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Experimental Vibration Analysis for Civil Engineering Structures

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Preface

Research, development, and applications in experimental vibration analysis of civil engineering structures are being fed by the continuous progress in the fields of sensor and testing technologies, instrumentation, data acquisition systems, computer technology, data analysis techniques, and computational modeling and simulation of large and complex civil infrastructure systems. The objectives and challenges are to understand the behavior and state of health of structural, geo-structural, and soil-foundation-structural systems as well as predicting their remaining useful life using vibration data collected from these systems when subjected to operational and/or extreme loads. Advanced data analysis methods (e.g., system and damage identification, machine learning, and deep learning) are employed to extract information and knowledge from the data and to gain the insight required to support decision-making related to maintenance and inspection, retrofit, upgrade, rehabilitation, and emergency response of these systems.

EVACES, the International Conference on Experimental Vibration Analysis for Civil Engineering Structures, is a premier venue where recent progress in the field are presented and discussed by experts from all over the world. After the first eight successful editions of EVACES which took place in Bordeaux, France (2005), Porto, Portugal (2007), Wroclaw, Poland (2009), Varenna, Italy (2011), Ouro Preto, Brazil (2013), Dübendorf, Switzerland (2015), San Diego, United States of America (2017), and Nanjing, China (2019), EVACES 2021 was successfully held online from September 14–17th, 2021 and hosted by the University of Tokyo and Saitama University.

In the 2021 version of EVACES, a total of 201 participants were registered and 56 papers were presented. The topics of EVACES 2021 included but not limited to (1) damage identification and structural health monitoring, (2) testing, sensing and modeling, (3) vibration isolation and control, (4) system and model identification, (5) coupled dynamical systems (including human-structure, vehicle structure, and soil-structure interaction), (6) application of artificial intelligence techniques. Two special topics: (7) drive-by based technology, and (8) damage free and resilience for seismic disaster were also presented and discussed.

The conference was full of presentations of state-of-art studies, lively discussions, and friendly communications. Among many young participants and presenters, Chun-Man Liao, Elyas Bayat, Silvia Monchetti, Sal Saad Al Deen Taher, Haoqi Wang, and Fengming Yu were selected as the recipients of the Young Researcher Award of EVACES 2021.

Even though participants were physically away from each other, the online conference was a chance to meet old friends and make new friends. We hope these proceedings can be a collection of the excellent works presented at EVACES 2021, a proof of the progress in the research and a milestone of this area.

We would also like to thank the keynote speakers, Prof. Yozo Fujino, Prof. Yang Wang, Prof. Kazuhiko Kasai, and Prof. Eugene J. O'Brien for their splendid lectures. We believe their impressive research and their thought behind inspired all participants, in particular young researchers.

The International Scientific Committee and the National Advisory Committee, as listed in later pages, gave us tremendous support and guidance in our difficult time during the pandemic. Here, we would like to express our respect and appreciation for those help. The Organizing Committee members, as listed in the later pages, worked very hard the last two years to substantialize this conference. We appreciate for their great contributions very much. We would also like to express our gratitude to student assistants from the University of Tokyo and Saitama University for their help in the online conference management.

Hitachi, Japan
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September 2021

Zhishen Wu
Ji Dang
Tomonori Nagayama
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Damage Assessment of Civil Structures Using Wave Propagation Analysis and Transmissibility Functions

Chun-Man Liao and Yuri Petryna

Abstract A common damage detection method in civil engineering is to monitor dynamic characteristics such as natural frequencies and modal shapes, which are directly related to the structural stiffness. However, the discrepancy in measured natural frequencies may result from environmental changes, the soil-structure interaction or effects caused by earthquakes. This makes it difficult to decide whether the local change in structural properties is caused by damage or other factors. To address this challenge and thus improve the current damage detection method, the wave propagation analysis method and the transmissibility relationship were considered. In our study, the wave propagation field in structures was reconstructed by applying the Normalized-Input-Output-Minimization (NIOM) method to vibration recordings. Wave velocities and transmissibility functions were considered as reference values for the damage indicators. This paper demonstrates the evaluation of local property changes in two examples of large-scale structures: a 14-story RC building and a 64 m long pedestrian bridge. The proposed damage indicators show a clear correspondence to structural changes.

