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Motion Magnification Technique for the Monitoring of Masonry Structures

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Abstract: Motion magnification (MM) is a recently introduced technique that allows displaying small structural vibrations, otherwise imperceptible to the naked eye, by amplifying movements from videos taken with common cameras. Vibrations of structures caused by micro-earthquakes, such as traffic-induced tremors, are perceived through pixels comparison in video frames as their intensity is increased so that they become visible. Motion magnification analysis allows to identify which parts of the building are most vulnerable to earthquakes and to determine structural natural frequencies.
Three simple structures are first considered to check the method reliability, then the technique is applied to different structures in situ as bell towers as well as bridges. The results show a clear correspondence between the theoretical frequencies of vibration and those identified by the processed videos. As such, motion magnification can be considered as a valid tool for a non-invasive, fast and low-cost analysis of the dynamic characteristics of buildings.

Keywords: motion magnification, masonry structures, mode shapes, natural frequencies, video frames, amplification, structural vibrations, amplified movements.

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1 Introduction

Italy is classified as a seismic territory since 2003, as a consequence, monitoring building response to earthquakes has become of outermost importance.

In this context, modal parameters, namely the frequencies of vibration, the mode shapes and the damping ratios are considered key information in the structural monitoring of historical constructions. Several techniques have been proposed to measure over time the response of the structure from which dynamic parameters can be extracted (Shieh et al., 2001). Among the available strategies, networks of accelerometers and/or interferometric sensors positioned on the structure to be monitored are generally used (Pieraccini et al., 2008), (Fratini et al., 2011), (Pieraccini et al., 2014), (Pieraccini et al., 2017). Their main limitation consists in the difficult deployment of the sensor network which might require bulk and expensive work to access structures like tall buildings, bridges, etc. Conversely, optical measurements like LIDAR or other techniques that use laser beams and methods based on white light (including photogrammetry), allow for full-field measurement of the structural vibration in a contactless fashion at a certain distance (Baqersad et al., 2017). This could be of great benefit on post-earthquake scenarios for a first assessment of buildings integrity. However, the above-mentioned techniques require dedicated and costly equipment, which practically limit their use.

In this scenario, motion magnification (MM), a new and expeditious technique capable to detect building vibrations using only a common camera (even a simple mobile phone), a tripod and an ambient source of vibration energy (e.g., traffic) could be an efficient alternative to more complex methods (Fioriti et al., 2017; Fioriti et al., 2018a; Fioriti et al. 2018b; Zhang et al., 2017). The technique is based on algorithms devoted to magnify small movements in a video by comparing consecutive frames of the video and amplifying them by a certain factor α (between 1 and 100), chosen by the user, within a certain frequency range, (Wu et al., 2012). In essence, each pixel of the video represents a virtual sensor and its changes of position can be analyzed throughout the video. As such, motion magnification provides a full-field measurement of the structural vibrations of the target object that can be evaluated at low cost and without any need to affect the structure, providing the possibility to analyze the building before an earthquake occurs.

