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DYNAMIC MONITORING OF BRIDGES: TRADITIONAL VS VIDEO-BASED APPROACHES

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Abstract

The degradation of civil engineering infrastructures is a significant concern in Italy and worldwide, where several existing structures are beyond their expected lifespan and built design capacity. Therefore, monitoring their health condition is of upmost importance for their maintenance and preservation. Dynamic monitoring plays a crucial role in the non-intrusive structural health analysis, as it allows the damage state of the building to be assessed by monitoring its fundamental frequencies. Traditional dynamic monitoring methods rely on physical sensors that are limited to only some parts/sections of structures and struggle to detect subtle structural movements. As the world digitalizes, video/image processing techniques are emerging solutions to be adopted for structural health monitoring. Within this framework, this paper contributes to the enhancement of digital technologies for infrastructure monitoring through the application of video-based approaches for the dynamic identification of bridges. A video-based procedure to identify the fundamental vibration frequencies, using Eulerian phase-based motion-magnification algorithms, and post-processing analysis of both grey intensity variation and motion tracking, is presented and applied to the case study of a three spans pre-stressed reinforced concrete bridge located in Atina, Lazio region – Central Italy. The outcomes of the video-based approach are compared to those derived from traditional monitoring through accelerometers for validation purposes. The findings of this research proved the suitability of visual dynamic monitoring methods for precise, sustainable and cost-effective health monitoring of existing infrastructures.

Keywords: Dynamic monitoring, motion magnification, Reisz pyramid, structural safety, video-based monitoring, wavelet denoising.

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1 INTRODUCTION

Health monitoring provides significant information representative of the overall condition of structures, which are subjected to deterioration, due to impact of static, dynamic loads, environmental effects, surrounding vibrations and design issues [1,2]. Assessing structural health conditions of structures is a major concern for modern societies. Indeed, a total of 115 significant collapses of bridges have taken place worldwide since the year 2000. These incidents signal the need for enhancing and update the current structural health monitoring techniques [3].

Traditional monitoring methods require bonding measuring instruments (such as strain gauges, accelerometers, velocimeters, or testing equipment) to the structure or retrieval of samples for laboratory testing with possible detrimental effects on the integrity of structures. Furthermore, these approaches are not always viable or economical, need high level of technical expertise and pricey testing equipment or devices [4].

To cope these drawbacks, it is essential to adopt sustainable, feasible, efficient, precise, and inexpensive methods to monitor the structural performance remotely by using innovative, advanced remote sensing visual based methods. This is in line with the current trend towards digitization in the field of bridge maintenance and monitoring [5].

Advances in visual inspection by MIT researchers [6] have contributed improved solutions to detect small movements that are not visible to naked eye, by using motion magnification methods to extract the dynamic properties of objects through videos. Prominent motion magnification approaches [7,8] examine the time-dependent intensity of pixels, tracking of motion in a video sequence and amplifying the variations that indicate movement. However, they have some limitations. When amplifying subtle motion, noise is also amplified along with the motion due to artifacts and fluctuations, leasing to undesirable results in extracting actual motion. Additionally, they are unable to support small and large amplification factors combinedly [9].

In recent years the implementation of video based structural monitoring has seen emerging concern. Nonetheless, although comprehensive research is conducted on churches and masonry structures [10,11], very limited studies are conducted for the monitoring of bridges [12], which are subjected to continuous dynamic loading under influence of vehicular and extraneous environmental loads. Improving the resilience of computer vision approaches for the dynamic monitoring of existing infrastructures represents, therefore, a significant challenge.

Within this framework, in this research, the suitability of video-based techniques for the dynamic monitoring of bridges is shown. An advanced video-based procedure is presented, which aims to exploit the potential of motion magnification processes by reducing noise problems. The case study of a three spans pre-stressed reinforced concrete bridge located in Atina, Lazio region – Central Italy is used for validation purposes. Comprehensive study is conducted by validating the outcomes of the video-based methodology with traditional monitoring techniques.

2 METHODOLOGY: THE VISION-BASED PROCEDURE FOR DYNAMIC MONITORING

In this section the main content of the proposed methodology to perform the dynamic identification through video recording and processing is described. Further details can be found in [9], although some slight modifications are here proposed.

