Modal analysis of a footbridge under pedestrian traffic and additional shaker loading

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Abstract. This paper investigates the possibility of identifying the modal properties of footbridges while they are subjected to pedestrian traffic using the CSI algorithm. The analysis is based on vibration data collected from a footbridge under different pedestrian densities. The results show that the CSI algorithm provides consistent modal properties, but the identified damping ratio seems to be significantly influenced by pedestrians. This is likely due to the human-structure interaction. Identified apparent damping ratios appear plausible, but of course not representative of the bare structure. Overall, while the CSI algorithm helps alleviate the limitations of the authors' previous approache to modal identification with a custom shaker, the practical usefulness of identifying modal properties of footbridges under pedestrian traffic is therefore limited.

1. Introduction

Advancements in structural materials and manufacturing techniques have enabled engineers to create lighter and more slender structures. However, these designs are susceptible to greater levels of vibration compared to traditional structures. To ensure structural stability and prevent damage, it is crucial to thoroughly study the behavior of these structures. Modal identification methods can help achieve this by providing valuable insights into the modal properties of a structure, including eigenfrequencies, damping ratios, and mode shapes. These properties serve as critical parameters for characterizing the structure's behavior and guiding its design and operation.

Among others, the OMAX method is one of the possible modal identification methods. It consists in a combination of experimental modal analysis (EMA) and operational modal analysis (OMA). While the former would use appropriately chosen forces only, the latter would use ambient forces only (which are unmeasured so unknown) to determine the modal properties of the structure. In this paper we assume that the experimental (chosen) forces are applied through a shaker. The OMAX method is applicable in case of combined excitations and smoothly degenerates into either EMA either OMA configurations as the magnitude of one type of loading becomes negligible with respect to the other. The recognized advantages of OMAX [2, 3] are (i) to rely on two families of excitations to excite many modes, (iii) to deal with situations where the vibration level of the two types of loading (measured/unmeasured) are similar, (iii) to be able to determine mass-scaled quantities even in case of environmental noise [2, 4, 5], which would not be possible with OMA on its own.

The University of Liège has created a shaker capable of moving masses ranging from 80-320 kg within a frequency range of 0 to 12 Hz and an amplitude of up to 150 mm, see Figure 2. This innovative system is powered by V2i, and controlled by an automata that allows for various types of excitations, including bandlimited white noise and harmonic loading. This shaker is commonly used to identify modal properties of footbridges and building floors, following the procedure presented in [1]. This procedure falls within the family of EMA methods, since the ambient excitation is neglected. This identification method is typically well suited in applications where the pedestrian traffic can be controlled, which is unfortunately not always the case. Recently, an experimental campaign was performed to identify the modal properties of La Belle Liégeoise, a 294-m footbridge located in Liège, with a main span of 163m, while the traffic was not restricted. It has revealed that our standard identification method struggled at properly identifying the modes with natural frequencies inside the frequency range affected by pedestrians. However, the modal properties (frequency, mode shape, modal mass and damping ratio) of modes outside this frequency band could be accurately identified.

To minimize the limitations associated with pedestrian passage on the footbridge during model identification tests, the OMAX method was implemented and extensively tested on a shorter span footbridge. As the OMAX method is known to perform better than EMA when the ambient vibration level is higher compared to the chosen vibration level, the tests were conducted by gradually increasing the number of pedestrians passing over the footbridge. Do this, the maximum number of pedestrians passing over a footbridge while testing and performing identification with our standard EMA approach could be determined. This article is structured as follows: the methodology used in this study is established, the structure to be analyzed is presented, and the results and main findings are discussed.