Keywords Damage detection · Damage indices · Normalized-Input-Output-Minimization · Transmissibility function · Wave propagation

1 Introduction

Structural health monitoring is an essential part in the prevention of structural failures that can threaten life safety. Many engineers prefer the vibration approach to obtain the dynamic response of structures. In civil engineering, the modal analysis is

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a useful tool for the vibration approach to identify the natural frequencies and mode shapes of structures. In terms of dynamic analysis, these characteristics are directly related to the structural stiffness and the system mass. Therefore, the change in vibration response is considered to be a direct influence of structural damage [1]. Since a decrease in frequency is expected as the damage progresses (causing a lower stiffness), some studies [2–4] aimed to determine the representative natural frequency of structures. However, vibration measurement is susceptible to change in temperature [5] or the sudden external excitation from earthquakes [6]. Accordingly, the change in measured dynamic properties is not reliable for damage detection.

To overcome this challenge, we applied wave propagation analysis, which is very commonly used in geophysics for characterizing soil properties [7]. The superiority of wave propagation lies in its continuum property, which can fulfil the wave screening in large-scale structures. Assuming that the wave features in the building structure are independent of the coupling of the building to the ground [8, 9] and the temperature, the detection of damage by the wave velocity change is more credible than by observing the global vibration response change. Thus, the wave velocity is more sensitive to the local structural properties change than to the natural frequency. Regarding this, wave propagation analysis has been proposed in this work for damage detection. We demonstrated how to determine the wave propagation in civil structures in practice. In this case, the dynamic response of the real structures was recorded first. Then the seismic interferometry technique was applied to the vibration recordings.

The seismic interferometry technique is based on the correlation of waves recorded at different receivers. The deconvolution of the motion recorded at several locations in a system results in an impulsive wave propagation in the system [9]. This impulse response is used to investigate earthquake records [10–14] and ambient vibrations [15] of building structures. However, the wave parameters estimated by the impulse response method are rather different from those during a strong earthquake motion, and thus bias the simplified wave propagation model. The Normalized-Input-Output-Minimization (NIOM) method [16] has been proposed for modeling wave propagation in multiple linear systems. This method has been used to study the strong motion records for buildings [17], but has not yet been applied to seismic noise vibration measurements.

This paper, according to the research work in [18], shows the application of NIOM to the ambient vibration measurement to retrieve the wave propagation in the real structure. The relationship between the wave velocities and the structural properties was revealed. To verify the wave propagation analysis for damage detection, the transmissibility function (TF) was introduced. The TF characterizes the structural properties, e.g. the mass, stiffness and damping ratio, in the frequency domain. The frequency amplitude of the TF reflects the critical frequency, which interprets the dominant modal frequency in the operational modal analysis [19]. The damage indicator is based on the shift of the frequency amplitude of the TF. For the definition of damage indices, the difference of the TF in two states (e.g. intact and damaged) was quantified.

2 Wave Propagation Analysis Method

2.1 Background

Generally, geophysicist use the wave propagation approach (seismic interferometry) to investigate the motions at the surface or along the depth of the soil. The deconvolution method is one of the interferometry techniques and can retrieve Green's function between two receivers. The feature of Green's function is the impulsive wave propagation, based on which the wave velocity can be estimated [9]. Since the wave propagation velocity depends only on the characteristics of the materials through which the wave propagates, the application of seismic interferometry in the subsoil has been extended to building structures [3, 10]. The assumption of the building structure is a layered continuum and can be considered as a multiple linear system.

2.2 Normalized-Input-Output-Minimization (NIOM)

In the following, a brief overview of the NIOM method for analyzing wave propagation in structures is given [16]. Taking the soil structure as an example, the statistical correlation of earthquake motions at different observation points is considered. When a time-invariant linear soil system is subjected to earthquake motion, the input and output of the system can be related in the frequency domain by means of transfer function $H(\omega_i)$.

$F(\omega_i)$ and $G(\omega_i)$ are the Fourier transforms of the actual ground motion input and output, respectively. The output at each frequency is given by:

$$G(\omega_i) = H(\omega_i)F(\omega_i), \tag{1}$$

where $i = 0, \ldots, N-1$ and $\omega_i = i\frac{2\pi}{N\Delta t}$. N is the number of samples, Δt is the sampling rate in the time domain.

