# EURODYN 2020

*XI International Conference on Structural Dynamics*

## PROCEEDINGS

### Volume I

M. Papadrakakis, M. Fragiadakis, C. Papadimitriou (Eds.)

EASD
European Association
for Structural Dynamics

# EURODYN 2020

**Proceedings of the XI International Conference on Structural Dynamics**

Streamed from Athens, Greece

23-26 November 2020

Edited by:

**M. Papadrakakis**
National Technical University of Athens, Greece

**M. Fragiadakis**
National Technical University of Athens, Greece

**C. Papadimitriou**
University of Thessaly, Greece

**A publication of:**

Institute of Structural Analysis and Antiseismic Research
School of Civil Engineering
National Technical University of Athens (NTUA)
Greece

**EURODYN 2020**

**XI International Conference on Structural Dynamics**

M. Papadrakakis, M. Fragiadakis, C. Papadimitriou (Eds.)

First Edition, September 2020



ISBN (set): **978-618-85072-2-7**
ISBN (vol I): **978-618-85072-0-3**

## PREFACE

This volume contains the full-length papers accepted for presentation at the XI International Conference on Structural Dynamics EURODYN 2020, streamed online from Athens, Greece on November 23-26, 2020.

EURODYN Conference Series is organized under the auspices of the European Association of Structural Dynamics (EASD). EASD was founded in 1990 as a joint European initiative of experts in Structural Dynamics, with the purpose of sponsoring and overseeing the organization of the EURODYN conferences, scheduled to take place with a three-year interval. The first EURODYN Conference was held in Bochum in 1990, organized by the founding president of EASD Prof. Wilfried Krätzig. Following Bochum, the conferences were held in Trondheim (1993), Florence (1996), Prague (1999), Munich (2002), Paris, (2005), Southampton (2008), Leuven (2011), Porto (2014), Rome in 2017 and this year in Athens, the city where the EURODYN 2020 conference would have taken place in June 2020.

In view of the first signs of the COVID-19 pandemic at the beginning of this year, we were forced to postpone the conference dates at the end of November 2020. This was expected to give the opportunity to the participants to attend the conference either physically or remotely. Unfortunately, and contrary to what we had all anticipated, the COVID-19 was still around at the end of June 2020, and hence we were left with no other choice but to abandon the idea of a physical conference and organize a fully online event. This transition was very painful and created many administration complications. Nevertheless, EASD and the organizing committee have seen this sanitary crisis as an opportunity to organize a different type of event and to propose a new approach for scientific collaboration and communication that respects both the legacy of the conference series and the health of the members of the European Community of Structural Dynamics.

EURODYN conferences have been established as the top scientific events in the area of theoretical, numerical and experimental Structural Dynamics worldwide and are highly-anticipated every three years by the international community of Structural Dynamics. For the 2020 edition of EURODYN series, more than 1000 abstracts were submitted, of which 830 were selected for presentation and among them 400 full-length papers were accepted for publication in the EASD Open Access Procedia, indexed by Scopus Database.

The editors of this volume would like to thank all authors for their contributions. Special thanks go to the 88 colleagues who were involved in the organization of 38 Minisymposia and to the reviewers who contributed to the scientific quality of this e-book with their work.

We would particularly like to thank the Members of the EASD Executive Board, and especially Álvaro Cunha, the President of EASD, Guido De Roeck, the Honorary Chairman of EURODYN 2020 and Fabrizio Vestroni the Chair of the EURODYN 2017, for their valuable advice, suggestions and interest, during the three-year preparation period of EURODYN 2020. Their contributions were significant to the successful outcome of this undertaking.

**Manolis Papadrakakis**
National Technical University of Athens, Greece

**Michalis Fragiadakis**
National Technical University of Athens, Greece

**Costas Papadimitriou**
University of Thessaly, Greece

## ACKNOWLEDGEMENTS

The conference organizers acknowledge the support towards the organization of the "XI International Conference on Structural Dynamics", to the following organizations: European Association for Structural Dynamics (EASD), Greek Association for Computational Mechanics (GRACM), Hellenic Society for Earthquake Engineering (HSEE), School of Civil Engineering, National University of Athens (NTUA).

### Plenary, Semi-Plenary Speakers and Minisymposia Organizers

We would also like to thank the Plenary and Semi-Plenary Speakers and the Minisymposia Organizers for their help in the setting up of a high standard Scientific Programme.

**Plenary Speakers:** Geert Degrande, Tracy Kijewski-Correa, Yi Qing Ni

**Semi-Plenary Speakers:** Eleni Chatzi, Joel P. Conte, Geert Lombaert, Andrei Metrikine, Sotirios Natsiavas, Filippo Ubertini

**MS Organizers:** I. Antoniadis, M. Arnst, K. Bakalis, B. Balachandran, C.C. Baniotopoulos, M. Barbato, J. Beck, M. Beer, G. Bonnet, C. Borri, C. Boutin, L. Bruno, E. Caetano, F. Casciati, C.A. Castiglioni, E. Chatzi, A. Cicirello, F. Clementi, D. Clouteau, J. Conte, M. Corradi, A. Cunha, G. De Roeck, G. Degrande, V. Denoël, D. Duhamel, J. Edelmann, D. Forcellini, A. Formisano, F. Foti, M. Fragiadakis, V. C. Fragkoulis, V. Fragkoulis, C. Gentile, R. Ghanem, D. Giagopoulos, A. Giaralis, P.B. Gonçalves, R. Höffer, A. Kanyilmaz, I. A. Kougioumtzoglou, S. Lenci, G. Lombaert, F. Magalhães, C. Maniatakis, E. Marino, T. Mazilu, C. E. N. Mazzilli, V. Melissianos, A. Metrikine, A.V. Metrikine, G. Milani, I.P. Mitseas, B. Moaveni, C. Moutinho, H. Mouzakis, H. P. Mouzakis, G. Müller, J. Naprstek, S. Natsiavas, P. Omenzetter, C. Papadimitriou, M. Papadrakakis, I. Papaioannou, A. Pavic, F. Pellicano, F. Perotti, M. Ploechl, I. Psycharis, G. Rega, J. Rodellar, E. Sapountzakis, J-F. Semblat, V. Sepe, C. Soize, S. Sorokin, C. Spyrakos, A. Taflanidis, F. Tubino, D. Vamvatsikos, K.N. van Dalen, P. Van den Broeck, K. Van Nimmen, M. Vasta, P-M. Vasta, I. Vayas, D. Wagg, K. Worden, W.M. Zhai