The process consists of an initial video acquisition phase, followed by wavelet denoising and gaussian smoothing algorithms to filter out high-frequency noise and distortion below a certain threshold [13,14], which could interfere with the subsequent motion magnification process. These artifacts are typically induced by camera movements due to soil vibrations and wind, and poor lighting conditions.

Then, motion magnification is carried out to enhance subtle displacements within a specified (f_{min}-f_{max}) frequency range, isolated through a band-pass filter to suppress background noise and improve the visibility of amplified motion. This enhancement is achieved using the Eulerian phase-based motion magnification algorithm [8]. The Riesz pyramid image representation proposed in [15] is used in the magnification process. This differs from the complex steerable pyramid representation adopted in [9], and allows for a reduction of the computational time required for the magnification, by even avoiding artifacts related to the spatial wraparound in the spatial decomposition phase of images.

Afterwards, a post-processing step is conducted, and the structural motion is assessed by monitoring a representative parameter. This involves two possible methods, that is grey intensity variation tracking (GIV) and motion tracking (MT). The former, which is a Eulerian approach, consists in tracking the variation in grey intensity of pixels in a region of interest (ROI), previously selected on the basis of frames entropy. The latter, a Lagrangian approach, mainly consists in following displacements of pixels, formerly identified through feature tracking algorithms [16].

Since the extracted time histories may contain noise and redundant data, dimensionality reduction techniques are applied. Correlation Analysis (CA) is used to isolate the most significant signals, while Principal Component Analysis (PCA) reduces computational complexity by retaining only the most relevant information [17, 18].

Finally, the filtered time series are analyzed in the frequency domain, and the Power Spectral Density (PSD) is computed to identify the fundamental vibration frequencies of the monitored building.

3 DYNAMIC IDENTIFICATION OF THE BRIDGE OVER THE MOLLARINO TORRENT

3.1 The case study

Figure 1: Bridge over the Mollarino torrent – Atina (Frosinone, Italy): overview (a), beams layout of lateral spans (b) and central span (c).

The structure under investigation is a three-span prestressed reinforced concrete skewed bridge located in Atina (province of Frosinone, Lazio region - Central Italy) (Figure 1), built in 1981 to serve as a crossing for vehicular traffic, including heavy traffic, of the Mollarino Torrent.

The deck, with a total length of 54 m, consists of two 11-metre side spans under which passage is permitted, and a 32-metre span through which the watercourse is bypassed. From a structural standpoint, the bridge consists of a girder deck bridge, with prestressed concrete I-beams, simply supported at the ends and with the road surface interconnected to the adjacent ones by means of expansion joints. This is a recurring type of medium-size bridges in Italy.

3.2 Traditional dynamic monitoring

To determine the fundamental frequencies of the bridge, a dynamic monitoring was performed by using triaxial accelerometers with a 9.13-to-10.66 V/g sensitivity. As shown in Figure 2, ten different points were monitored, through three different setups, each consisting of four accelerometers. The accelerometric recordings were performed at a sampling rate of 984 Hz, each lasting about one hour.

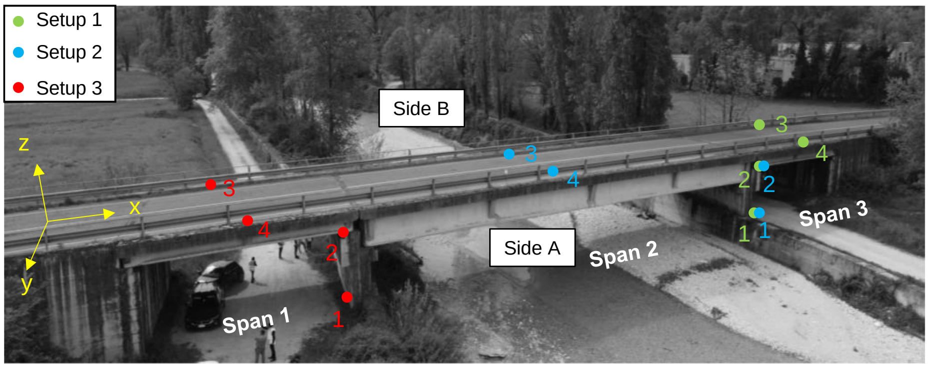

Figure 2: Traditional dynamic monitoring: acquisition setup.