2. Methodology

As explained in the introduction, the OMAX method is a combination of the EMA and OMA methods where both ambient and imposed forces are taken into account. The method is implemented with the Combined Subspace Identification (CSI) algorithm developed in [6]. It consists in a generalisation of the Stochastic Subspace Identification (SSI) and Deterministic Subspace Identification (DSI). Similarly to SSI, the algorithm is based on the idea of first forming a Hankel matrix from the measured response data, and then applying a singular value decomposition (SVD) to the Hankel matrix to extract the dominant modes of vibration. The Hankel matrix is constructed by arranging the measured response data into a matrix, where the rows correspond to different time instants and the columns correspond to different measurement locations on the structure. The SVD of the Hankel matrix yields a set of left and right singular vectors, which can be used to estimate the modal shapes and natural frequencies of the structure. The CSI algorithm is particularly useful for identifying the modal properties of structures in situations where the excitation forces or loads are partly known and partly unknown. It is also well-suited for identifying closely spaced modes and for handling noisy or incomplete response data. More information about the essence of this code can be found in [6, 8] but will be detailed in a few words hereafter.

We consider a structure subjected to both ambient (unmeasured/unknown) and imposed (measured/known) loads, which are represented by the red and green labels in Figure 1. The response of the structure (in blue) is measured. The CSI algorithm takes as arguments the measured imposed load and the structural response (see block labelled "CSI" in Figure 1) and returns estimates of the modal parameters.

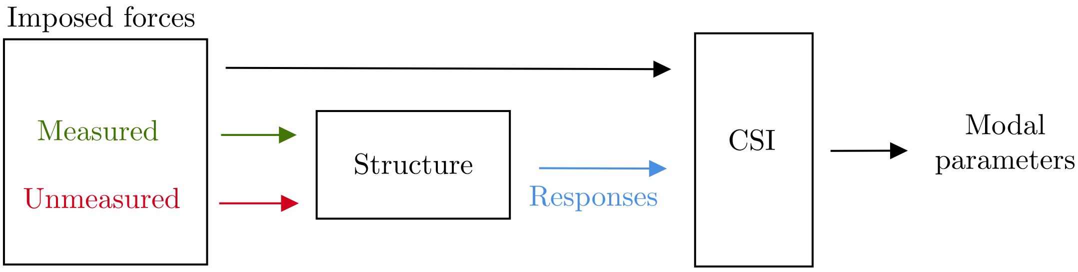

Figure 1. Methodology to determine the modal properties of a structure using the CSI algorithm.

3. Equipment

A measurement campaign was held on the Tilff cable-stayed footbridge in order to collect some vibration data of the structure. To do so, a shaker, pedestrians and accelerometers were used.

3.1. Shaker: excitation device

The shaker used in this campaign was developed by University of Liège and V2i and allows to impose different types of excitations. Indeed, thanks to a moving mass attached to a linear actuator, it is possible to impose random or sinusoidal excitations to the structure. The frequency range that can be excited with this shaker ranges from 0 to 10 Hz and the amplitude of displacement of the moving mass is from about 20 cm peak-to-peak at 1 Hz to 2 mm at 10 Hz. The moving mass consists of the yellow conveyor of about 80 kg and up to four pairs of ballasting steel plates can be added to boost the dynamic force generated by the device by increasing the total moving mass up to 320 kg. A picture of this shaker is shown in Figure 2.

Figure 2. Picture of the shaker developed the University of Liège and V2i

3.2. Pedestrians
As indicated below, the tests were carried out under controlled but not measured pedestrian traffic on the footbridge. Among the methods implemented within the framework of this experimental campaign, an important component is based on the selection of pedestrians as well as the respect of a relatively strict experimental protocol as explained below.

3.3. Acquisition
In order to apply the CSI algorithm for modal analysis of the footbridge, it is necessary to collect data on its excitation and response. The excitation refers to the external forces or loads that cause the structure to vibrate, while the response refers to the resulting acceleration of the structure. By placing accelerometers at different locations on the footbridge and measuring the acceleration response over time, it is possible to obtain a set of vibration data that can be used for the modal analysis. In this particular case, wireless G-Link-200 8G accelerometers are used for data acquisition. These accelerometers are capable of measuring acceleration in the range of +- 40g, with a sampling frequency of up to 4096 Hz [9]. Once the data has been collected using the accelerometers, it can be processed using the CSI algorithm to obtain the modal properties of the footbridge, including its natural frequencies, damping ratios, and mode shapes.