This transfer function satisfies the relation of the new input model, $X(\omega_i)$, and the new output model, $Y(\omega_i)$, because the transfer function depends only on physical properties of the soil systems.

Assuming the amplitude of the new input is desired to be constant at an arbitrary point in time, the constraint holds:

$$\frac{1}{N\Delta t}\sum_{i=0}^{N-1} X(\omega_i) = 1. \tag{2}$$

Thus, the value of the new input is defined to be normalized to unity.

Using the method of Lagrange multipliers, squared Fourier amplitude spectra of the new input and the new output are minimized if they are subject to the constraint. Therefore,

$$L = \sum_{i=0}^{N-1} \left\{ |X(\omega_i)|^2 + |Y(\omega_i)|^2 \right\} - \lambda \left\{ \frac{1}{N\Delta t} \sum_{i=0}^{N-1} X(\omega_i) - 1 \right\}, \tag{3}$$

where λ is the Lagrange multiplier.

Consequently, the simplified new input model is determined by

$$X(\omega_i) = N\Delta t \frac{\frac{1}{1+|H(\omega_i)|^2}}{\sum_{n=0}^{N-1} \frac{1}{1+|H(\omega_n)|^2}} \tag{4}$$

and the response of the linear system by

$$Y(\omega_i) = N\Delta t \frac{\frac{H(\omega_i)}{1+|H(\omega_i)|^2}}{\sum_{n=0}^{N-1} \frac{1}{1+|H(\omega_n)|^2}}. \tag{5}$$

The impulsive wave propagation is obtained by the inverse Fourier transform of Eqs. (4) and (5).

3 Transmissibility Relationship

3.1 Transmissibility Function

A transmissibility function (according to the review [20]) is defined as the ratio of the Fourier transforms of two output responses in a stable linear dynamic system, i.e.

$$T_{lm}(\omega_i) = \frac{X_l(\omega_i)}{X_m(\omega_i)}, \tag{6}$$

where $X_l(\omega_i)$ and $X_m(\omega_i)$ denote the Fourier coefficients of the output response at the DOFs, l and m, respectively. The output at m is the reference.

This function of frequency ω_i gives the scalar product. Furthermore, the input information is not considered, which is an advantage in structural health monitoring during operation of structures.

3.2 Damage Index

To detect local damage in the large-scale structure, the transmissibility function (TF) based technique was adopted. Two output records at two sensor locations result in one TF. The sensitivity of a TF is reflected in the high value of the TF, corresponding to the critical frequency. If the structural properties in the partition between two receivers change, the critical frequency shifts. Thus, the difference of TF in two states (intact and damaged) is considered as the damage indicator. The damage index is defined as the total difference of the TF in the vicinity of the critical frequencies.

$$DI = \sum_{\omega_i} \left| T_{lm}^{o}(\omega_i) - T_{lm}^{d}(\omega_i) \right|, \tag{7}$$

where the superscripts “o” and “d” represent for the original state and the damaged state, respectively.

For the investigation of vertical vibrations of bridges, we propose the following equation:

$$DI = \sum_{\omega_i} \left| \frac{T_{lm}^{o}(\omega_i)}{\text{mean}(T_{lm}^{o})} - \frac{T_{lm}^{d}(\omega_i)}{\text{mean}(T_{lm}^{d})} \right|, \tag{8}$$

where $\text{mean}(T_{lm}^{o})$ and $\text{mean}(T_{lm}^{d})$ are the mean values of all amplitudes. They are used to normalize the TF.

The damage location will show a high damage index, which can potentially indicate the most weakened part due to damage in the structure.

4 Experimental Wave Propagation Analysis

4.1 14-Story Reinforced Concrete (RC) Building

We show a preliminary investigation of the NIOM method applied to reconstruct the wavefield in a 14-story reinforced concrete (RC) building (Fig. 1, left). The total height is 47 m. It is a twofold symmetric structure, except for the stiff shaft for stairwell (Fig. 1, right). There are three geophones on each floor (position reference to A, B and C). The measurement data are available in the TU Berlin research database.

