions

This work presents the results of an experimental campaign performed with the purpose of investigating the actual feasibility of an indirect frequency estimation approach. The proposed analysis is based on the processing of onboard acceleration signals acquired during 10 passages, performed at the travelling speed of 30 km/h, over a mixed multiple span bridge in Lombardy, Italy.

The described work led to the following conclusions:

- By a simple algebraic sum of lead and rear car acceleration it was possible to get rid of the hiding effects due to vehicle pitching motion. The first two bending frequencies of the bridge were extracted with promising accuracy. Best outcomes were obtained for the first bending frequency.
- Expansion joints are confirmed to strongly affect vehicle's dynamics, causing significantly higher excitation. Nevertheless, the proposed methodology showed to be resilient to joints presence. Differences were found in terms of signals magnitude, but not in terms of indirect identification of bridge's frequencies.
- Increasing the number of crossed spans considered in the analysis led to a remarkable improvement of the accuracy of the proposed method. In case we consider more than 70 spans in the analysis, the estimation accuracy of the first frequency sharply improves, while no accuracy increase is observed for the second one.

According to the authors, some outlooks of the present research could be the following:

- Identify the number of spans, considered for frequency estimation, over which the accuracy in the identification of the first frequency becomes insensitive to it.
- Investigate the proposed method, on the same bridge, considering higher travelling speed.
- Investigate the proposed method sensitivity to a change of vehicle.

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