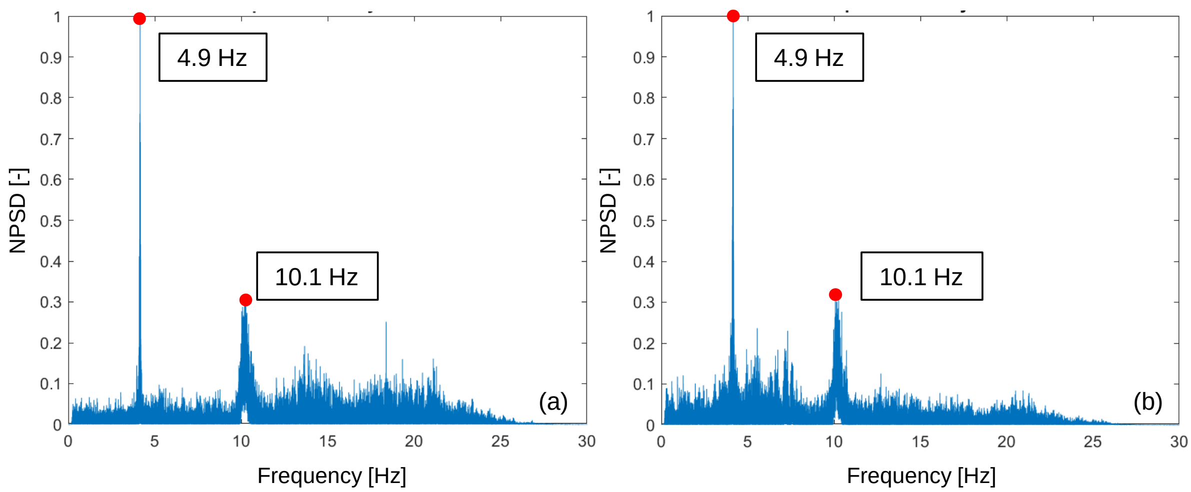

Figure 3: Normalized Power Spectral Density (NPSD) of vertical (z-axis) accelerometric recordings of Setup 3: measurement point 3 (a) and 4 (b).

In the post-processing phase, as a first step the recorded acceleration histories were sub-sampled with a frequency of 100 Hz, and then filtered using a fourth-order bandpass filter in the frequency range 0.2-25Hz and baseline correction, to precisely identify frequency components and to isolate unwanted distortions. Afterwards Fast Fourier transform (FFT) and Power Spectral Density (PSD) (subsequently normalized to obtain the Normalized PSD - NPSD) of signals were evaluated to obtain their frequency content.

In the present paper, the attention is focused on Setup 3, and in particular on the z-components of recordings of accelerometers 3 and 4, placed at the mid-length of the central span (Span 2). As it is possible to see in Figure 3, two main frequencies were identified, amounting at 4.9 Hz and 10.1 Hz, relating respectively to a flexural mode in the vertical direction (z-axis) and, probably, to a torsional mode of the deck (analyses are still ongoing on the latter mode).

3.3 Video-based vibrational monitoring

Video-based dynamic monitoring was performed through the approach briefly presented in §2. Video recordings were captured from the Side A of the central span (Figures 2,4). A Nikon D610 digital camera was adopted, featuring a 24.3 MP resolution, a 36 mm × 24 mm CMOS sensor, and an effective focal length of 50 mm. The videos had a spatial resolution of 1280 × 720 pixels and were recorded at a frame rate of 60 fps. To minimize noise and maintain consistent lighting conditions, the recordings were conducted during the midday hours of a clear, sunny day.