## SUMMARY



## VOLUME I

**Minisymposia**

## VOLUME II

### Minisymposia

# CONTENTS

## VOLUME I

### Minisymposia

**MS 1: ADVANCES IN COMPUTATIONAL STRUCTURAL DYNAMICS**

**MS 2: NON-LINEAR DYNAMICS**

**MS 3: DYNAMIC BUCKLING**

**MS 4: DYNAMICS OF COMPOSITE MATERIALS**

**MS 5: DYNAMIC FLUID-STRUCTURE INTERACTION**



**MS 6: VEHICLE DYNAMICS**

**MS 7: SYSTEM IDENTIFICATION AND DAMAGE DETECTION**

**MS 8: STRUCTURAL HEALTH MONITORING**

**MS 9: STRUCTURAL CONTROL**

**MS 10: ADVANCES ON INERTER-BASED STRUCTURAL VIBRATION CONTROL**



**MS 11: BRIDGE DYNAMICS**

**MS 12: FOOTBRIDGE VIBRATIONS**

**MS 13: HUMAN INDUCED VIBRATIONS IN FLOORS, STAIRCASES AND STADIA**

**MS 14: WIND INDUCED VIBRATIONS OF SLENDER STRUCTURES AND FATIGUE**

**MS 15: DYNAMICS OF ON- AND OFF-SHORE WIND ENERGY STRUCTURES (WES)**

**MS 16: VIBRATION-BASED ASSESSMENT AND SHM OF CULTURAL HERITAGE STRUCTURES**

**MS 17: VIBRATIONS DUE TO CONSTRUCTION AND INDUSTRIAL ACTIVITIES**

## VOLUME II

### Minisymposia

**MS 18: VIBRO-ACOUSTICS**



**MS 19: BLAST AND IMPACT LOADS**

**MS 20: MOVING LOADS**

**MS 21: TRAFFIC INDUCED VIBRATIONS**



**MS 22: DYNAMIC SOIL-STRUCTURE INTERACTION AND WAVE PROPAGATION**

**MS 23: ASSESSMENT OF INDUSTRIAL STRUCTURES AND INFRASTRUCTURE UNDER NATURAL HAZARDS**



**MS 24: SEISMIC PROTECTION OF STEEL STRUCTURES BY MEANS OF DISSIPATIVE SYSTEMS AND COMPONENTS**

**MS 25: EXPERIMENTAL EARTHQUAKE ENGINEERING**

**MS 26: UQ AND PROBABILISTIC LEARNING IN COMPUTATIONAL DYNAMICS**

**MS 27: STOCHASTIC DYNAMICS AND RELIABILITY ANALYSIS OF STRUCTURAL AND MECHANICAL SYSTEMS UNDER ENVIRONMENTAL EXCITATION**



**MS 28: UNCERTAINTIES ON MATERIALS AND ENVIRONMENTAL LOADS**

**MS 29: BAYESIAN UPDATING, FILTERING AND INVERSION FOR DYNAMIC SYSTEMS**



**MS 30: RECENT ADVANCES IN PERFORMANCE-BASED ENGINEERING AND DESIGN OF STRUCTURES AND CIVIL INFRASTRUCTURE SYSTEMS SUBJECTED TO SINGLE OR MULTIPLE HAZARDS**

**MS 31: EUROPEAN ETN "DYNAMIC VIRTUALISATION: MODELLING PERFORMANCE OF ENGINEERING STRUCTURES" (DYVIRT)**

**MS 32: COMPUTATIONAL METHODS FOR STOCHASTIC DYNAMICS**



**MS 33: NUMERICAL SIMULATIONS FOR EARTHQUAKE-RESILIENT SYSTEMS**

**MS 34: VIBRATION ABSORPTION**

**MS 35: NEW TRENDS IN THE COMPUTATIONAL AND EXPERIMENTAL STRUCTURAL DYNAMICS FOR THE PRESERVATION OF HISTORICAL MASONRY STRUCTURES IN SEISMIC AREAS**

**MS 36: DAMPING MODELLING AND EXPERIMENTS**



**MS 37: CONSERVATION, RETROFIT AND STRENGTHENING OF EXISTING STRUCTURES: INNOVATIONS IN APPLIED METHODS AND MATERIALS**

**MS 38: GENERAL SESSION ON STRUCTURAL DYNAMICS, STABILITY AND VIBRATIONS**

EURODYN 2020
XI International Conference on Structural Dynamics
M. Papadrakakis, M. Fragiadakis, C. Papadimitriou (eds.)
Athens, Greece, 23–26 November 2020

# AN INTEGRATED MONITORING STRATEGY FOR CURRENT CONDITION ASSESSMENT OF HISTORIC BRIDGES

**Gabriele RAVIZZA**[1], **Rosalba FERRARI**[1], **Egidio RIZZI**[1*], **Vasilis DERTIMANIS**[2] **and Eleni N. CHATZI**[2]

[1]University of Bergamo, Department of Engineering and Applied Sciences,
viale G. Marconi 5, I-24044 Dalmine (BG), Italy
*Corresponding Author, e-mail: egidio.rizzi@unibg.it

[2] ETH Zürich, Institute of Structural Engineering,
Department of Civil, Environmental and Geomatic Engineering,
Stefano-Franscini-Platz 5, CH-8093 Zürich, Switzerland

**Keywords:** Structural Health Monitoring (SHM); Heterogeneous Data Fusion (HDF); Denoising techniques; historic reinforced concrete bridge; acceleration data; displacement data; modal identification.

**Abstract.** *Nowadays, the need for effective Structural Health Monitoring (SHM) strategies, aiming at preserving the integrity and safety of strategic and historic infrastructures, is increasingly urgent. Within SHM, several vibration-based methodologies have been developed, including those exploiting Heterogeneous Data Fusion (HDF) procedures, as well as Denoising techniques for the treatment of response signals detected through appropriate sensor technologies. In this paper, these two approaches are reconsidered and rejoined, toward developing an innovative signal processing methodology for current condition assessment, specifically referring to historic bridges. In particular, a HDF approach, i.e. the process of combining information from multiple sources, in an effort to enhance the reliability of the monitoring process, and a denoising approach, devoted to the cleaning of spurious noise from the acquired signals, are combined all together, in an integrated strategy. The effectiveness of the proposed platform is tested on data from a real structure (historic bridges). Both dynamic acceleration and displacement response signals, directly detected under operational conditions, can be processed within the proposed methodology, and subsequently employed toward modal dynamic identification purposes and possible model updating of the structure at hand.*

## 1 INTRODUCTION

This study is motivated by the awareness quest on the critical health conditions that may characterize existing and historical infrastructures, especially those nearing the end of their life cycle. Despite their age, these structures often continue to play a critical role in everyday life, constituting essential connections within the transportation network of several territories and communities. Consequently, a prompt and effective adoption of appropriate and modern strategies and action models toward their conservation and protection shall be set in place. In this scenario, the development of monitoring-based strategies toward structural condition assessment of such important infrastructures, shall constitute a fundamental tool toward the competent analysis.

Accordingly, within the civil engineering context, the Structural Health Monitoring (SHM) research field is becoming increasingly important, since the goal of achieving structural safety is only possible through the possibility to extract more abundant and precise information about the health conditions of a structure to be monitored, for instance by analyzing its current structural dynamic response. As a consequence, within SHM applications, after the signal acquisition stage, to be acquired directly on the structure by predisposing appropriate sensor networks, the subsequent phase of signal processing displays a determinant role, toward the success of the whole monitoring procedure.

In this paper, two complementary and possibly interacting approaches for the post-processing of structural response signals are considered, i.e. a denoising approach, as well as a Heterogeneous Data Fusion (HDF) procedure, aiming at achieving a better screening of real structural response signals, which may be corrupted by some amount of noise, especially in case of a low-cost instrumentation.

In particular, denoising techniques aim at clarifying the signal content, by directly acting on the contaminating noise, reducing its amount, while preserving the useful information embedded in the signal itself. Several denosing-based techniques may be employed for this purpose, including those exploiting Singular Value Decomposition (SVD) or Discrete Wavelet Transform (DWT), as recently investigated in Ravizza et al. [18, 19], where the effectiveness of these approaches has been inspected for both stationary (ambient vibration) and non stationary (seismic excitation) synthetic response signals, and for instances of real vibration signals.

Instead, Heterogeneous Data Fusion (HDF)-based approaches are procedures through which heterogeneous measurements may be combined all together, with the analogous purpose to enhance their quality, by alleviating the amount of noise on the signals and, consequently, reducing the induced uncertainties affecting the monitoring results. Several virtuous examples of HDF applications within the civil engineering field may be found in the literature, as for instance in Chatzi and Fuggini [2, 3], Ferrari et al. [4–6] and in Ravizza et al. [17], where a Kalman Filter (KF) has been involved in a HDF scheme between artificially generated acceleration and displacement response signals, aiming at obtaining enhanced displacement response measurements, for a 3-DOFs numerical dynamic system.

