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Informed assessment of structural health conditions of bridges based on free-vibration tests

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ABSTRACT: A consolidated procedure for the evaluation of current structural health conditions in bridges consists in the comparison between estimated modal features from in-situ tests and numerical values. This strategy allows making informed decisions for existing bridge structures to ensure structural safety or serviceability. Free vibration tests are common in bridges monitoring since they allow a quick and cost-effective determination of dynamic information about the structure, using a sparse network of few sensors and avoid long-lasting monitoring campaigns. Exploiting an identification method based on a tuned version of Variational Mode Decomposition and an area-ratio based approach, modal parameters are determined from free vibration tests. This technique is applied to the dynamic identification of cables in a stay-cabled bridge assumed as case study: the obtained results prove reliability of the adopted method as a useful tool for objective dynamic identification purposes, with focus on the structural health conditions of bridges.

1 INTRODUCTION

Modal parameters are key structural properties in characterization of dynamic behaviour of constructions: the comparison between experimental values obtained from the identification process and theoretical ones represents a significant tool to investigate the state of health in an existing structure as well as to identify possible defects. Particularly in large-scale civil structures such as bridges, the dynamic characterization via free vibration tests is becoming quite popular: the advantages are the use of a temporary network made up of a limited number of sensors, the possibility of carrying out a complete monitoring campaign in a relatively short time frame and the cost effectiveness.

Li et al. (2014) estimated the modal damping ratios of the cables of a cable-stayed bridge from their free vibration response. Both Clemente et al. (1998) and Tomaszkiewicz et al. (2022) dealt with the dynamic identification of cable-stayed bridges using free vibrations produced by a truck moving over a step fixed on the paving.

The identification of modal parameters in a multi-degree-of-freedom structure may be carried out prior to selection of significant components from dynamic response: this can be achieved using adaptive decomposition methods.

This study presents the results of a monitoring campaign in which free vibration tests were performed on the cables of a stay-cable bridge to investigate their actual condition via dynamic identification. The single-degree-of-freedom modal components are isolated using a variational decomposition framework. Modal frequencies are compared with estimation obtained from practical formulas whereas estimated modal damping ratios are compared with the ones obtained from ambient vibration.

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2 IDENTIFICATION PROCEDURE

In this section a procedure for modal identification of structures such as existing bridges based on free vibration tests is recalled. This methodology combines a tuned version of the Variational Mode Decomposition (VMD) to isolate each modal mono-component signal and its correspondent natural frequency with an area ratio-based approach. An important feature of the method is its automatic implementation which averts user's subjective choices in the selection of VMD parameters. The adopted method has already been tested on benchmark signals and existing deck bridges (Mazzeo et al. 2023) proving its reliability in the dynamic identification of modal parameters.

2.1 *Tuned Variational Mode Decomposition*

Variational Mode Decomposition algorithm (Dragomiretskiy et al. 2014) achieves an adaptive decomposition of a multi-component target signal considering a variational framework in which the bandwidth associated to each modal component, called Intrinsic Mode Function (IMF), is assessed looking for the optimal solution of a constrained variational problem.

The optimization process is carried out in the frequency domain: each mode is iteratively obtained as the signal produced by a narrow-band Wiener filter applied to the signal estimation residual of all other modes. The assessment of the bandwidth for each mode is carried out calculating the associated analytical signal via Hilbert-Huang Transform, shifting its spectrum to baseband due to multiplication for a proper exponential function and subsequently calculating the H_1 Gaussian smoothness of demodulated signal:

$$\mathrm{BW}_k = \left\| \partial_t \left\{ \left[\left(\delta(t) + \frac{j}{\pi t} \right) * v_k(t) \right] e^{-j\omega_k t} \right\} \right\|_2^2 \tag{1}$$