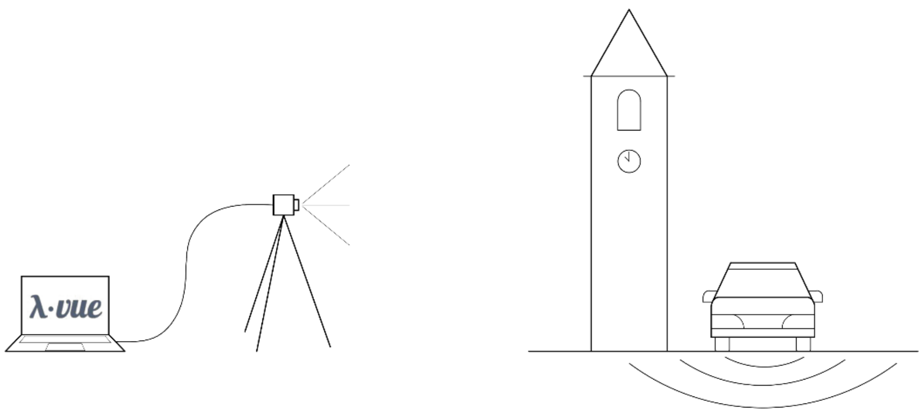
As an example, in (Poozesh et al., 2017), video magnification in conjunction with stereo-photogrammetry techniques is used to measure the higher-frequency operating shapes of a cantilever beam and a wind turbine blade. Other applications of MM to extract modal frequencies, damping ratios, and full-field mode shapes of a bench-scale building structure and a cantilever beam are described in (Yang et al., 2017). From the research experience within COBRA project of the Casaccia ENEA Research Center (Italy), it also emerged that with the use of shaking tables, motion magnification can be adopted to test materials or scale models without leading them to complete failure, involving a significant saving of specimens that can be reused (Fioriti et al., 2017; Fioriti et al., 2018a; Fioriti et al. 2018b). This allows to compare their behavior in different conditions, for example with and without structural reinforcements. More recently, in (Civera et al., 2020) this technique was successfully applied for damage detection on a multidamaged box beam with different damage sizes and angles. In (Yang et al., 2018) and in (do Cabo et al. 2020), MM was applied to detect damage on laboratory structures such as a cantilever beam, a building structure as well as a truss scale bridge. A first attempt to quantitative measure the amount of physical motion associated with the degree of magnification was made in (Valente et al. 2022).

In the present study, motion magnification is first applied to three cases for which the frequencies of vibration are computed by classical approaches: an oscillating pendulum, a lab-scaled frame structure and a continuous simply supported beam. Next, once demonstrated motion magnification applicability to simple structures, the study focuses on real constructions in open air such as bell towers and bridges.

2 Motion Magnification Procedure

As mentioned above, motion magnification is an innovative technique that requires a simple instrumentation as a camera on a tripod that records small vibrations of a structure due to, for example, a vehicle transit, Fig. 1. The simulation of a seismic tremor can be simply obtained in laboratory tests with a hammer or a shaker, and for real cases with a car transition in the proximity of the structures. In fact, the literature review has revealed that stresses generated by traffic and by earthquakes have a comparable transitory nature as they are made up of the same type of waves, both superficial and bulk ones (Seto et al., 2011). Software Lambda Vue, developed by the MIT of Boston (Wu et al., 2012) and (Chen et al., 2014) processes the recorded videos making possible to evaluate natural frequencies of the studied construction. Motion magnification algorithms use camera time-space resolution to study the dynamic behavior of the analyzed structures. In particular, movements in each video are amplified by a factor α for different frequency ranges. From the simple inspection of the outputs, it becomes clear for which frequencies there are the greatest movements: in the obtained frequency ranges falls the natural frequency of the structure.

Figure 1 Motion magnification instrumentation for the dynamic analysis of a structure: a camera positioned on a tripod that records the structure during the vibrations generated by a vehicle transit.



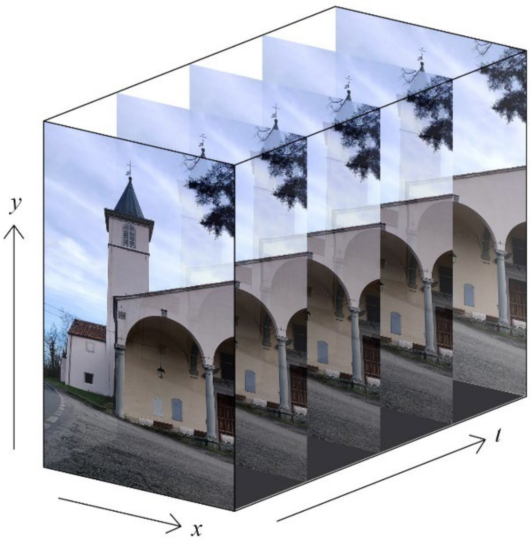
In detail, each frame of the video is studied as a 2D matrix of dimensions *A* x *B,* with *A* and *B* representing the number of pixels in the vertical (y) and horizontal (x) direction, respectively, Fig. 2. Pixels have an intensity value *I*, in the space and in the time domain. Each pixel is considered as a virtual sensor that generates a signal given by intensity variation, that is studied by using traditional frequency analysis.