In the present investigation, a denoising-based approach, and a HDF procedure are considered all together and possibly coupled within an integrated monitoring methodology for the purification of real response signals, specifically displacement signals, which usually appear to be affected by higher levels of noise, if compared to accelerations. The obtained post-processed enhanced displacement measurements may then be employed toward modal dynamic identification purposes (see e.g. Pioldi et al. [10–12] and Pioldi and Rizzi [13–16]), and this might result of a crucial interest for real applications related to the SHM context.

Although the proposed methodology aims at a general formulation, as to be suitable for the monitoring of different structural systems, here, a specific real test structure is assumed as a case study for the analysis, in order to highlight the feasibility of the proposed monitoring strategy and show its effectiveness. For this purpose, the historic reinforced concrete (RC) bridge at Brivio (1917), i.e. a strategic infrastructure for some local connections within the northern Italy automotive road notwork, has been considered (Santarella and Miozzi [20], Ferrari et al. [7]).

The multiple goals that this study aims at achieving are:

- to pursue an effective denoising of real acceleration response data, detected on the monitored structure, through appropriate (wireless) acceleration sensors. In fact, although accelerations usually display a good resolution, when the sensor instrumentation employed during the signal acquisition stage is somehow poor, this may become necessary;
- to successfully perform a denoising-based approach on the original (raw) displacement signals, aiming at clarifying their content in the time domain, then resulting in a better representation and reading of the time domain signal features;
- to perform a successful HDF, by involving a KF within the fusion procedure between denoised acceleration and denoised displacement response signals, in order to obtain a further enhancement of the displacement data in the time domain;
- to employ the enhanced displacements, downstream from the HDF processing, toward possible modal dynamic identification purposes within the frequency domain, aiming at estimating the modal characteristics of the considered infrastructure.

To prove that the proposed monitoring methodology is competitive, leading to visible benefits to the structural identification process, the modal natural frequencies identified from post-processed displacements are then compared with the frequencies identified from raw data. The effectiveness of the method is proven, as well as its possible generalization to different typologies of structures.

The paper is organized as follows. In Section 2, a brief description of the structure of interest is outlined, with the reasons behind the choice of taking the Brivio bridge as a benchmark structure for the present analysis. In Section 3, the proposed monitoring strategy is formulated and presented. Then, the obtained results are reported and discussed in Section 4. Finally, last remarks and summary comments are provided within the conclusions reported in Section 5.

## 2 PRESENTATION OF THE MONITORED STRUCTURE

The peculiar class of structural systems to which this study is addressed to, aims at covering civil engineering structures characterized by a significant and strategic importance, possibly combined with a historical-architectural value. In particular, the monitored structure considered as a case study within the current analysis, is the RC Brivio bridge (1917) (Santarella and Miozzi [20], Ferrari et al. [6]), represented in following Fig. 1.

The bridge, located in northern Italy (Lombardia region), constitutes an important automotive connection between the provinces of Lecco and Bergamo, linking the banks of the Adda river (Brivio (LC) and Cisano Bergamasco (BG)), at an approximate height of 8 m from water.

About its description, the Brivio bridge consists of three spans, each characterized by a couple of parabolic arches, symmetrically located to the mid-longitudinal plane. The two spans

**Figure 1:** *RC three-span arched Brivio bridge (1917) over the Adda river.*

aside the river banks are 43.4 m long; the central span is 44 m long, for a total length of 130.8 m. The deck is 9.2 m wide and hosts two roadway lanes and two cantilever sidewalks, of a 0.8 m width each. The deck structural frame of each span is constituted by a grid supporting a RC slab of a thickness of 0.15 m. The peculiar parabolic arches of the bridge display a span of 42.80 m and a rise of 8.00 m. The symmetric arches show a cross section that is 0.60 m wide, with a height varying from 1.25 m (at the middle) to 1.37 m (at the ends). Sixteen vertical RC hangers, characterized by a rectangular cross section of sides of 0.32 m and 0.60 m, connect the deck to each arch. The bridge is supported on the river bed through two tapered concrete piers, each one presenting maximum dimensions at the basis equal to 12.8 m (transverse direction) and 3.8 m (longitudinal direction). The piers rest on foundation RC piles driven into the riverbed for a depth of 13 m to 16 m (Froio and Zanchi [9]).

The choice of Brivio bridge being taken as a benchmark structure for this study is motivated by the fact that, despite its age of more than one hundred years, the bridge is still subjected to continuous traffic loading, likely much heavier than that for which it was originally designed way back in 1917. Present use includes daily transit of heavy-duty and various vehicles in both rush hours and all day long. Indeed, similarly to other bridges located in the nearby territories (see e.g. the Paderno d'Adda bridge, Ferrari et al. [8], placed south downstream for just a few kilometers), the Brivio bridge still plays a crucial role in the local transportation network and, for this reason, it may largely benefit from a condition monitoring under operational conditions.

It is worth noting that all signals processed in the present analysis have been acquired during a three-day measurement campaign, performed directly on the Brivio bridge, in June 2014. Further details about such a measurement campaign, as for instance information about the employed measurement instrumentation, as well as on the sensor location, may be found in Ferrari et al. [4–7].

## 3 MONITORING METHODOLOGY DESCRIPTION

In this section, a comprehensive monitoring strategy for the health condition assessment of historic bridges is presented, by specifically assuming for illustration the case study of the

RC Brivio bridge under operational loading conditions. Both acceleration and displacement response signals, directly detected on the structure as an integrated sensor network are involved within the proposed scheme. In fact, acceleration-based and displacement-based recordings are commonly exploited towards vibration-based monitoring purposes, and the choice of which approach should be preferred, usually depends on the specific monitoring goals to be pursued, as well as on the physical configuration of the analyzed structure.

In particular, acceleration-based monitoring allows to detect changes in the structural health conditions, which may be revealed by identifying variations in the structural modal properties, such as natural frequencies, mode shapes or modal damping ratios, since these quantities may then be employed within damage detection strategies for the current condition assessment of the monitored structure. Displacement-based monitoring, on the other hand, is often exploited both for evaluating the presence of excessive loads under standard service conditions, and for quantifying regular operational loads (e.g. traffic), to serve as reference in bridge design practice.

In this sense, acceleration- and displacement-based monitoring approaches may be considered as complementary, in providing useful tools toward an effective global assessment of historic and strategic infrastructural systems. However, especially due to the increasing demand for the adoption of low-cost monitoring instrumentation during the signal acquisition stage, these measurements may typically be accompanied by a significant amount of noise, which contaminates the structural response itself, by increasing the induced uncertainties and rendering more difficult their employment for SHM purposes. Such a deleterious noise effect is generally more evident on displacement data rather than on acceleration data, due to the intrinsic limits characterizing the present displacement sensor technology.

To address this issue, in the proposed monitoring methodology, a denoising-based approach is possibly integrated with a HDF-based procedure, aiming at exploiting the (more reliable) acceleration measurements for clarifying the dynamic displacement response signal of the bridge, acquired by means of a non-contact QDaedalus system (Bürki et al. [1]). The so obtained purified displacement data may then be employed toward modal identification purposes, e.g. for extracting the natural frequencies and the mode shapes of the monitored structure, and assessing its current structural conditions.

The present methodology combines a time domain analysis and a frequency domain analysis, as illustrated in the flowchart of Fig. 2, representing a global conceptual view of the considered monitoring scheme.

The time domain analysis aims at a better appreciation of the raw displacement recordings, to be later exploited for modal identification purposes. In doing so, the additional availability of acceleration response data, collected by means of wireless MEMS accelerometers, can be taken at a disposal.