Based on these steps, the following constrained variational problem is obtained:

$$\min_{\substack{v_1(t),\dots,v_K(t) \\ \omega_1,\dots,\omega_K}} \left\{ \sum_{k=1}^{K} \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * v_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \right\} \text{ s.t. } \sum_{k=1}^{K} v_k(t) = v(t) \tag{2}$$

where ∂_t is the gradient operator and $\|.\|_2$ the L^2-norm operator. By using a quadratic penalty term and the Lagrange multipliers technique to enforce the constraints, the search for the solution of this variational problem leads to the following augmented Lagrangian function:

$$\begin{aligned} L(v_1(t),\dots,v_K(t),\omega_1,\dots,\omega_K,\lambda) = {} & \alpha \sum_{k=1}^{K} \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * v_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \\ & + \left\| v(t) - \sum_{k=1}^{K} v_k(t) \right\|_2^2 + \left\langle \lambda, v(t) - \sum_{k=1}^{K} v_k(t) \right\rangle \end{aligned}$$

where α is the quadratic penalty factor, λ is the Lagrangian multiplier and $\langle . \rangle$ is the L^2-inner product. The solution of the governing constrained problem is thus equivalent to the evaluation of the saddle point of the augmented Lagrangian function. This can be achieved using alternating direction method of multipliers, which solves two parallel sub-optimization problems which provide an estimation of the k-th IMF $v_k(t)$ and the center frequency ω_k, the latter is correspondent to the modal frequency in the adopted identification framework.

The performance of the VMD technique is highly dependent on the proper tuning of two main parameters, namely the number of IMFs to be extracted K and the penalty factor α. Therefore, a suitable procedure for the choice of this parameter is implemented to significantly limit the subjectiveness of the results. This tuning method evaluates the optimal K and α

separately: the selection for number of modes K starts considering a range of possible values $\tilde{K} \in [K_{\min}, K_{\max}]$ and for each one of them exploits the mean correlation measure $\rho_{k,k+1}$ between each two consecutive sampled IMFs:

$$K = \underset{K_{\min} \leq \tilde{K} \leq K_{\max}}{\arg\min} \left\{ \frac{1}{\tilde{K} - 1} \sum_{k=1}^{\tilde{K}-1} \rho_{k,k+1} \right\} \tag{4}$$

Repeating this procedure for each value of α in a fixed range $[\alpha_{\text{start}}, \alpha_{\text{end}}]$, a stabilization diagram is built from each couple (α, K) and the number of IMFs is sought in the range $[\alpha_{\min}, \alpha_{\max}] \subseteq [\alpha_{\text{start}}, \alpha_{\text{end}}]$ in which K remains stable.

The estimation of the optimal penalty factor starts calculating for each value of $\tilde{\alpha} \in [\alpha_{\min}, \alpha_{\max}]$ two parameters called Power spectrum information entropy $\text{PSIE}_k(\tilde{\alpha})$ and uncorrelation factor $\text{UC}_k(\tilde{\alpha})$ defined as in literature (Yang et al. 2020). The optimal value of the penalty factor is obtained as:

$$\alpha = \underset{\alpha_{\min} \leq \tilde{\alpha} \leq \alpha_{\max}}{\arg\min} \left\{ \overline{\text{PSIE}}(\tilde{\alpha}) + \overline{\text{UC}}(\tilde{\alpha}) \right\} \tag{5}$$

where $\overline{\text{PSIE}}(\tilde{\alpha})$ and $\overline{\text{UC}}(\tilde{\alpha})$ represent the dimensionless averaged values of the two parameters with respect to the selected number of modes K.

2.2 *Modal damping ratios estimation*

For each modal component the correspondent modal damping ratio can be obtained using an area-based approach (Huang et al. 2007). Under the assumptions that the k-th modal component can be seen as the free vibration response of the correspondent k-th SDOF modal oscillator and that it has $2N_k+1$ zero-crossing points, it is possible to relate the modal damping ratio with the $2N_k$ areas $S_{i,k}$ enclosed between the response function and the time axis as follows:

$$\zeta_k = \frac{1}{\sqrt{1 + (2N_k\pi/A_k)^2}} \tag{6}$$

being A_k the area ratio evaluable with any quadrature method and defined as:

$$A_k = \ln\left[\frac{\sum_{i=1}^{N_k} S_{i,k}}{\sum_{i=N_k+1}^{2N_k} S_{i,k}}\right] \tag{7}$$

The advantage of using this method for damping estimation is due its robustness against the noise: the area evaluation is less affected from local distortions due to noise in the signal which on the contrary may significantly influence the estimation of local maxima used in traditional logarithmic decrement method.

3 CASE STUDY: BRIDGE OVER GARIGLIANO RIVER

The case study herein analysed is the cable-stayed bridge over the Garigliano river (see Figure 1), part of the highway infrastructures connecting the cities of Naples and Rome (Italy). The structure consists of two spans of equal length for a total of 180 m and the deck consists of precast multicell block girders in prestressed reinforced concrete assembled in situ with height 2.45 m and width 26.1 m (see Figure 2). Both spans are simply supported at one end and constrained to a central pylon at the other one.