Motion magnification algorithm processes pixel movements, amplifying them by α. For simplicity, the basic analysis in one-dimension that can be extrapolated in 2D is reported below, (Wu et al., 2012).

At zero time (t = 0), pixel intensity *I* is defined as:

$$I(x, 0) = f(x) \tag{1}$$

Figure 2 Video frames in the space domain (x,y) and in the time domain t.



Since the image withstands a translation movement of pixels, it is possible to write the intensity in terms of the displacement function $\delta(t)$:

$$I(x, t) = f(x + \delta(t)) \tag{2}$$

Characteristic expression of motion magnification is obtained by amplifying the movement for α factor:

$$\hat{I}(x,t) = f(x + (1+\alpha)\delta(t)) \tag{3}$$

Considering a sufficiently small $\delta(t)$, the intensity can be represented using a Taylor series truncated at the first order:

$$I(x,t) \approx f(x) + \delta(t)\frac{\partial f(x)}{\partial x} \tag{4}$$

A temporal passband filter, $B(x,t)$, is defined as:

$$B(x,t) = \delta(t)\frac{\partial f(x)}{\partial x} \tag{5}$$

Then, in motion magnification technique, the bandwidth signal is multiplied by the amplification coefficient α and added to the intensity $I(x,t)$:

$$\tilde{I}(x,t) = I(x,t) + \alpha B(x,t) \tag{6}$$

Using Eqs. (4), (5) and (6) it is possible to write:

$$\tilde{I}(x,t) \approx f(x) + (1+\alpha)\delta(t)\frac{\partial f(x)}{\partial x} \tag{7}$$

Assuming the Taylor expansion valid for the amplified displacement $(1+\alpha)\delta(t)$:

$$\tilde{I}(x,t) \approx f(x + (1+\alpha)\delta(t)) \tag{8}$$

This process represents how the displacement $\delta(t)$ of the local image $f(x)$ at time t is amplified for the quantity $(1+\alpha)$, imposed by the user, using motion magnification. More details about the theoretical framework of MM technique can be found in (Wu et al., 2012).

It is important to remind that in this study the described operation is applied to the same video for different frequency ranges in order to recognize those to which the structure is more sensitive. In each of the output videos, there are:

- elements with their own frequency contained within the chosen frequency range, clearly visible by the naked eye for their increased motion;
- elements with their own frequency falling outside the chosen frequency range, with movements unchanged from the original video.

The acquisition frame rate of the camera, namely f_{fps}, is another feature that has to be taken into account. For the Nyquist – Shannon sampling theorem, the maximum frequency value, f_{max}, is related to f_{fps} by the following relation:

$$f_{fps} \geq 2f_{max} \tag{9}$$

For example, using a 25 f_{fps} camera, the highest frequency processable by the software corresponds to 12.5 Hz.

3 MM technique: experimental validations

3.1 Single degree of freedom system: Pendulum

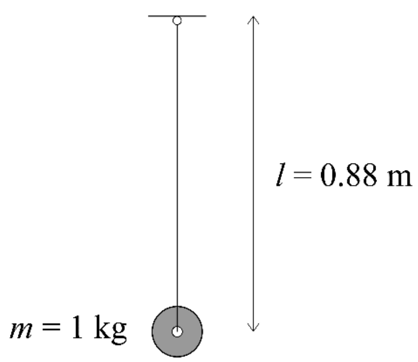
As an example of motion magnification application, a simple one-degree of freedom is considered, as the pendulum represented in Fig. 3.

The mass *m* and the length *l* of the pendulum are 1 kg and 0.88 m, respectively. Using the following equation for one degree of freedom system, the pendulum natural frequency is obtained:

$$f_n = \frac{1}{T_n} = \frac{1}{2\pi}\sqrt{\frac{g}{l}} = 0.53 \text{ Hz} \tag{10}$$

being *g* the acceleration of gravity. The pendulum dynamic behavior is studied using motion magnification. The pendulum motion is generated by moving it from its equilibrium position and letting it swing until it returns to stasis. The scene is filmed using a 25 f_{fps} camera on a tripod at an adequate height.