Differently from data acquired through wired piezoelectric accelerometers, which may be considered as a rather reliable recording devices, even such raw acceleration data may first need to be purified, by applying appropriate denosing techniques, for reducing the noise level affecting the signal, while preserving the useful information within the recorded signal. To this purpose, a Discrete Wavelet Transform (DWT)-based denoising technique is implemented within the monitoring platform, resulting in the clarification of the detected acceleration response signal. Details about the calibration of the DWT-based denoising settings, adopted within this study, are provided in the next section. It is worth mentioning that also a Singular Value Decomposition (SVD)-based approach might be employed for the denoising of dynamic response signals; however, dealing with non stationary signals, such as those involved in this analysis,

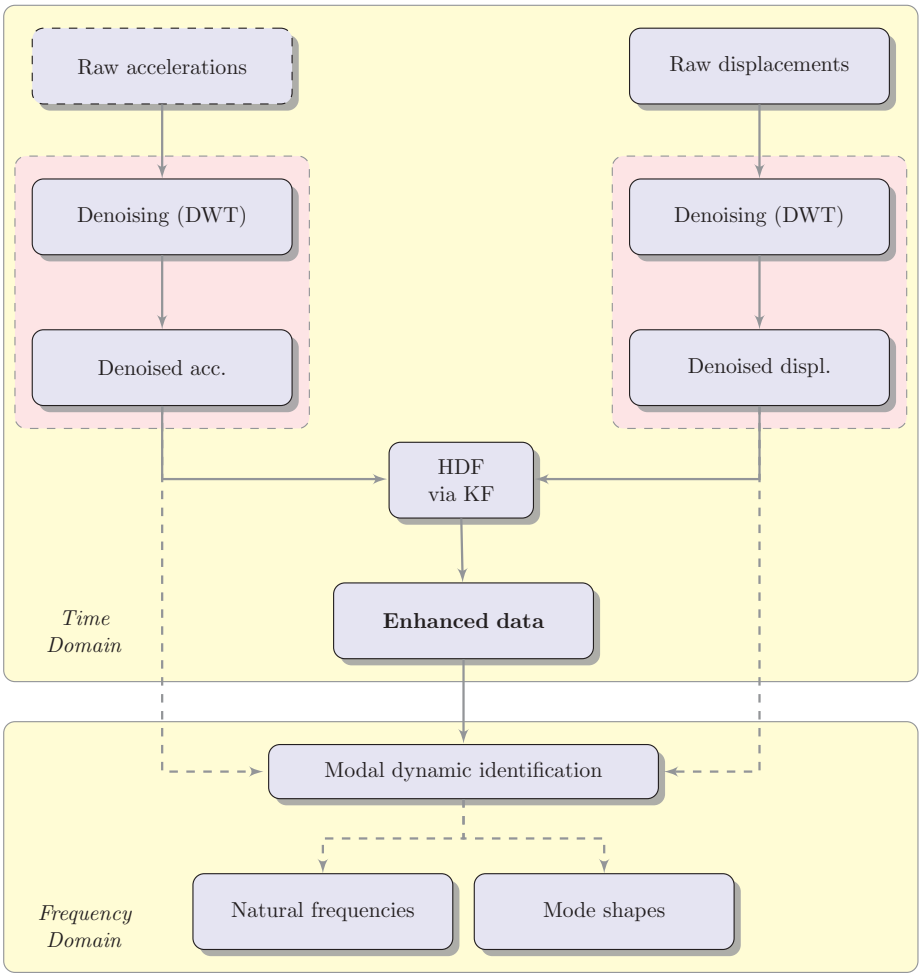



**Figure 2:** *Flowchart of the proposed monitoring methodology, integrating a denoising-based and a HDF-based approach for the enhancement of response data collected on the structure, and a subsequent structural dynamic identification.*

the DWT-based denoising approach should be preferred, as deeply shown and discussed in Ravizza et al. [18, 19].

In parallel to the (optional) acceleration denoising, a more frequently needed denoising of QDaedalus displacements is also foreseen. The same DWT-based technique is adopted, for the aforementioned reasons, and a preliminary cleaning effect on the signal is made achievable.

The core of the current implementation is now represented by the involvement of a Kalman filter (Chatzi and Fuggini [2]) within the HDF process, resulting in the merge of denoised QDaedalus displacements with acquired denoised accelerations, and an enhanced displacement response signal may be obtained.

A subsequent analysis within the frequency domain is also performed, in which the ambitious goal of successfully performing the modal dynamic identification on displacement data is inspected. In particular, the enhanced displacement response signal is employed for pursuing this purpose and, through an automatic peak-picking procedure performed on the Welch periodogram, the modal natural frequencies of the Brivio bridge may be identified.

It is worth noting that, as it can be appreciated from the flowchart in Fig. 2, the monitoring platform also contemplates the possibility to perform the modal dynamic identification of the structure by solely using either the denoised accelerations or the denoised displacements (dashed arrows in Fig. 2), but the results may be less reliable, especially considering just the displacements. However, they can be exploited for comparative purposes, aiming at highlighting the benefits deriving from a HDF-based methodology in assessing the current health conditions of the specific analyzed bridge, although such a monitoring platform also aims at assuming a more general connotation, being useful for the structural monitoring of any characteristic infrastructure.

## 4 RESULTS

In this section, some first outcomes obtained by applying the proposed monitoring methodology to the real case of the RC Brivio bridge, are shown. Time domain analysis results are firstly presented, followed by outcomes derived from a subsequent analysis within the frequency domain. Signals are taken from a measurement campaign as acquired and reported in Ferrari et al. [6].

### 4.1 Time domain analysis

The present analysis (upper box in Fig. 2) aims at purifying a raw displacement signal, making its features to emerge more clearly in the time domain, through an effective HDF with recorded accelerations, supposed to be more reliable. However, in some cases, a preliminary denoising of such acceleration data may also become necessary, e.g. when the sensor instrumentation employed in the signal acquisition phase is not so performing. Therefore, a DWT-based denoising technique is implemented on the detected (original) accelerations (from wireless sensors), and the obtained denoised signal is reported in Fig. 3, as compared with the original one.

Given the non-stationary nature of the response data, a 60 seconds length acceleration response signal from a wireless sensor is denoised, by applying a DWT-based denoising technique, which shall best fit with this signal typology, as shown in Ravizza et al. [18, 19]. In the same study, the optimal calibration of the parameters involved within this technique to deal with non-stationary signals is also inspected, resulting in the adoption of a *Smylet2* mother wavelet, combined with a *Heursure* hard thresholding rule, at decomposition level 2. Thus, the same setting is here assumed.

The effect of the denoising application is visible especially in the time window between 25 s and 40 s, as it may be appreciated in Fig. 3, leading to a signal reduction of 6.58%, in terms of Root Mean Square (RMS). The acceleration peak value is also considered, as it represents one most peculiar time domain signal feature, and a reduction of 9.11% is recorded. Such values are reported in following Table 1, for both the original and the denoised acceleration response signals.

An analogous DWT-based denoising approach is now implemented, for the preliminary clarification of the 60 seconds length QDaedalus displacement response signal, acquired on the Brivio bridge. Despite the very small amplitude of such recordings, which might affect the success of the denoising technique, the denoised estimates appear to be considerably clearer, if compared to the original (raw) data, as represented in Fig. 4.