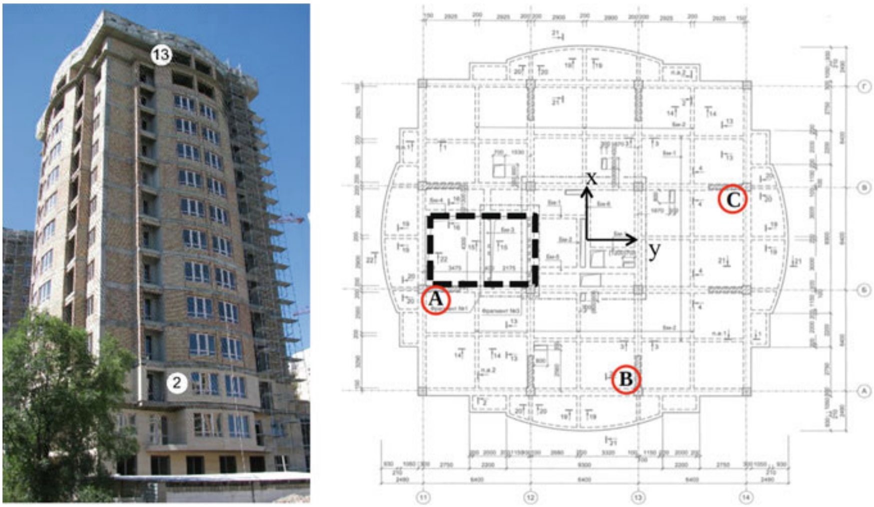

Fig. 1 Left: 14-story RC building in Bishkek, Kyrgyzstan. Right: Floor layout (image from project: Earthquake Model Central Asia)

4.2 Wave Propagation in the RC Building

Assuming the building structure as a multiple degree-of-freedom linear system, the NIOM method was applied to the ambient vibration recordings. This resulted in the wave propagation in two directions as shown in Fig. 2. The second floor is considered as the input position as the reference level.

4.3 Wave Velocity

We obtained the time lag of the wave peaks at position A, B and C in two directions. The wave velocities (Table 1) were estimated by the wave travel distance divided by the time lag.

The results reveal that the wave velocity is very sensitive to the local position. For instance, the wave velocities in two directions are not equal because the stiff shaft makes the overall structural stiffness higher in the y-direction than in the x-direction. In addition, the wave velocity in the x-direction is higher at position A than at the other positions because position A is close to the stiff shaft.

These results confirm the known fact: The higher the stiffness, the higher the wave velocity. This statement is considered to indicate the damage position causing the weak stiffness.

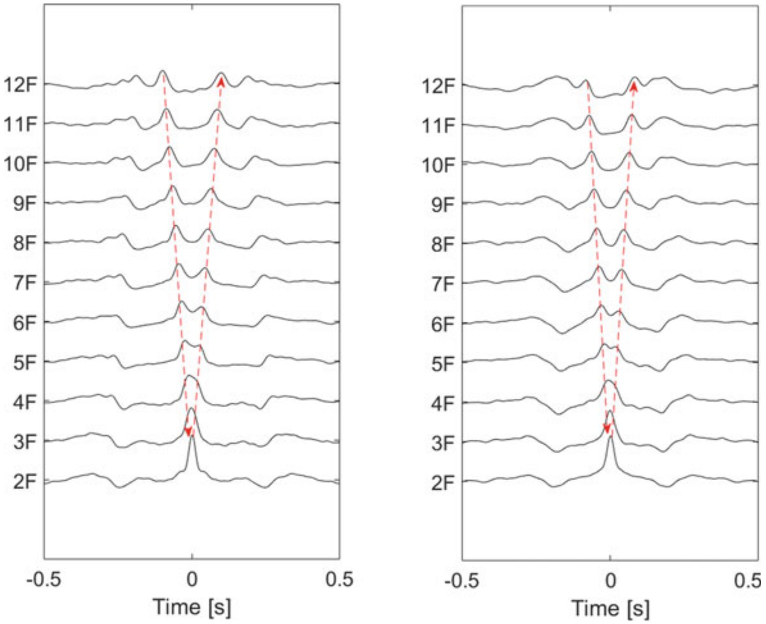

Fig. 2 Wavefield at position C in x direction (left) and in y direction (right)

Table 1 Wave velocities in the distance between 2 and 12 F [m/s]

Direction	Position A	Position B	Position C
x	371.8	342.9	334.2
y	400.0	394.0	400.0

5 Example of Damage Assessment

5.1 *64 m Long Pedestrian Bridge*

We carried out the ambient vibration measurement on a 64 m long pedestrian bridge in Berlin (Fig. 3, left). The geophones were placed on the bridge along the longitudinal direction (Fig. 3, right).