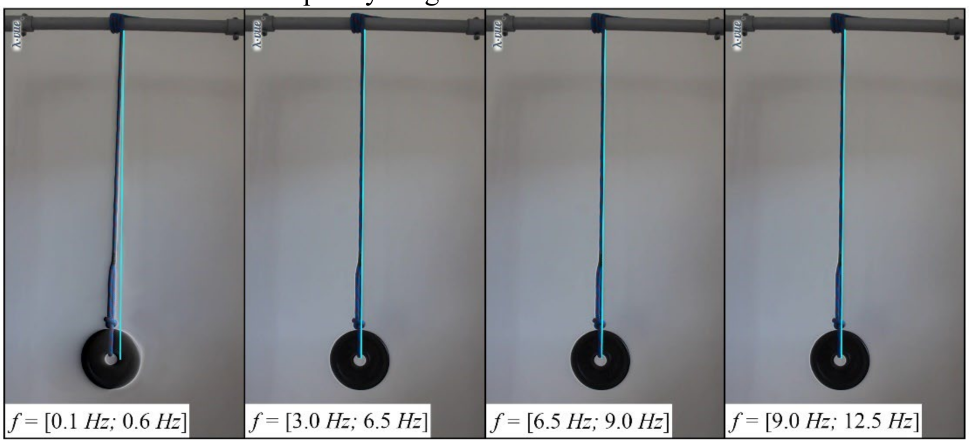
Figure 3 One degree of freedom system: the pendulum.



As mentioned above, for Nyquist-Shannon theorem, this type of camera allows the analysis of a maximum frequency equal to 12.5 Hz, being characterized by a resolution of 25 f_{fps}. Using Lambda Vue online software, the video is processed by setting five different frequency intervals with the same amplification factor (α =

28). The comparison in Fig. 4 between frames at the same instant in output videos shows that only for the interval f = [0.1; 0.6] Hz the pendulum motion is amplified. It can be concluded, that the first frequency falls within this frequency range and this result agrees with the mathematical solution in Eq. (10). This simple example shows the reliability of the technique in detecting the natural frequency of the structure.

Figure 4 Output frames (obtained with motion magnification) for different frequency ranges at the same instant.



3.2 Multi-degree of freedom system: lab-scaled frame structure

In this section, motion magnification technique is applied to a multi-degree of freedom system: the lab-scaled frame structure represented in Fig. 5.

Figure 5 Multi-degree of freedom system: lab-scaled frame structure ($l = 43\ cm, h = 30\ cm$).

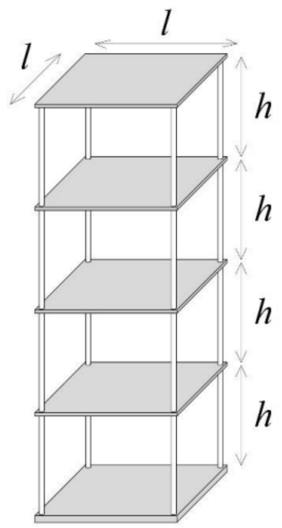


Figure 6 Output frames obtained with motion magnification.

Table 1. Comparison between frequency results obtained with the different methods.

Vibration mode	*Analytical calculation*	*Experimental result*	*MM technique*
First	$f_{1,an}$ = 3.08 Hz	$f_{1,exp}$ = 2.08 Hz	$f_{1,MM}$ = [2.5; 3.5] Hz

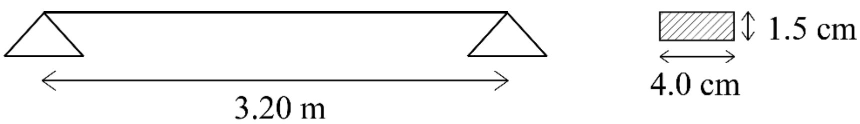
Second	$f_{2,an}$ = 8.87 Hz	$f_{2,exp}$ = 8.5 Hz	$f_{2,MM}$ = [8.0; 9.0] Hz

Natural frequencies were obtained analytically ($f_{*,an}$), experimentally ($f_{*,exp}$) and by motion magnification technique ($f_{*,MM}$). Experimentally, the frequencies were obtained positioning the structure on a shake table, and exciting the base with a sinusoidal loading for increasing frequencies. However, it was possible to derive only the first two natural frequencies due to a limitation of the shake table. In Table 1, a comparison among the frequencies obtained with the different methods is reported. In Figs. 6a and 6b, output images extracted from the amplified videos through motion magnification with amplification factor α = 25 are shown at time instants t_1 and t_2, respectively. In Fig. 6b, the first mode shape can be clearly observed.