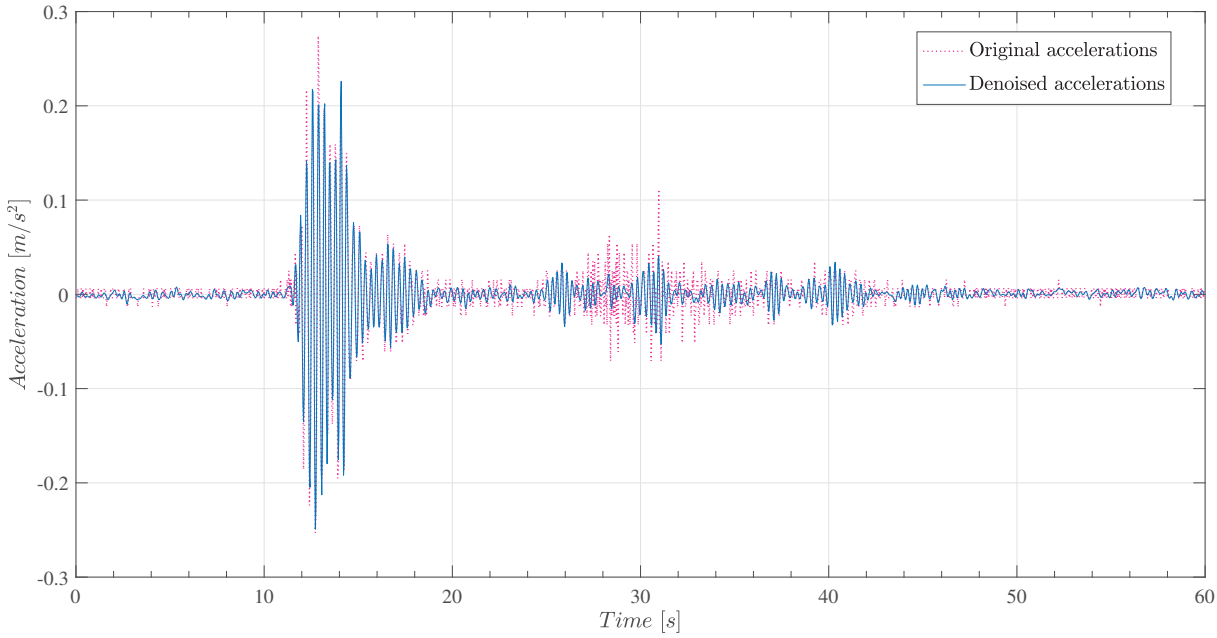



**Figure 3:** *Brivio bridge (wireless) acceleration response signal, pre and post DWT-based denoising.*

| **Acceleration signal** | **RMS** $[m/s^2]$ | $\Delta$ [%] | **Peak** $[m/s^2]$ | $\Delta$ [%] |
|---|---|---|---|---|
| Original (raw) signal | 0.0319 | | 0.2742 | |
| DWT denoised signal | 0.0298 | $-6.58$ | 0.2492 | $-9.11$ |

**Table 1:** *Characteristic values of the analyzed acceleration response signals in the time domain and their variation with respect to the original (noise-affected) signal: RMS and peak acceleration values.*

After this preliminary phase, devoted to the pre-treatment of the acquired data, the obtained denoised acceleration and displacement response signals are then processed within a HDF-based implementation, aiming at further enhancing the measured displacements, by enriching them through the information embedded within the denoised accelerations. To this end, a Kalman Filter algorithm is exploited, allowing for the effective merge of the two heterogeneous source signals (Chatzi and Fuggini [2], Ferrari et al. [6], Ravizza et al. [17]). The result is represented by a new enhanced displacement signal, as shown in Fig. 5, which more reliably reflects the response of the monitored bridge.

To complete the time domain analysis, RMS and peak deflection values of the displacement signals are also computed, and summarized in Table 2. A reduction of both values, although lighter than that recorded in the previous acceleration case, is still observable, configuring itself as a peculiar feature of such techniques, as shown for synthetic signals in Ravizza et al. [19].

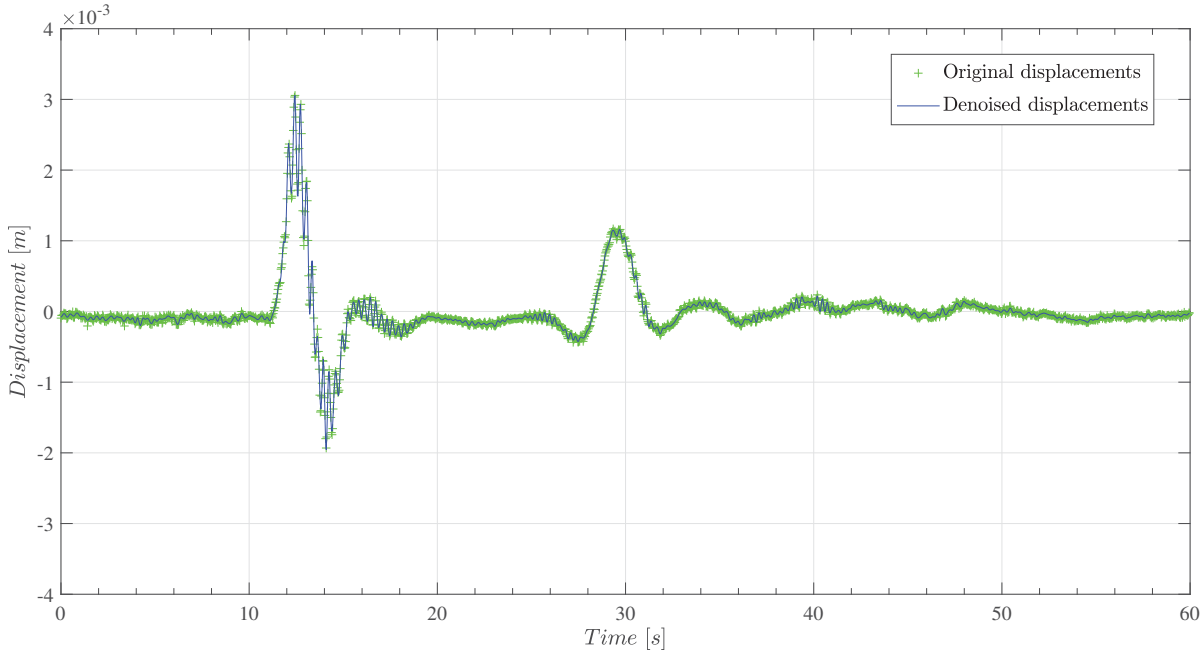



**Figure 4:** *Brivio bridge (total station) displacement response signal, pre and post DWT-based denoising.*

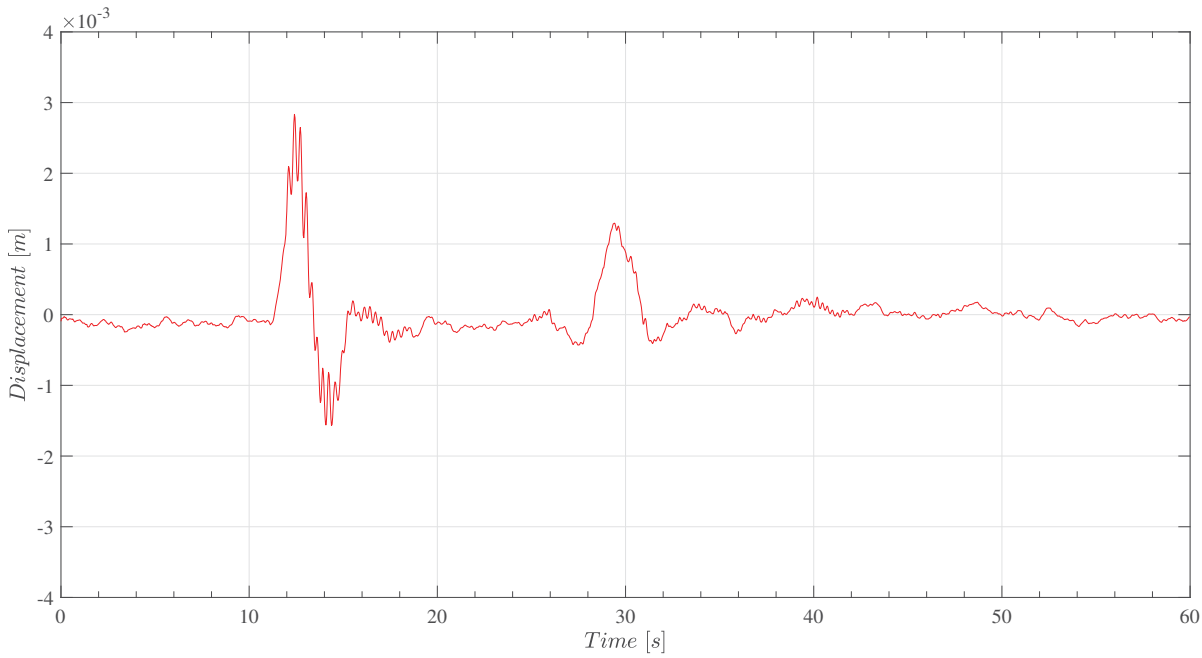



**Figure 5:** *Enhanced Brivio bridge displacement response signal, obtained by HDF via KF with the denoised acceleration response signal.*

