Journal of Physics: Conference Series

Modal Parameters identification in existing bridges based on free vibration tests

To cite this article: M Mazzeo *et al* 2024 *J. Phys.: Conf. Ser.* **2647** 182026

Modal Parameters identification in existing bridges based on free vibration tests

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Abstract. The dynamic identification of modal parameters plays a fundamental role in structural health monitoring: mode shapes, frequencies and damping ratios can be exploited to assess the current state of a structure, used for damage detection or in numerical model validation. In recent years, vibration-based methods have become a popular solution for the state of health estimation of strategic civil infrastructures such as bridges: in particular, free vibration tests represent a fast and economic method only requiring the temporary installation of a limited number of sensors on the structure. This contribution presents a procedure for the identification of modal properties of existing bridges exploiting their free decay responses: each mode's contribution is adaptively extracted from free vibration tests data using the Empirical Fourier Decomposition and a noise-robust area-based approach is exploited to identify modal damping ratios. The method is preliminarily validated on a synthetic multi-modal signal showing excellent results even in case of closely spaced modes. The performance of the proposed approach is also tested for a real existing structure: the selected case study deals with the identification of modal parameters for a steel railway bridge deck.

1. Introduction

Dynamic identification is a popular solution adopted in structural health monitoring (SHM) to assess the condition of an existing structure. Modal parameters e.g., frequencies and damping ratios, may be used as structural damage indicators [1]: fluctuations from theoretical values may be symptomatic of possible defects.

For large-scale structures (e.g., bridges) monitoring, dynamic identification via free vibration tests is becoming popular: this depends on several advantages of this approach to the traditional long term monitoring approach. In fact, a limited number of sensors, temporarily attached to the structure, is required to retrieve essential dynamic information, thus limiting the economic impact of the monitoring campaign. In this context Li et al. [2] as well as Clemente et al. [3] dealt with identification of cable-stayed bridges using free vibrations. Furthermore, Yang et al. [4] exploited free vibration responses for the estimation of modal parameters focusing on railway bridges.

It is known that modal parameters estimation, in multi-degrees-of-freedom structures, depends on a proper selection of the significant components from the recorded signals. This may be achieved using adaptive decomposition techniques [5,6]. About that, Mazzeo et al. [7] recently proposed a VMD-based modal identification framework which exploits bridge free vibration responses: different types of bridge were analyzed and the comparison of the results with traditional monitoring techniques showed the reliability of the proposed approach. Recently Zhou et al. [8] proposed a new adaptive method, exploiting an improved spectrum segmentation technique and a zero-phase filter bank to achieve an accurate decomposition performance, called Empirical Fourier Decomposition (EFD).

In this contribution, the latter is used as decomposition technique for the analyzed signals and to retrieve the modal frequencies. An area-based approach is chosen for the damping ratios estimation from free vibrations due to its robust performance against the noise which is quite common for in-situ measurements. The proposed methodology is therefore validated on a synthetic signal and subsequently it is employed for the dynamic identification of a steel railway bridge deck.

2. Identification procedure

The proposed identification procedure relies on EFD method which is an adaptive decomposition technique used to extract unimodal components of the recorded structural response and their corresponding center frequencies, herein assumed as modal frequencies.

EFD is a method which combines an improved Fourier spectral segmentation to the usage of zero-phase filter banks, to achieve an accurate signal decomposition performance. The first step in the procedure consists in expressing the Fourier spectrum of the signal in the normalized frequency domain $[-\pi,\pi]$. The frequency spectrum segmentation is therefore carried out focusing on the frequency band $[0,\pi]$: to this aim, the corresponding frequencies to the first N maxima are sorted in the vector $[\Omega_1,\ldots,\Omega_N]$ with the assumptions $\Omega_0 = 0$ and $\Omega_{N+1} = \pi$. The n-th boundary frequency is expressed as follows:

$$\omega_n = \begin{cases} \arg\min\limits_{\omega} \hat{X}_n(\omega) & \text{if } 0 \le n \le N \text{ and } \Omega_n \ne \Omega_{n+1} \\ \Omega_n & \text{if } 0 \le n \le N \text{ and } \Omega_n = \Omega_{n+1} \end{cases} \tag{1}$$

where $\hat{X}_n(\omega)$ is the Fourier spectrum amplitude between Ω_n and Ω_{n+1}.