The first four mode shapes (Fig. 4) were identified from the vibration measurement.

It is noticeable that the first bending motion on the longer span (44 m) is shown in the first mode shape ($f = 2.15$ Hz). The first bending motion on the shorter span (20 m) is shown in the third mode shape ($f = 5.80$ Hz). These two mode shapes are considered as the dominant deformation on the longer and shorter span respectively.

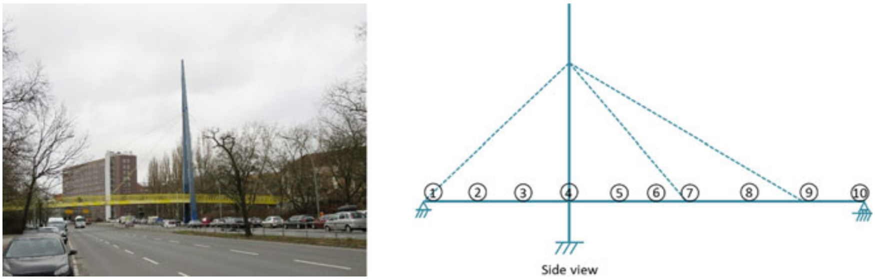

Fig. 3 Left: Pedestrian bridge "Volksparksteg" on Bundesallee in Berlin. Right: sensor position

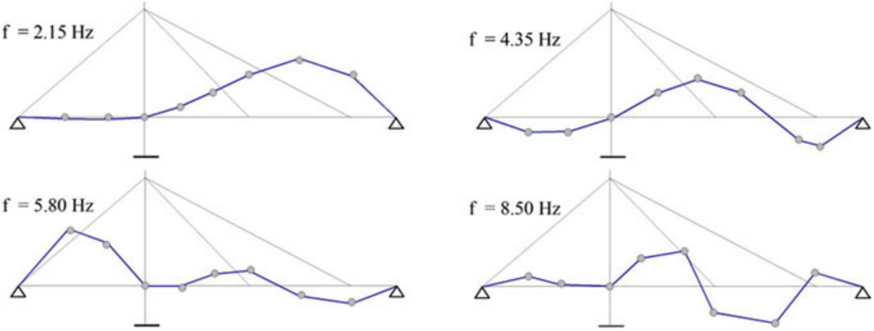

Fig. 4 Operational modal analysis results of the original bridge

5.2 *Damage Scenarios*

To investigate the proposed damage detection methods based on the wave velocity and damage index, the structural property change was intentionally induced by adding mass (approx. 150 kg) on the specific area (at sensor position 2, 7 and 8). The first mode shape of the bridge under three different conditions is shown in Fig. 5. The corresponding natural frequencies of the bridge are listed in Table 2.

The change in natural frequency indicated the different structural condition. However, the additional mass at position 2 cannot be identified by the natural frequency.

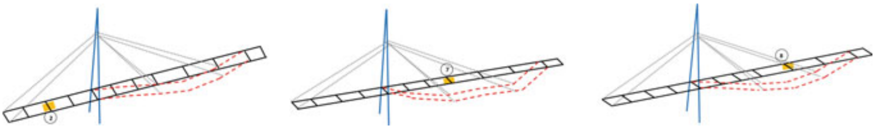

Fig. 5 The first bending mode shape in three different conditions

Table 2 Natural frequencies [Hz]

Original	Additional mass at (2)	Additional mass at (7)	Additional mass at (8)
2.15	2.15	2.00	2.02

Table 3 Wave velocities in the "cut-off" bridge [m/s]

Cut-off bridge	Original	Additional mass at (2)	Additional mass at (7)	Additional mass at (8)
Shorter span	588.0	622.5	588.0	588.0
Longer span	353.6	304.1	325.1	353.6

5.3 Wave Velocity

The application of NIOM was extended to the vertical vibration of the bridge. Since the wave field was disturbed on the pylon position separating the longer and shorter spans, we reconstructed the wave fields in two "cut-off" bridges. The wave velocities are listed in Table 3.

The wave velocity on the shorter span was increased by the additional mass at position 2, while no difference occurred due to the additional mass at positions 7 and 8. The local wave velocity change was more sensitive than global natural frequency.