4. Application on Tilff cable-stayed footbridge
4.1. Tested structure
The Tilff cable-stayed footbridge is a 74-m long footbridge built around 1970 allows pedestrians to cross the river Ourthe and is situated near Liège, Belgium. It is a cable-stayed footbridge composed of a concrete pylon. The deck consists in a concrete slab supported by a steel box cross section, which gives a large torsional stiffness to the deck. The deck is simply supported on the intermediate support where it passes through the legs of the pylon, as shown in the picture in Figure 3

Figure 3. Picture of the Tilff cable-stayed footbridge

4.2. Setup
On the 2nd of September 2022, a preliminary measurement campaign was held on the Tilff cable-stayed footbridge in order to roughly extract its modal properties with the CSI algorithm. The location of the shaker was chosen after this preliminary test, by identifying the location where none of the first four modes of the bridge deck would take small values. Doing so, we avoided to place the shaker near modal nodes. In the preliminary tests, ambient vibrations of the footbridge have been recorded for 20 minutes at various places of the deck; then a Fourier analysis

revealed the major natural frequencies and appropriate excitations have been used, in the form of knee-bending excitations with a metronome, in order to more accurately identify mode shapes.

A couple of weeks after the preliminary tests, the actual campaign with the shaker and groups of pedestrians was held. The selected position of the shaker is shown in Figure 4, quite close to the mid-span, as expected. One accelerometer (No. 1) was placed on the moving mass of the shaker in order to measure exactly the imposed dynamic force. Five other accelerometers (No. 2-6) were spread all along the deck of the footbridge in order to measure the acceleration at several locations and be able to recreate the mode shapes of this structure, with the CSI algorithm, under both the ambient and imposed loads. The setup is sketched in Figure 4.

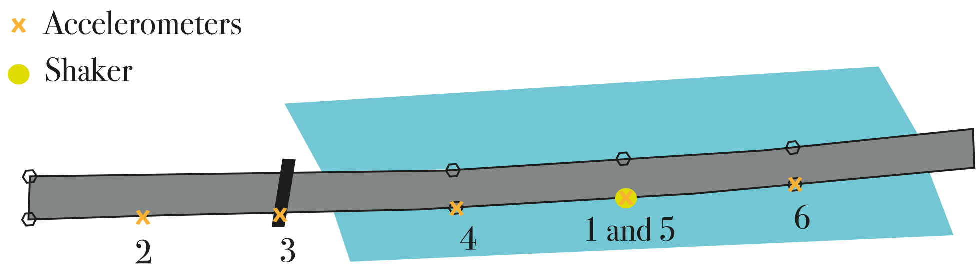

Figure 4. Schematic top view of the Tilff cable-stayed footbridge

4.3. Experimental protocol

First, a wideband random load was applied on the structure by the shaker in order to roughly determine again the eigenfrequencies of the footbridge. It should be noted that for this part of the measurements no pedestrians were walking on the footbridge. Figure 6 shows the Power Spectral Density (PSD) of the accelerations of sensor No. 1 (on the moving mass), as well as of the five other sensors. These later reveal the first few interesting natural frequencies.

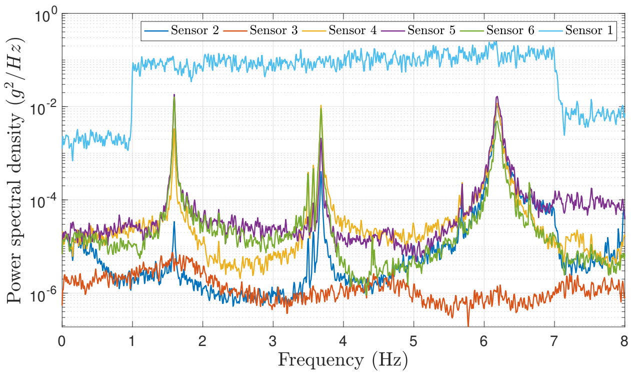

Figure 5. Power spectral density of the signal recorded on the structure for a wide band random excitation.