The successive step in the procedure consists in the definition of a zero-phase filter bank assuming, as each filter cut-off frequencies, a couple of consecutive frequencies ω_{n-1} and ω_n determined in the previous step:

$$\hat{\mu}_n = \begin{cases} 1 & \text{if } \omega_{n-1} \le |\omega| \le \omega_n \\ 0 & \text{otherwise} \end{cases} \quad \forall n \in [1,N] \tag{2}$$

The generic filtered signal component, in the frequency domain, may be expressed as follows:

$$\hat{f}_n(\omega) = \hat{\mu}_n(\omega)\hat{f}(\omega) = \begin{cases} \hat{f}(\omega) & \text{if } \omega_{n-1} \le |\omega| \le \omega_n \\ 0 & \text{otherwise} \end{cases} \quad \forall n \in [1,N] \tag{3}$$

The component is therefore converted in time domain ad follows:

$$f_n(t) = \int_{-\omega_n}^{-\omega_{n+1}} \hat{f}_n(\omega) e^{j\omega t} d\omega + \int_{\omega_n}^{\omega_{n+1}} \hat{f}_n(\omega) e^{j\omega t} d\omega \tag{4}$$

Lastly, the estimated reconstructed signal is obtained by summation of the components:

$$\tilde{f}(t) = \sum_{n=1}^{N} f_n(t) \tag{5}$$

The central frequencies of the extracted components are obtained as the frequency values in the Fourier spectrum at which the first N highest local maxima are attained and are assumed as the modal frequencies in this modal identification framework.

Modal damping ratios may be estimated using an area-based approach: under the assumption that each modal component exhibits a free vibration response with $2M_n + 1$ zero-crossing points, the modal damping ratio may be expressed as a function of the $2M_n$ areas $S_{i,n}$ enclosed between the time axis and the response function:

$$\zeta_n = \frac{1}{\sqrt{1+\left(2M_n\pi / A_n\right)^2}} \tag{6}$$

being A_n the area ratio defined as follows:

$$A_n = \ln\left[\frac{\sum_{i=1}^{M_n} S_{i,n}}{\sum_{i=M_n+1}^{2M_n} S_{i,n}}\right] \tag{7}$$

3. Validation on a synthetic signal

The validation of the proposed identification approach is carried out on a synthetic signal which simulates the free vibration response recorded from a multi-degree-of-freedom system. The selected benchmark signal (see Figure 1.(a)) is sampled at a sampling frequency of 1kHz and is expressed by:

$$s(t) = \sum_{n=1}^{N} A_n \exp\left(-\zeta_n 2\pi f_n t\right)\cos\left(2\pi f_n \left(1-\zeta_n^2\right)^{1/2} t - \phi_n\right) \tag{8}$$

where the following values are assumed: $A_1 = 8$, $A_2 = 7$ and $A_3 = 5$ for the amplitudes; $f_1 = 2.2\,\text{Hz}$, $f_2 = 4.8\,\text{Hz}$ and $f_3 = 5.3\,\text{Hz}$ for the frequencies; $\zeta_1 = 3\%$, $\zeta_2 = 1.5\%$ and $\zeta_3 = 0.9\%$ for the damping ratios. All the components are assumed to be in phase i.e., $\phi_n = 0$.

The frequency boundaries are detected via the spectrum segmentation procedure as reported in Figure 1.(b). The effect of the noise is also considered by summing up to the synthetic signal a Gaussian white noise with a noise-to-signal ratio (NSR) assumed equals to 5%. The proposed procedure allowed the extraction of 3 modes whose modal frequencies and damping ratios are summarized in Table 1. An excellent agreement is reached between theoretical and estimated modal parameters. Moreover, a comparison between the extracted signals and the theoretical counterparts, for the case without noise, is shown in Figure 2 highlighting the accuracy in the estimation of modal responses.