On the other hand, the additional mass at position 2 and 7 caused the wave velocity to be low on the longer span. However, the additional mass at position 8 enhanced the cable strength. This ultimately made the damaged condition (mass and stiffness change simultaneously) too complicated to identify.

5.4 Damage Index by Use of Transmissibility Functions

We used Eq. (8) to compute the damage indices. The TF between successive sensors was taken into account. Therefore, comparing the damage indices in Fig. 6 helps to locate the damage position. Obviously, the high damage indices correlate well with the "damaged" part of the bridge.

6 Conclusion

This paper presents an exploratory study of the wave propagation analysis and the transmissibility function for damage detection in civil structures. The seismic interferometry technique based on deconvolution was applied to investigate the global vibration recordings. This is the first application of NIOM to ambient vibration response of a building structure and a pedestrian bridge. The wavefields in both structures were reconstructed. Discrepancies in wave velocity were revealed due to the

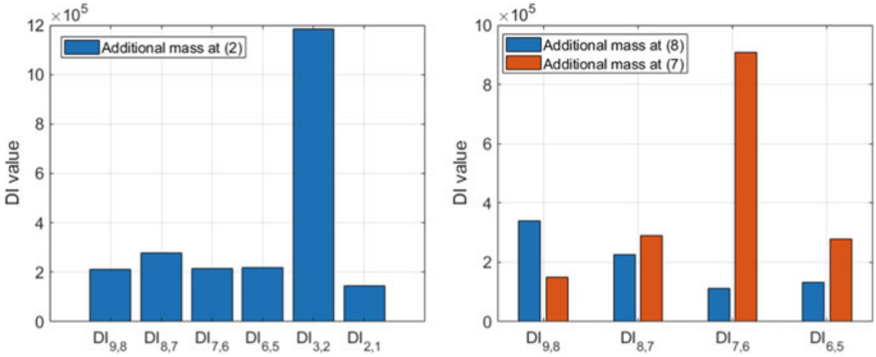

Fig. 6 The damage indices influenced by the additional mass at position 2 (left) and at position 7 and 8 (right)

difference in local structural stiffness. The similar phenomenon was also observed in the pedestrian bridge. The wavefields corresponding to the dominant bending modes indicated the individual wave velocity in the "cut-off" bridge. Moreover, the proposed damage index was used to verify the wave propagation result. This parameter is more beneficial than the natural frequencies to detect the local damage.

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SHM Campaign on 138 Spans of Railway Viaducts by Means of OMA and Wireless Sensors Network

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Abstract Condition-based monitoring applied to railway bridges represents a topic of major importance and interest among developed countries, such as Italy. In fact, bridges and viaducts represent key components of the transportation network, and therefore they increasingly draw infrastructure managers' attention. The present work is the result of a project carried out by Politecnico di Milano, consisting of a large experimental campaign conducted on a series of viaducts of the Italian railway network. The ensemble of structures under investigation is composed by 11 viaducts, for a total amount of spans equal to 138. According to a similarity criterion, the latter were subdivided into 8 groups, featured by different properties. Due to its transient nature, the experimental campaign was conducted by means of wireless accelerometers, and it consisted in the extraction of the main modal parameters of each analyzed viaduct span, as well as the characterization of the trains travelling on the line. Through the adoption of an operation modal analysis (OMA) technique, it was then possible to construct a large database of the dynamic features concerning the studied viaducts. This database may be exploited for future studies as an important baseline reference condition, by which potential outlier values may be captured, as a sign of damage occurrence among the monitored structures.

Keywords Operational modal analysis · Railway bridges · Wireless sensors network · Structural health monitoring · Condition-based monitoring

1 Introduction

High-speed railway lines play an important role in passengers and goods transportation within Italy. To ensure ride comfort and safety, infrastructure managers are continuously seeking improved condition-based monitoring systems, able to assess in real-time the health status of the structure and its time-trend [1]. As described in [2], the condition-based assessment of high-speed railway line usually focuses