| **Displacement signal** | **RMS** $[mm]$ | $\Delta$ [%] | **Peak** $[mm]$ | $\Delta$ [%] |
|---|---|---|---|---|
| Original (raw) signal | 0.4039 | | 3.056 | |
| DWT denoised signal | 0.4001 | $-0.94$ | 3.015 | $-1.34$ |
| HDF enhanced signal | 0.3972 | $-1.66$ | 2.833 | $-7.30$ |

**Table 2:** *Characteristic values of the analyzed displacement response signals in the time domain and their variation with respect to the original (noise-affected) signal: RMS and peak deflection values.*

### 4.2 Frequency domain analysis

The enhanced displacement data, downstream obtained from the HDF procedure with the denoised accelerations, are now employed for performing a modal dynamic identification analysis in the frequency domain. In particular, by applying a Welch method on such displacements, the Power Spectral Density (PSD) function of the signal may be obtained. In following Fig. 6, the response spectrum derived from the HDF displacement signal and from the original (raw) displacement signal are represented and compared.

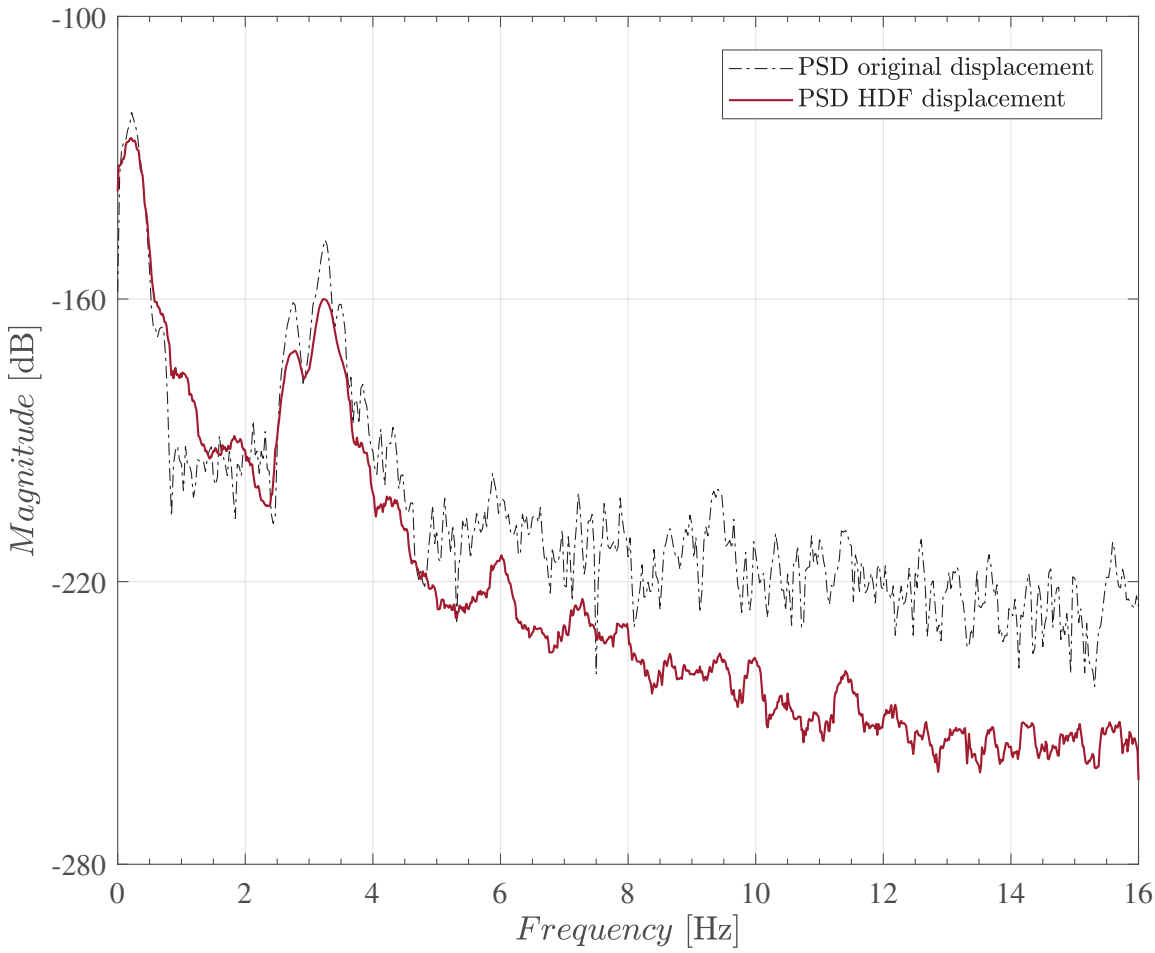



**Figure 6:** *Brivio Bridge displacement (PSD) response spectrum: original (raw) displacement signal vs. HDF (enhanced) displacement signal.*

The effect of the previously applied time domain filtering techniques (i.e. DWT-based denoising and KF application) is evident, resulting in smoother curves, as well as in the reduction of the signal magnitude, especially within the medium-high frequency region (approximately greater than 6 Hz), where the embedded noise mainly affects the data.

The benefits that the proposed methodology has brought to the identification process emerge by the comparison between the frequency content of the two signals. In fact, whether the original signal allows for the detection of just one frequency peak, corresponding to the first natural frequency of the bridge, the post-processed displacement signal reveals a greater number of frequency response peaks, which were previously indistinguishable, due to the deleterious effect of spurious noise. Consequently, a greater number of natural frequencies may be extracted.

However, due to the limited length of the time window, even the peaks associated to the external loading acting on the bridge (i.e. traffic load) might appear in the response spectrum, making the identification process harder. Thus, to distinguish such peaks from structural modes, an automatic peak-picking procedure is performed on the Welch periodogram, and the first eight natural frequencies of the monitored structure may be identified. To emphasize the benefits that the proposed methodology may bring to the identification process, the same peak-picking technique is performed on the PSD of the original (raw) displacement signal, leading to the identification of the first natural frequency only. Such a comparison is represented in Fig. 7, where the modal natural frequencies are marked by vertical red lines and, then, further reported in Table 3, which coherently compare to analogous results provided in Ferrari et al. [6], namely frequencies identified through a classical FDD method on acceleration signals acquired out of standard wired accelerometer sensors.