In the range [1-7] Hz, where the random excitation was applied for 15 minutes, three peaks stands out on the signal. They are situated at about 1.59 Hz, 3.68 Hz and 6.18 Hz and correspond to the eigenfrequencies of the structure involving significant deck motions. The reddish curve does not show any peak as this sensor (No. 3) was placed very near the support of the pylon where no vibration is expected.

One can apply the CSI algorithm to the previously recorded signals. To do so, the transient part is removed from the recorded signals and as the signal is random, a moving average is performed in order to obtain several estimations for the modal parameters. Indeed, a portion of five minutes of the signal is taken at the beginning of the signal and the CSI is applied to that portion, allowing to obtain the modal properties of the structure. Another portion of five minutes is taken, 3 seconds later and the process is repeated until the end of the signal. This allows to obtain several estimations with the same signal and to obtain the mean value of estimations of each modal property.

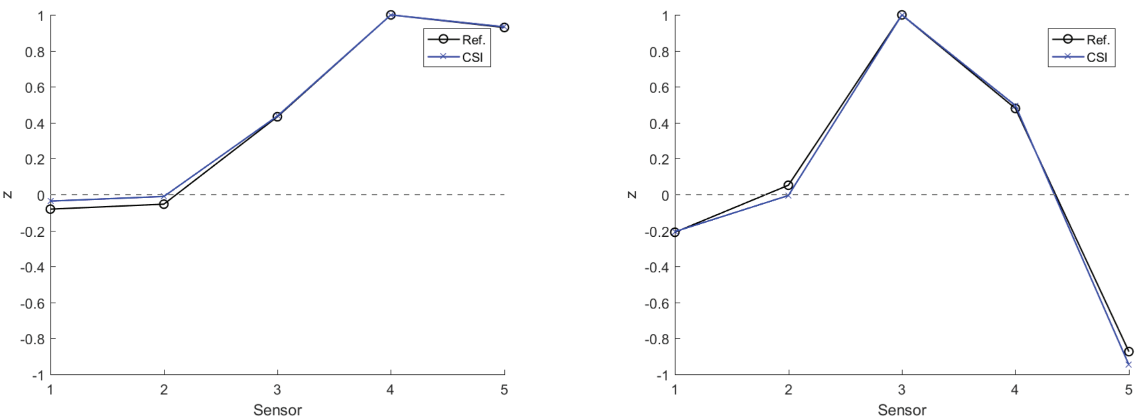

Figure 6. First two identified mode shapes corresponding to vertical bending. They are obtained with a reference method (stepped sine sweep as described in [1] or with the CSI algorithm.

Mode	f_{ref} [Hz]	f_{CSI} [Hz]	ξ_{ref} [%]	ξ_{CSI} [%]
1	1.59	1.59	0.33%	0.34%
2	3.67	3.64	0.33%	0.32%

Table 1. Identified modal properties with the two different identification methods

The identified mode shapes, natural frequencies and damping ratios are shown in Table 1 and Figure 6. Two types of results are shown: one with our standard reference stepped sine approach, as described in [1] and one with the CSI method applied on the data collected without pedestrians on the footbridge. Results are in a very good agreement, which validates the approach.

Now in order to answer the question of the possibility to identify with the same quality the modal properties of the footbridge, with the CSI method, while pedestrians are crossing, the same operations are repeated for various pedestrian traffic intensities on the footbridge. The influence of an increasing number of pedestrians on the identification has been studied. Indeed, a number of 1, 5, 8 and 10 pedestrians were asked to cross the footbridge back and forth during all the simulation time. Once a pedestrian reached an end of the footbridge, he/she would u-turn so that the total number of pedestrians on the footbridge was constant during each test. The simulation time for one configuration last 10 minutes. Unfortunately the traffic could not be perfectly controlled and some spurious pedestrians crossed the bridge from time to time. In spite of this, it is interesting to highlight that the accelerations measured under the crossing of a single pedestrian cannot be considered as stationary processes (at least on the short duration window), while recorded accelerations looked very stationary under the passage of 10 pedestrians.