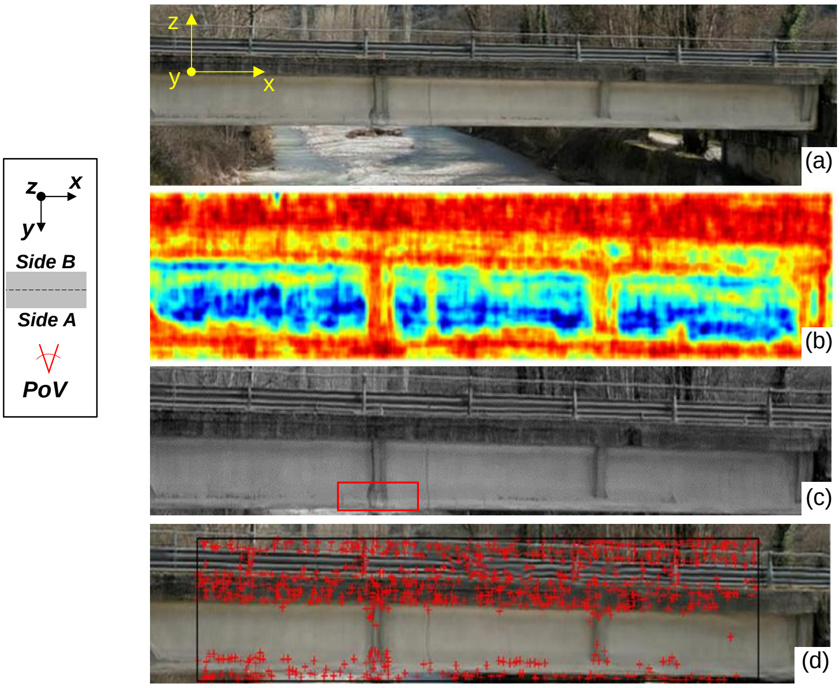

Figure 4: Video-based monitoring: magnified video frame (a), and post-processing - entropy map (b), selection of the high-entropy ROI for grey-intensity variation study (c) and selection of pixels for motion tracking study (d). PoV: point of view.

Prior to analysis, the videos underwent both spatial and temporal cropping, resulting in a final duration of approximately 90 seconds. The initial and final segments were removed to discard any unintended motion caused by starting and stopping the video. This precaution was taken despite the use of a professional tripod to minimize vibrations.

A frequency range of f_{min} = 0.5 Hz to f_{max} = 13 Hz was applied, along with an amplification factor of α = 30, were used for motion magnification processing. The processing phase focused on tracking both grey intensity variations and pixel displacements in the magnified videos, in the latter case along the -z direction (from top to bottom) (Figure 4a).

Results are shown in Figures 4 and 5. From the power spectral density PSD plots (Figure 5c,d), it can be observed that two main frequencies were detected, the first at about 4.7-4.9 Hz (grey intensity variation method – motion tracking method), and the second at 9.9-10.2 Hz (grey intensity variation method – motion tracking method). These values are comparable to the frequencies obtained through the traditional dynamic monitoring (f_{tdm}), equal to 4.9 Hz and 10.1 Hz respectively.

Although these results should be considered preliminary, as further video processing is currently being developed to perform a more detailed dynamic identification of the case study, including a wider range of vibration modes, the proposed method appears promising for applications in the field of civil infrastructure monitoring.