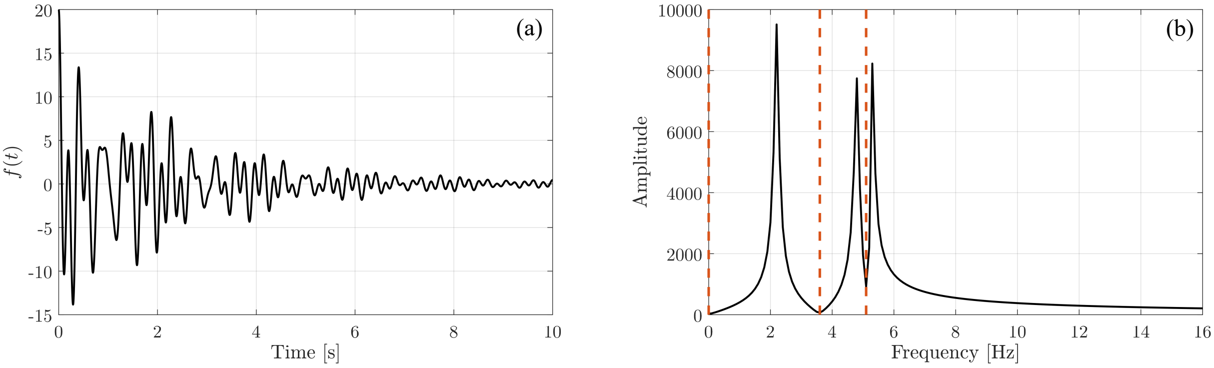

Figure 1. (a) Analysed signal and (b) corresponding segmented frequency spectrum.

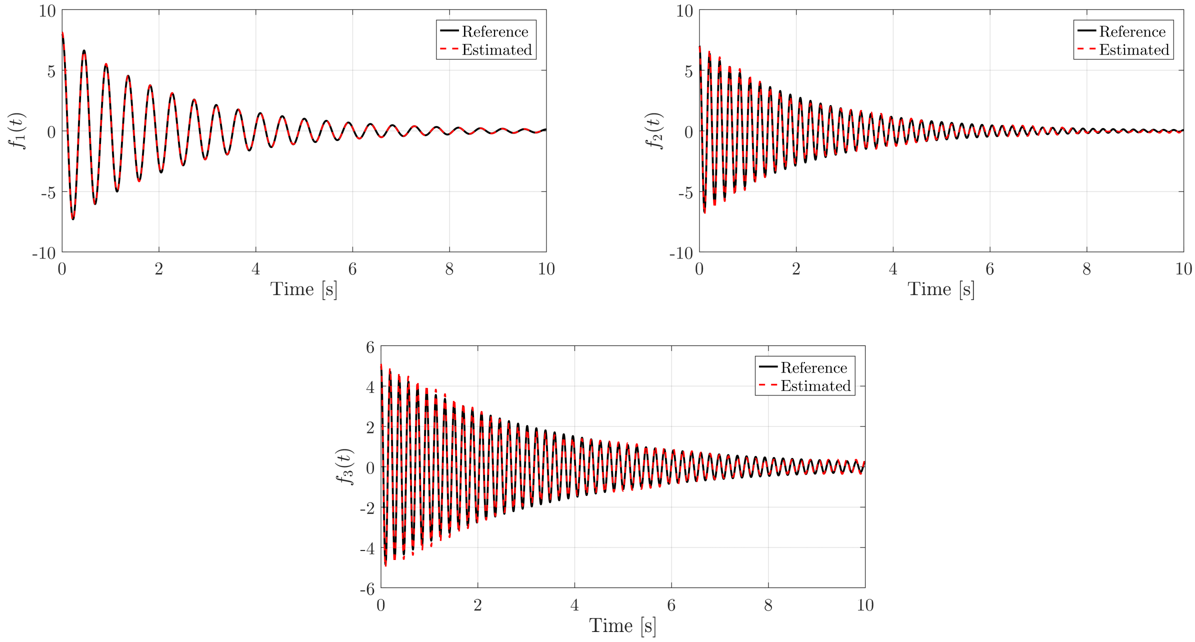

Figure 2.Comparison between theoretical and estimated modal free vibration responses.