Figure 7, borrowed from the SETRA guidelines to assess the comfort of footbridges, shows the weighting factor of the dynamic load in the first harmonic in the vertical direction. It recalls that pedestrians excite the structure in the frequency band 1.6Hz-2.4Hz. For this reasons it is expected that the modal identification of the first eigenfrequency of the footbridge (1.59 Hz) will be rather challenging, as it is close to the frequency range excited by the pedestrians. This is why this mode is considered in the sequel.

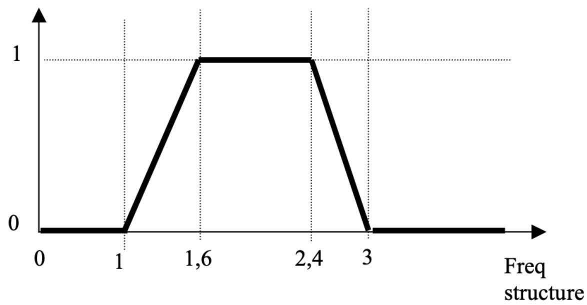

Figure 7. Frequency range excited by the pedestrians for vertical vibrations [7].

4.4. Analysis of the results

First, tests were performed for the pedestrians without shaker, in order to determine the frequency content of the pedestrian loading. Some recorded signals and their associated PSDs are shown in Figure 8.

One can see that as the number of pedestrians increases, the acceleration of the structure also increases and the perturbations are less perceived. Indeed, when looking at the purple curve corresponding to the acceleration of the footbridge with one pedestrian walking back and forth, some high variations can be spotted in the signal. We notice that it is difficult to interpret every increase of vibration amplitude since the footbridge was not closed to pedestrian traffic and some other passengers, dogs, motorbikes and cyclists also crossed the footbridge, but very occasionally, during the whole duration of the measurements. The measurement with one pedestrian was the most disturbed. One can also observe that as the number of pedestrians increases, the measured accelerations become less transient and so more stationary. Moreover, the frequency content of the signal widens between 1.6 Hz and 2.3 Hz as the number of pedestrians increases. Several peaks can be observed for the different curves corresponding to the pacing rate of the pedestrians. However, the first peak at 1.59 Hz is the first eigenfrequency of the structure that is indeed excited. As the number of pedestrians increases, the peak at 1.59 Hz is less distinguishable. This, added to the fact that the ambient forces does not allow to excite all the eigenfrequencies of the footbridge, justifies the use of the shaker.

For the second part of the tests, a random excitation between 1.5 and 1.65 Hz was applied for 10 minutes, while a defined number of pedestrians crossed the footbridge back and forth.

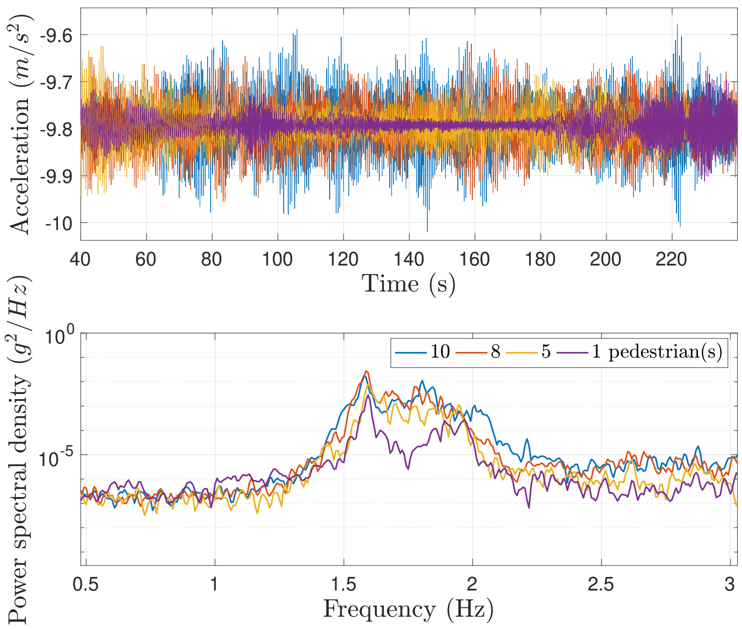

Figure 8. Acceleration profile of the signals and frequency content of the pedestrians for the detailed measurement campaign

The number of pedestrians was 1, 5, 8 and 10. Unfortunately, the tests with 0 pedestrians for this level of shaker were not performed so that the results cannot be compared with a reference value with 0 pedestrians. However, they can still be compared to the value obtained with the EMA fitting method of [1].