3.3 Continuous system: simply supported beam

The third test is carried out on a steel simply supported beam, Fig. 7.

Figure 7 Continuous system: simply supported beam.



The geometrical and mechanical properties of the beam are: length L = 3.20 m, cross-sectional dimensions 4.00 cm x 1.50 cm, Young's Modulus E = 190000 N/mm^2 and mass for unit length m = 5.37 kg/m.

For this case study, two different methods are used to estimate the beam first two natural frequencies of vibration: analytical calculation and motion magnification outputs.

The obtained results are compared in Table 2 and in Fig. 8 two frames (of the processed video) at different time instants are shown. From the frames, the first mode shape of the simply supported beam can be clearly observed, while in Fig. 9 the second mode shape is visible. Through motion magnification technique, two frequency intervals are obtained, which contain the beam first two natural frequencies.

Table 2. Comparison between frequency results obtained with the different methods.

Vibration Mode	*Analytical calculation*	*MM technique*

First	$f_{1,an} = 3.06$ Hz	$f_{1,MM} = [2.5; 3.5]$ Hz
Second	$f_{2,an} = 12.24$ Hz	$f_{2,MM} = [11.5; 12.5]$ Hz

Figure 8 Sequence of output frames that shows the first mode shape of the beam.

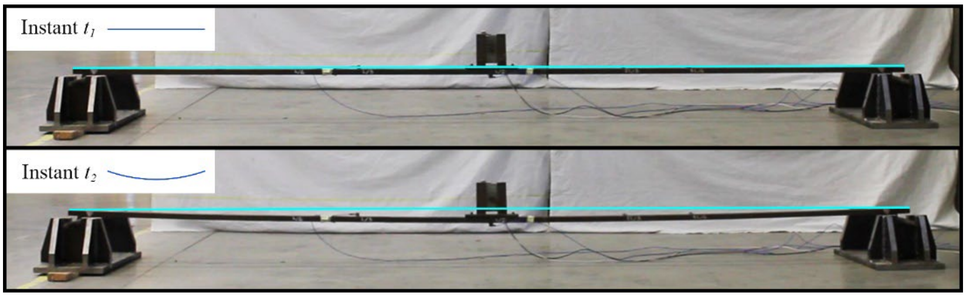
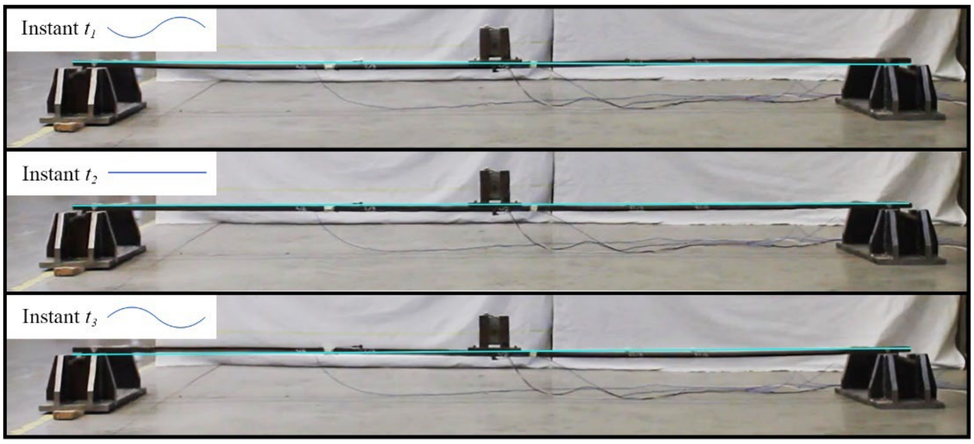


Figure 9. Sequence of output frames that shows the second mode shape of the beam.