Table 1. Theoretical and identified modal parameters for different NSR thresholds and the corresponding relative errors.

Theoretical		Identified (NSR=0%)		Identified (NSR=5%)	
Frequency [Hz]	Damping Ratio [%]	Frequency [Hz]	Damping Ratio [%]	Frequency [Hz]	Damping Ratio [%]
2.2	3	2.2 (0%)	3 (0%)	2.2 (0%)	3.04 (1.3%)
4.8	1.5	4.8 (0%)	1.5 (0%)	4.8 (0%)	1.48 (1.3%)
5.3	0.9	5.3 (0%)	0.9 (0%)	5.3 (0%)	0.95 (5.5%)

4. Real case-study

The proposed real case-study is a bridge part of the Italian railway infrastructure (see Figure3): the structure is made up of a central span 34.72 m long and two symmetric lateral ones 28.54 m long. Each span consists of two steel longitudinal truss girders transversally spaced at 5m and connected at the lower chords by means of transverse steel elements and cross bracing systems. The lateral span, object of this study, was monitored by means of 6 accelerometers placed at ¼, ½ and ¾ of the span at the deck level and the sampling frequency used for the signal acquisition is 1.6 kHz. The structure was excited by the passage of a Frecciarossa train, and the resulting free vibration portion of the recordings was considered for dynamic identification purposes (see Figure 4).

The proposed modal identification approach allowed the estimation of the first two modes: in this study, the results for the signals recorded from the sensors located at midspan and at a quarter of the span are considered. Table 2 lists the identified modal parameters: consistent estimations of both frequencies and damping ratios are obtained, considering signals recorded at different locations on the structure.

Figure 3. A typical steel railway bridge of Italian Railway infrastructure.

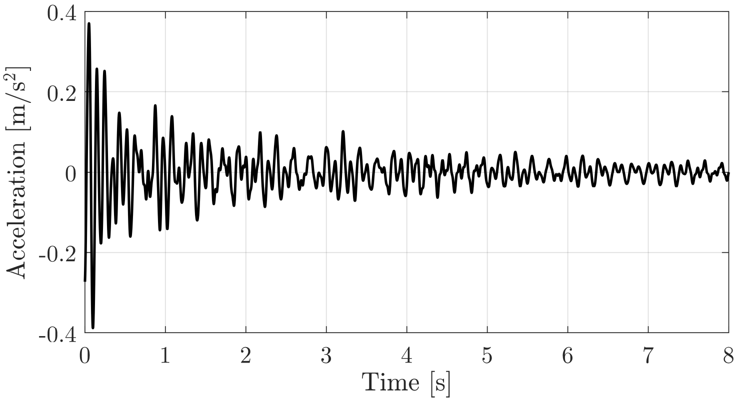

Figure 4. A typical free vibration response recorded in the analysed bridge.

Table 2. Identified modal parameters for the railway bridge at different sensors locations.

	Midspan		Quarter of the span	
Mode Number	Frequency [Hz]	Damping Ratio [%]	Frequency [Hz]	Damping Ratio [%]
1	9.80	1.67	9.80	1.09
2	10.89	2.23	10.89	2.44

5. Conclusion

In this contribution it was presented a modal identification framework which combines Empirical Fourier Decomposition Method, to isolate modal responses, with a robust area-based approach for damping estimation. In the procedure validation, exploiting a synthetic signal, it is shown how EFD allowed an accurate estimation of the modal free vibration responses. For both the benchmark application and the real case-study, the dynamic identification process produced reliable and consistent estimations of modal parameters highlighting the reliability of the proposed approach.

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