The results for the evolution of the first frequency and its corresponding damping ratio for an increasing number of pedestrians can be seen in Figures 9 and 10, respectively.

It can be seen that, for this number of pedestrians, the identified frequency is quite close the identified value on the empty footbridge, by both methods investigated before. However, concerning the damping ratio, one can see that even with only one pedestrian, the median value is far from the identified one. Indeed, due to human-structure interaction the pedestrians significantly contribute to damp out the vibrations of the structure, which leads to an increase in the apparent damping ratio. This is even more pronounced as the number of pedestrians increases.

5. Conclusion

This study examined the feasibility of identifying the modal properties of footbridges under pedestrian traffic using the CSI algorithm. The results indicate that the CSI algorithm can provide consistent modal properties, but the identified damping ratio is heavily dependent on the pedestrian density. This suggests that the human-structure interaction plays a significant role in the dynamic behavior of the footbridge. While the identified damping ratio appears plausible, the practical usefulness of identifying modal properties of footbridges under pedestrian traffic is limited as the actual properties of the structure cannot be accurately identified. Overall, the CSI algorithm provides some useful insights into the dynamic behavior of footbridges under pedestrian traffic, but of limited interest as long as comparison with design guidelines

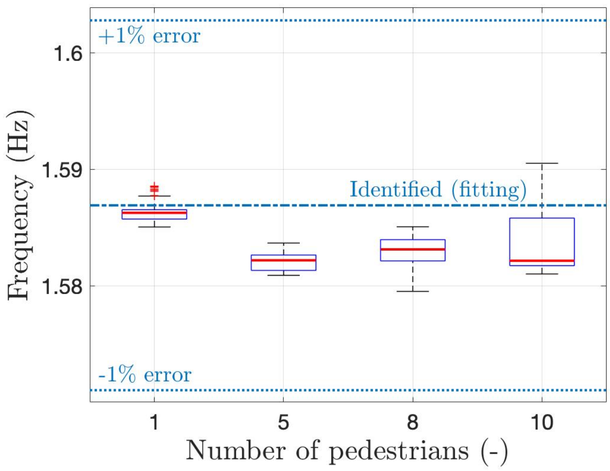

Figure 9. Identification of frequency 1 (1.59 Hz) thanks to CSI algorithm with increasing number of pedestrians.

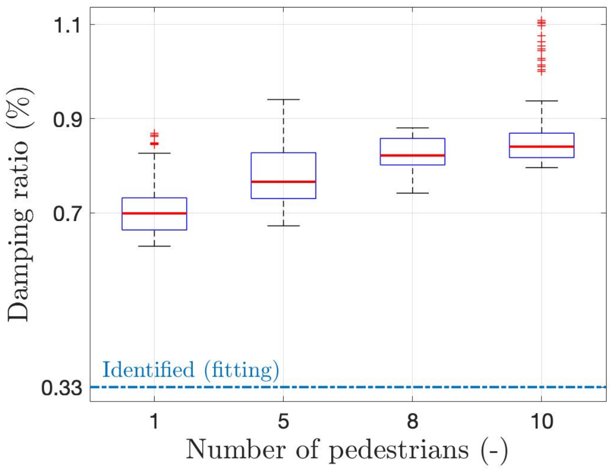

Figure 10. Identification of frequency and damping ratio of mode 1 of the Tilff cable-stayed footbridge thanks to CSI algorithm with increasing number of pedestrians.

is considered. Indeed, the design guidelines typically refer to the damping of the bare structure, which is therefore only accurately identifiable when the bridge is closed to traffic.

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