4 MM technique: application to real-scale structures

After having proven the reliability of motion magnification technique for discrete and continuous systems, the procedure is applied to existing structures. The study on real structures is mainly focused on tall and/or slender constructions, such as bell towers and bridges. In fact, on one hand, their geometric conformation allows for greater displacements than stocky buildings; on the other, Italian legislation classifies slender structures with a high risk of damage during earthquakes and as such these constructions are of great interest for their seismic vulnerability. All the videos are realized employing a camera, characterized by a resolution of 25 fps, positioned on a tripod, to show that is possible to obtain preliminary results on the frequency range of the structure with a non-professional instrumentation.

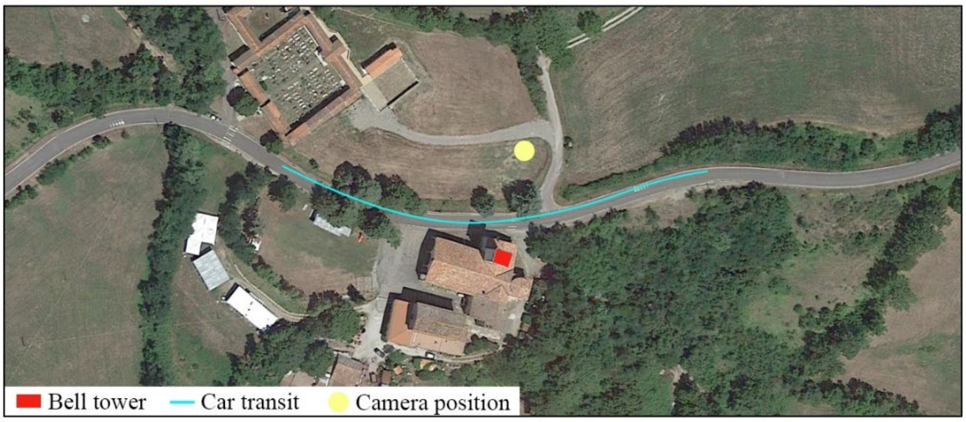
As observed in analogous tall and slender structures, the lowest vibration modes fall in the range 0-10 Hz (Lacanna et al., 2019; Standoli et al., 2021; Vincenzi et al., 2019) and, as a consequence, this type of building can be analyzed with the adopted instrumentation.

4.1 Masonry bell tower

The object of the first study is a masonry bell tower placed in the Bologna province (Italy). The construction of the architectural complex dates back to 1417, but the masonry bell tower was built during the last amplification operations in 1682-1684.

As a vehicle is travelling by, the scene is filmed with the camera. The camera is secured to the tripod and stationed where the car vibrations do not affect it, in an elevated position compared to the road, ensuring un-altered results, Fig. 10.

Figure 10. Satellite view of the area of interest: position of the masonry bell tower with respect to the camera.

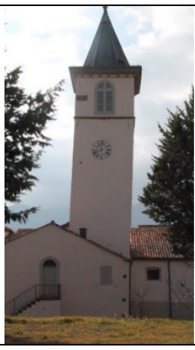


In Table 3, results are collected. It can be noted that the frequency range obtained from MM technique is f = [6.5 Hz; 9.0 Hz] as expected for similar structures (Monchetti et al., 2022). However, experimental frequencies to be compared with the obtained frequency range on this tower are not available.

It should be noted that some difficulties arise during the bell tower monitoring related to the presence of wind. In fact, wind vibrations may cause camera stability problems. However, it is still possible to have satisfactory outputs by repeating the procedure in suitable conditions (sheltered location and no-windy day).

As highlighted above, another limit concerns the range of processable frequencies, determined by the acquisition frame rate of the camera (for the Nyquist-Shannon theorem). The use of more sophisticated, powerful and professional devices could bring to a higher level of accuracy. In fact, a camera with a high acquisition frame rate would allow to investigate higher frequencies and structure vibration modes.

Table 3. Results of the bell-tower study with motion magnification technique.