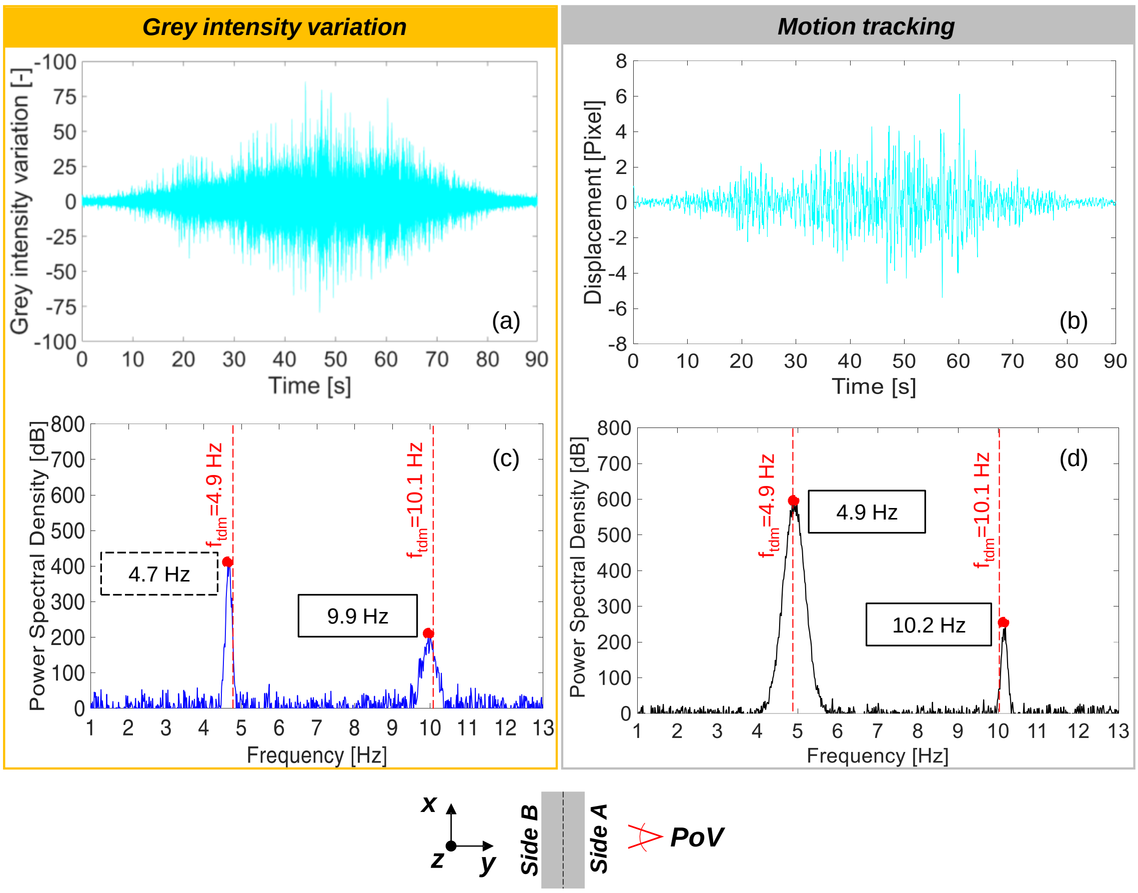

Figure 5: Video-based monitoring: grey-intensity variation (a), displacement (b) time histories, and Power spectral density derived from grey-intensity variation (c) and motion tracking (d) approach. PoV: point of view.

4 CONCLUSIONS

This comprehensive study explored the potentials of a video-based procedure for the dynamic monitoring of civil engineering infrastructures. More specifically, the paper focused on the video-based dynamic identification of bridges, through an application to the bridge over the Mollarino Torrent, a three-span prestressed reinforced concrete skewed bridge located in Atina (Frosinone, Lazio region - central Italy).

Videos were recorded by focusing on the longitudinal profile (side A) of the central span of the deck, with a 24.3 MP digital camera, at a frequency of 60 fps and a spatial resolution of 1280 × 720 pixels. After recording, wavelet and gaussian smoothing denoising filtering was applied. Afterwards, motion magnification was carried out through a Eulerian phase-based algorithm and magnified videos were post-processed to get both grey intensity variation and points displacements time histories. The frequency content of the structure was therefore evaluated trough the power spectral density, after cross-correlation and principal component analysis.

Two main vibrational frequencies were identified, namely 4.7-4.9 Hz, related to the vertical movement of the deck, possibly related to a flexural mode perpendicular to the length of the bridge (along the z-axis), and 9.9-10.2 Hz, possibly related to a torsional mode of the deck. These values are comparable to those obtained from traditional dynamic monitoring using accelerometers, through which two main frequencies, 4.9 Hz and 10.1 Hz, were identified.

Additional analyses are in progress to derive information from video-based monitoring of mode shapes, broadening the study to encompass other vibration modes of the bridge, with the aim of making these innovative monitoring techniques also suitable for the structural health monitoring of civil engineering infrastructures.

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