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on two aspects, namely track irregularity and bridge natural frequencies [3, 4]. Since damage-sensitive, natural frequencies may be chosen as an index of the actual health status of a monitored structure: indeed, phenomena such as a crack generation/propagation, resistant section corrosion, deterioration and material ageing lead to a decreased bending stiffness of the bridge span and therefore lower natural frequencies [5]. Therefore, the idea of keeping track of the time evolution and trend of the natural frequencies regarding a certain structure (or a set of them) subject to observation can be useful from a monitoring point of view. In fact, a sudden change in terms of natural frequency may indicate the occurrence of a damage along the bridge/viaduct span, thus alarming the infrastructure manager, that can readily act in order to fix it, as soon as possible. In this context, detecting a damage at its earliest stage would mean an important achievement in terms of passenger safety and maintenance costs: it would allow to avoid sudden catastrophic failures and head to huge savings (i.e., optimized maintenance strategy). To do so, it is mandatory to get rid of any other environmental and operational aspects that influence the time evolution of the natural frequencies (i.e., temperature): this implies the use of processing algorithms such as the principal component analysis (PCA), as illustrated by the authors in [6]. Exploiting the natural frequency evolution as a structural health monitoring tool [7] requires the definition of a reference baseline to compare the new data with. An outlier value with respect to the reference condition may highlight the fact that a damage occurred on the structure subject to study [8]. Therefore, in the health monitoring working flow, the first step to accomplish consists of constructing a database that is representative of the (healthy) reference baseline to which new measures will be compared, to capture any sudden changes. As briefly mentioned above, the present work is the outcome of an experimental campaign conducted on 11 viaducts of a stretch of the Italian high-speed railway line; this resulted in a total amount of instrumented spans equal to 138. The purpose of this campaign is not just to build up a reference database for future studies, but also to investigate the possibility to infer the health status of a certain span directly from the statistic population regarding a group of spans that share the same material properties and geometrical dimensions (i.e., width and length).

Due to the transient nature of this campaign and the large number of spans under investigation, to enhance and ease the experimental operations, a set of wireless sensors was adopted, as described in detail in the following section.

The content of this paper is organized as follows: the first section aims at describing the experimental setup, providing a brief insight on the general framework concerning the campaign. Moreover, the set up and the equipment used are described in detail. The second section deals with the description of the signal processing techniques adopted for extracting modal parameters and moving loads properties respectively. Then, in the following part, the main outcomes of the experimental campaign are gathered and discussed. Final conclusions and main remarks, with a focus on possible future outlooks, are drawn in the last section.

2 Description of the Experimental Campaign

2.1 General Framework

Each span of the viaducts treated during the experimental campaign was instrumented by means of a couple of sensors placed at midspan (Fig. 1, left): moreover, for each viaduct, one single span was instrumented by a larger number of sensors (Fig. 1, right), namely ten, in order to capture higher order torsional and bending modes and pier contribution to the span motion. In addition to this, for each day of measurement a set of four sensors was used in order to get the number of train passages on the viaducts and to identify the speeds as well as the loading properties of the rail vehicles. The general framework depicted above was adopted to measure the first torsional and bending mode shapes and their associated frequencies, since these modes are the ones featured by the highest participant modal mass. The total amount of instrumented span, as briefly stated before, is equal to 138 units, that correspond to 11 different viaducts under experimental investigation during the campaign: eleven of them are featured by a simply supported beam section, while just one is featured by a closed deck section. Since the aim of this paper is to draw conclusions on the possibility of grouping spans having analogous dynamic properties, given that they share the same constructing material, same section and length, the single viaduct with a different cross-section typology was then discarded. This results in a final ensemble of spans that can be then divided, through geometrical similarity (span length), into eight groups, according to Table 1.

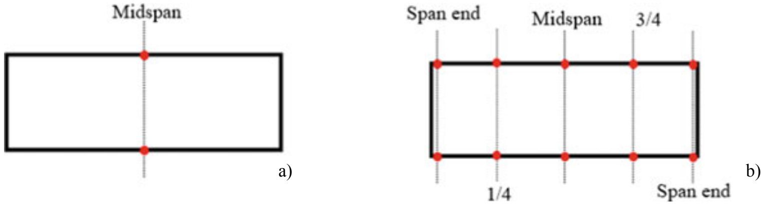

Fig. 1 Span top views: red circles represent sensors. **a**: span instrumented at midspan. **b**: finer mesh for the span

Table 1 Different span lengths

Span length (m)	23.6	24.7	31.2	33.6	34.5	34.7	35.6	36.5
Number of spans	4	15	3	14	7	40	8	38