Framing	*Amplification factor*	
	α = 35	
	Identified frequencies f	*On field issues*
	f = [6.5 Hz; 9.0 Hz]	Wind

4.2 Alvar Aalto bell tower

The complex of the Church of Santa Maria Assunta di Riola (Italy) is the only work of the famous architect Alvar Aalto present in Italy. The realization of the Church and the bell tower began in September 1976 (shortly after the architect's death) and the inauguration took place after the works ended on June 1978. Both the church and the bell tower are made of reinforced concrete. The bell tower is independent from the structure of the Church and stands in a central position with respect to the large square in front of the Church, Fig. 11. The tower is realized by four vertical concrete partitions connected transversely at three different heights.

Vibrations are generated by the transit of a vehicle along the surrounding road, Fig. 11. Videos are expanded with the Lambda Vue software. From the videos, it is possible to distinguish between the floor in the foreground, visibly still, and the bell tower, which is clearly vibrating according to the frequency range [9.0; 12.0] Hz as reported in Table 4. It should be noted that experimental and/or numerical frequencies are not available for this tower.

Figure 11. Satellite view of the area of interest: position of the Alvar Aalto bell tower with respect to the camera.

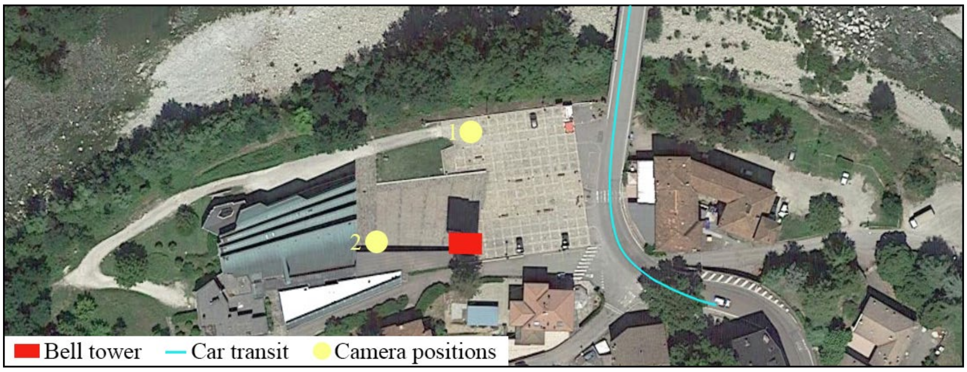


Table 4. Results of the Alvar Aalto bell tower study with motion magnification technique.

Framing	*Amplification factor*	
	$\alpha = 45$	
	Identified frequencies f	*On field issues*
 	f = [9.0 Hz; 12.0 Hz]	None

4.3 Pedestrian bridge

The pedestrian bridge that crosses the Reno river in Porretta Terme (Italy) was realized in the late seventies and it is selected as an object of investigation with MM technique to broaden the field of investigation also to structures loaded from people transit. The camera is placed on a small tripod to avoid wind vibration, resting on a supporting wall of the embankment river, Fig. 12.

The bridge is loaded in different ways: walking, running and jumping at regular intervals in the center of the greatest span. After processing the videos, for the frequency interval [3.0; 6.5] Hz, oscillations of the bridge deck are clearly visible, while in the frequency range [6.5; 9.0] Hz, the bridge cables oscillate with respect to the surrounding buildings, Table 5.

Figure 12. Satellite view of the area of interest: position of the pedestrian bridge with respect to the camera.

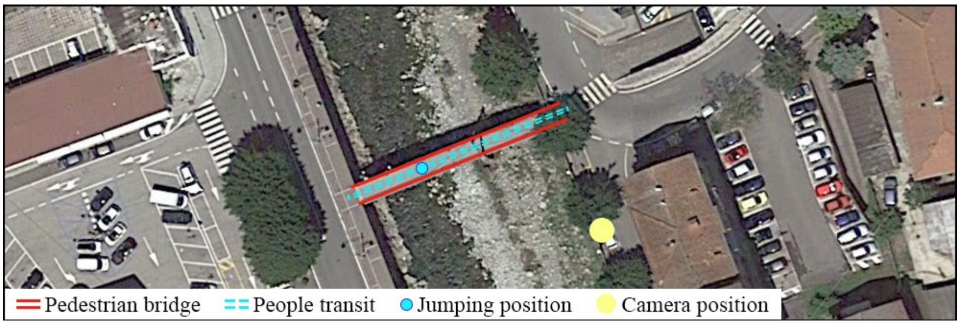


Table 5. Results of the pedestrian bridge with motion magnification technique.