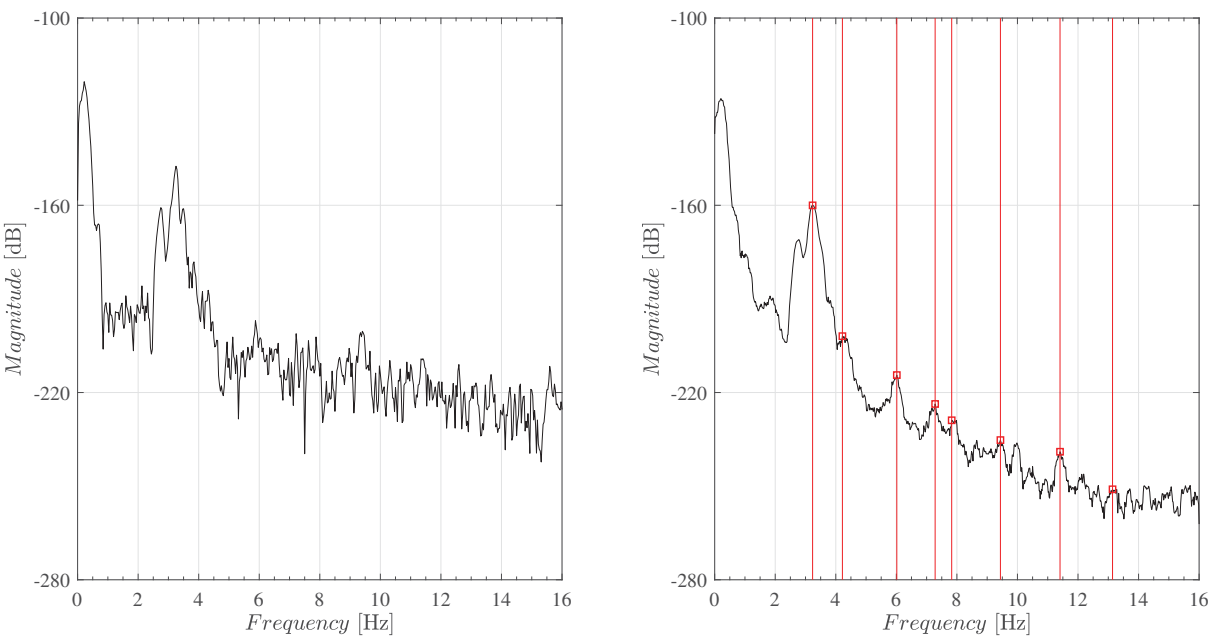



**Figure 7:** *Brivio bridge identified natural frequencies from displacement signals. Peak-picking procedure on Welch periodogram: original (raw) displacement signal vs. HDF (enhanced) displacement signal.*

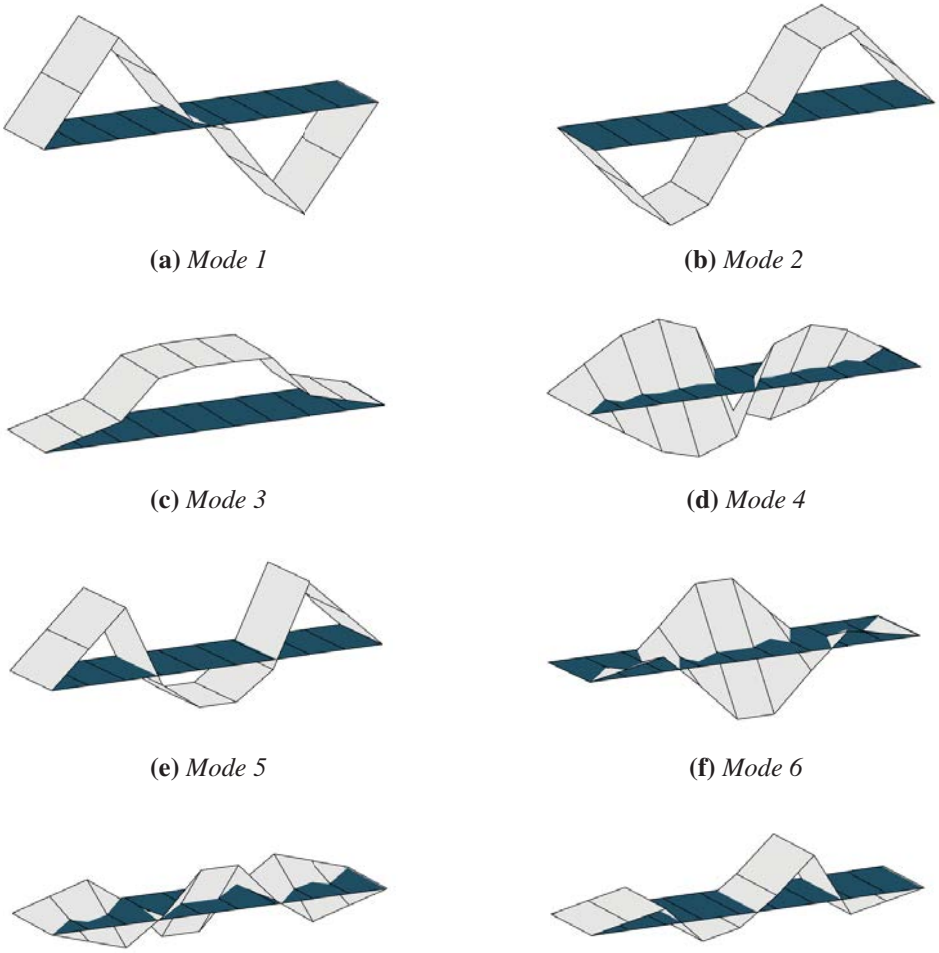
Except for the first two and the sixth natural frequencies, which display a not negligible discrepancy with the respective outcomes deriving from a FDD-based inverse analysis on wired

| **Modes** | **I** | **II** | **III** | **IV** | **V** | **VI** | **VII** | **VIII** |
|---|---|---|---|---|---|---|---|---|
| $f_{id,WD}$ [Hz] | 3.247 | 4.211 | 6.016 | 7.280 | 7.815 | 9.378 | 11.406 | 13.140 |
| $f_{id,AC}$ [Hz] | 3.564 | 3.857 | 6.018 | 7.178 | 7.690 | 9.009 | 11.377 | 13.086 |
| $\Delta$ [%] | −8.89 | 9.18 | −0.03 | 1.42 | 1.63 | 4.10 | 0.25 | 0.41 |

**Table 3:** *Brivio bridge natural frequencies $f_{id,WD}$ identified from a HDF displacement response signal (wireless sensor), compared to frequencies $f_{id,AC}$ (Ferrari et al. [6]) identified from an acceleration response signal (wired sensor), and their variation.*

accelerations, assumed here as reference, the results show a good agreement, as the percentage variation is in any case below 2%.

Finally, from a FDD analysis (Pioldi et al. [10–12]) on displacement signals (corroborated as above by acceleration data), the bridge first span mode shapes, corresponding to the previously identified frequencies, are obtained and represented in following Fig. 8. In particular, the QDaedalus displacement data, enriched by reliable accelerations, as those acquired through a wireless detection system, represent the selected 8-channel input considered within the current analysis, for the representation of the mode shapes of the monitored structure.



**(a)** *Mode 1* **(b)** *Mode 2*

**(c)** *Mode 3* **(d)** *Mode 4*

**(e)** *Mode 5* **(f)** *Mode 6*

**(g)** *Mode 7* **(h)** *Mode 8*

**Figure 8:** *FDD vibration mode shapes of Brivio bridge first span.*

Even concerning the vibration mode shapes, many analogies with the respective results reported in Ferrari et al. [6] may be observed. In particular, mode 1 and mode 2 show a very similar behaviour, although they are related to different natural frequencies. Moreover, most of the modes seem to be regular, characterized by bending or torsion, except for mode 7, in which bending and torsion appear to be coupled.

These similarities between the results may be considered as a further proof of the reliability of the proposed monitoring strategy, which provides an alternative approach aiming at evaluating the structural health condition of a generic civil structural system.