Framing	*Amplification factor*	
	$\alpha = 32$	
	Identified frequencies f	*On field issues*
	f = [3.0 Hz; 6.5 Hz] (bridge) f = [6.5 Hz; 9.0 Hz] (cables)	None

4.4 Concrete Bridge

The bridge, which connects the town of Castel di Casio with the town of Silla in the Bologna province (Italy), was built in the 1980s and is crossed daily by a large number of vehicles, from cars to trucks. In Fig. 13, the position of the bridge as well as the position of the camera, which is placed below the bridge, are highlighted.

It should be noted that since the record point is very close to a river and the constant presence of wind altered the videos, it is not possible to obtain satisfactory results with MM technique. In fact, despite the numerous attempts made to stabilize camera, all the output videos are altered by the slight motion caused from the wind on the camera. This aspect represents a limit of MM technique, as illustrated in the analysis of the masonry bell tower, where the effect of wind on the videos was easily solved employing a weight for stabilizing the instruments and this was enough to achieve good results. However, the use of more sophisticated instruments such as a professional tripod could avoid the harmful effect of wind.

Figure 13 Satellite view of the area of interest: position of the concrete bridge with respect to the camera.

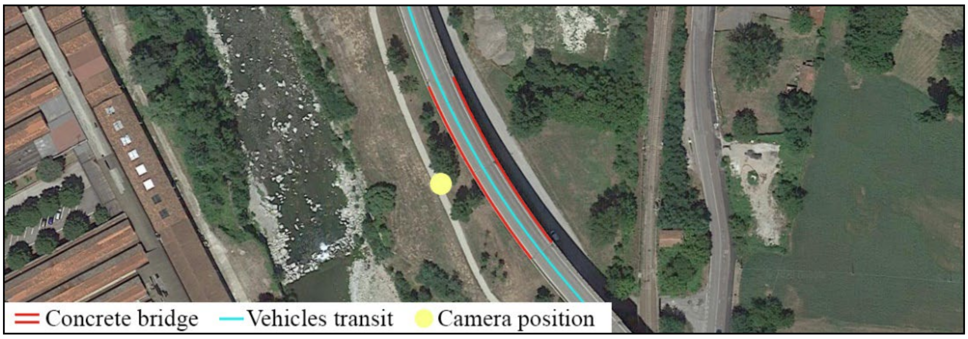


Table 6. Results of the concrete bridge study with motion magnification technique.

<table>
<tr><td>Framing</td><td colspan="2">Amplification factor</td></tr>
<tr><td rowspan="3"></td><td colspan="2">α = 35</td></tr>
<tr><td>Identified frequencies f</td><td>On field issues</td></tr>
<tr><td>None</td><td>Wind presence</td></tr>
</table>

5 Conclusions

In this paper, motion magnification technique is applied to obtain the first frequencies of three simple structures such as a pendulum, a lab-scaled frame structure and a simply supported beam. Frequencies obtained with MM technique are compared to analytical and/or experimental frequencies to check for the reliability of the method. Then, MM is applied to the analysis of real case structures as a masonry bell tower, a concrete bell tower and two bridges located in the Bologna province (Italy). The adopted instrumentation consists in a simple tripod and a common camera, to show the potentiality of the method that allows to obtain preliminary results on the dynamic behavior of complex structures without the need for installation of a monitoring network of sensors. The procedure relies in the comparison of consecutive frames of a video, allowing to study an entire surface of the structure where each pixel can be considered as a virtual sensor. As such, MM is a full-field, non-invasive and contactless technique, differently from the data obtained by an accelerometer, that are referred only to a localized point. It can be employed also to study post-earthquake damaged structures, difficult to analyze with traditional techniques.

Along with significant advantages, some technical limitations arise during the study as wind presence that may alter the results and the camera frame rate that limits the range of processable frequencies. However, with the appropriate instrumentations and attentions, these issues can be overcome. For example, the use of a professional tripod equipped with a stabilizer would ensure a better quality of recordings, avoiding the wind disturbance almost completely.

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