## 5 CONCLUSIONS

In this paper, an innovative monitoring methodology that integrates a denoising-based approach with a HDF-based strategy is proposed, for the structural health condition assessment of historic and strategic bridges. In particular, the main achievements that the present study has highlighted may be summarized as follows:

- the beneficial effect of the analyzed denoising technique is more pronounced within the time domain, where, after the DWT-based denoising application, the main signal features (i.e. peak value and RMS) may more clearly emerge;
- the acquired Brivio bridge acceleration and displacement response signals have been successfully denoised and, subsequently, involved within a HDF-based implementation, and an enhanced displacement response signal has been obtained;
- the output-only modal identification analysis performed on the enhanced displacement signal reveals the natural frequencies of the investigated structure, proving the effectiveness of the proposed methodology;
- by comparing the obtained results, by effective post-processing of response signals detected through wireless sensors, with those derived from signals acquired through standard wired sensors, no substantial differences emerge: this reinforces the belief that modern wireless sensor technology may become competitive at the signal acquisition stage, if adequately treated as here described, leading to reliable estimates.

In conclusion, the possibility of setting a monitoring platform that integrates a denoising-based approach with a HDF-based strategy may allow the user to achieve a more complete and reliable description of specific response signals, bringing to light their more peculiar characteristics, in both time and frequency domains. In this sense, the post-processing methodology presented in this study, may constitute a useful tool within structural monitoring applications.

**Acknowledgments**
Public research support from *"Fondi di Ricerca d'Ateneo ex 60%"* and a ministerial doctoral grant and funds at the ISA Doctoral School, University of Bergamo, Department of Engineering and Applied Sciences (Dalmine), are gratefully acknowledged. Prof. Chatzi and Dr. Dertimanis have received funding from Horizon 2020, the EU's Framework Programme for Research and Innovation, under grant agreement number 769373 (Project: FORESEE).

## REFERENCES

[1] Bürki, B., Guillaume, S., Sorber, P. and Oesch, H. (2010), DAEDALUS: a versatile usable digital clip-on measuring system for total stations. In: *International Conference on Indoor Positioning and Indoor Navigation*, Zürich, Switzerland, 15–17 September 2010.

[2] Chatzi, E.N. and Fuggini, C. (2012), Structural identification of a super-tall tower by GPS and accelerometer data fusion using a multi-rate Kalman filter. In: *Proceedings of the 3rd International Symposium on Life-Cycle Civil Engineering*, Delft, Netherlands, 3-6 October 2012, 10: 144–151.

[3] Chatzi, E.N. and Fuggini, C. (2015), Online correction of drift in Structural Identification using artificial white noise observations and an Unscented Kalman filter. *Smart Structures and Systems*, 16(2): 296–328.

[4] Ferrari, R., Froio, D., Chatzi, E.N., Gentile, C., Pioldi, F. and Rizzi, E. (2015), Experimental and numerical investigation for the structural characterization of a historic RC arch bridge. In: *COMPDYN 2015, 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Crete Island, Greece, 25-27 May 2015, 1: 2337–2353, available online in Eccomas Proceedia, www.eccomasproceedia.org/conferences/thematic-conferences/compdyn-2015/3542.

[5] Ferrari, R., Pioldi, F., Rizzi, E., Gentile, C., Chatzi, E.N., Klis, R., Serantoni, E. and Wieser, A. (2015), Heterogeneous sensor fusion for reducing uncertainty in Structural Health Monitoring. In: *UNCECOMP 2015, 1st ECCOMAS Thematic Conference on International Conference on Uncertainty Quantification in Computational Sciences and Engineering*, Crete Island, Greece, 25-27 May 2015, pp. 511–528, available online in Eccomas Proceedia, www.eccomasproceedia.org/conferences/thematic-conferences/uncecomp-2015/4289.

[6] Ferrari, R., Pioldi, F., Rizzi, E., Gentile, C., Chatzi, E.N., Serantoni, E. and Wieser, A. (2016), Fusion of wireless and non-contact technologies for the dynamic testing of a historic RC bridge. *Measurement Science and Technology*, 27(12): 1–19.

[7] Ferrari, R., Froio, D., Rizzi, E., Gentile, C. and Chatzi, E.N. (2018), Model updating of a historic concrete bridge by sensitivity- and global optimization-based Latin Hypercube Sampling. *Engineering Structures*, 179(January 2019): 139–160.

[8] Ferrari, R., Cocchetti, G. and Rizzi, E. (2019), Reference structural investigation on a 19th-century arch iron bridge loyal to design-stage conditions. *International Journal of Architectural Heritage*, Conservation, Analysis, and Restoration. Published online on 05 July 2019: 1-31. DOI: 10.1080/15583058.2019.1613453.

[9] Froio, D. and Zanchi, R. (2014), Finite element modelization and modal dynamic analyses of an historical reinforced concrete bridge with parabolic arches. *MSc Thesis in Building Engineering*, Advisor Rizzi E., Co-Advisor Ferrari R., University of Bergamo, School of Engineering, 232 pages.

[10] Pioldi, F., Ferrari, R. and Rizzi, E. (2015), Output-only modal dynamic identification of frames by a refined FDD algorithm at seismic input and high damping. *Mechanical Systems and Signal Processing*, 68-69(February 2016):265–291.

[11] Pioldi, F., Ferrari, R. and Rizzi, E. (2015), Earthquake structural modal estimates of multi-storey frames by a refined FDD algorithm. *Journal of Vibration and Control*, 23(13):2037-2063.

[12] Pioldi, F., Ferrari, R. and Rizzi, E. (2017), Seismic FDD modal identification and monitoring of building properties from real strong-motion structural response signals. *Structural Control and Health Monitoring*, 24(11):1-20.

[13] Pioldi, F. and Rizzi, E. (2017), Refined Frequency Domain Decomposition modal dynamic identification from earthquake-induced structural responses. *Meccanica*, 52(13):3165-3179.

[14] Pioldi, F. and Rizzi, E. (2017), A refined Frequency Domain Decomposition tool for structural modal monitoring in earthquake engineering. *Earthquake Engineering and Engineering Vibration*, 16(3):627-648.

[15] Pioldi, F. and Rizzi, E. (2018), Assessment of Frequency versus Time Domain enhanced technique for response-only modal dynamic identification under seismic excitation. *Bulletin of Earthquake Engineering*, 16(3):1547-1570.

[16] Pioldi, F. and Rizzi, E. (2018), Earthquake-induced structural response output-only identification by two different Operational Modal Analysis techniques. *Earthquake Engineering and Structural Dynamics*, 47(1):257-264.

[17] Ravizza, G., Ferrari, R., Rizzi, E. and Chatzi, E.N. (2018), Effective heterogeneous data fusion procedure via Kalman filtering. *Smart Structures and Systems*, 22(5): 631–641.

[18] Ravizza, G., Ferrari, R., Rizzi, E., Dertimanis, V. and Chatzi, E.N. (2019), Denoising corrupted structural vibration response: critical comparison and assessment of related methods. In: *Proceedings of the 7th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2019), An ECCOMAS Thematic Conference, An IACM Special Interest Conference, M. Papadrakakis, M. Fragiadakis (eds.), 24-26 June 2019, Hersonissos, Crete Island, Greece, Institute of Structural Analysis and Antiseismic Research, National Technical University of Athens (NTUA), Conference Proceeding ID: 19291, Category: RS02 - ALGORITHMS FOR STRUCTURAL HEALTH MONITORING*, 12 pages.

[19] Ravizza, G., Ferrari, R., Rizzi, E., Dertimanis, V. and Chatzi, E.N. (2020), Critical assessment of two denoising techniques for purifying structural vibration response signals. *To be submitted.*

[20] Santarella, L. and Miozzi, E. (1948), Ponti Italiani in Cemento Armato. Milano: Hoepli.

**EURODYN 2020**

**Proceedings of the**
**XI International Conference on Structural Dynamics**

M. Papadrakakis, M. Fragiadakis, C. Papadimitriou (Eds.)

First Edition, September 2020

ISBN (set): 978-618-85072-2-7
ISBN (vol I): 978-618-85072-0-3

**Institute of Structural Analysis and Antiseismic Research**
**National Technical University of Athens, Greece**