Figure 1. Overview of cable-stayed bridge over Garigliano river.

Each span is sustained by 9 couples of cables, each couple is spaced 1.7 m. The cables and have a variable number of 0.6″ galvanized sheathed high-strength prestressing steel strands, from 45 to 55, and a variable length from 23 m to 87.5 m. The pylon is made up of three parts: the first 5 m are in reinforced concrete with a linearly variable transversal section from 4.6 m x 2.5 m to 4 m x 2.5 m, the second part, from height 5 m to 10 m, is a steel box linearly variable up to a section of 2.9 m x 2.5 m, and the last part, from height 10 m to 25 m, has constant hollow section made of steel. The central pier on which the deck and the pylon are connected is 8.4 m high and it has a 10 m x 2.5 m reinforced concrete rectangular section with rounded corners with radius of 1.25 m.

A monitoring campaign was conducted to monitor the state of health of the structure cables and, because of their large number, a suitable solution consisted in free vibration tests which are less expensive and require a minimal equipment. For each stay-cable, the test setup consisted of two piezoelectric uniaxial accelerometer (sensitivity 10 V/g) positioned at a medium height of 3.8 m from the bridge deck extrados.

Each couple of accelerometers was mounted on both faces of a steel angle as in to record both horizontal and vertical accelerations. The steel angle was connected to the stay-cable using nylon tightening straps. The stay-cables were excited with an impulsive load applied to the bridge in its service conditions, i.e., concurrent with environmental vibrations due to wind and traffic in both directions. By the application of a vertical impulsive load, both the accelerations in vertical and horizontal direction were recorded and are herein labelled V/V and V/H respectively; similarly applying a horizontal impulsive load, the acceleration in the horizontal direction is labelled H/H whereas the one in vertical direction H/V.

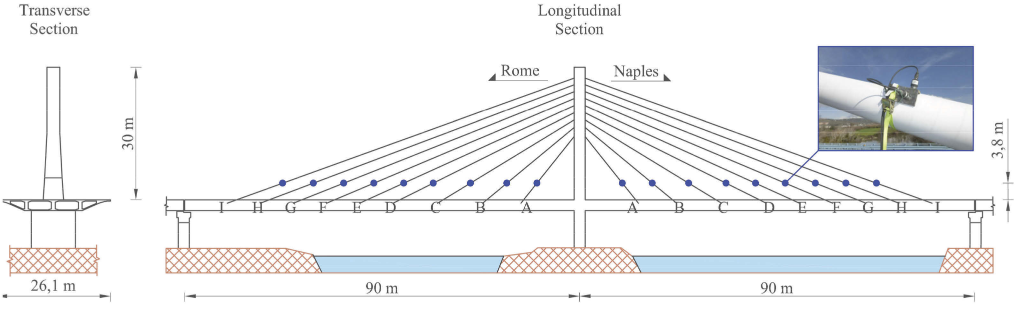

Figure 2. Bridge geometry and sensor layout of stay cables.

The selected ranges for VMD parameters are $K \in [2, 8]$ and $\alpha \in [1, 10000]$ respectively. In Figure 3, the IMFs retrieved for the stay cable B in Rome direction for the acceleration recording V/V are shown: the ideal number of IMFs is K=3 and the evaluation of the quadratic penalty factor α must be executed in the narrower range $\alpha \in [1, 8500] \subset [1, 10000]$ and it leads to $\alpha = 76$.

An estimation of the natural frequencies is obtained by means of practical formulas which relates them to the correspondent cable force obtained under the assumptions that prestressing steel has a Young Modulus equal to 198,000 MPa, the linear weight for strands and PHED sheath are 1.305 kg/m and 5.68 kg/m respectively and the density of the grout filling equal is 1,440 kg/m^3. The identified frequencies are compared with the obtained from practical formulas (Zui et al. 1996) for the first mode: data points focus on the quadrant bisector line showing a nice agreement between experimental and predicted values (see Figure 4). Predicted values of frequencies are slightly higher with respect to the experimental ones with differences under 7%. Missing outputs are dependent on the corruption of the related recordings.

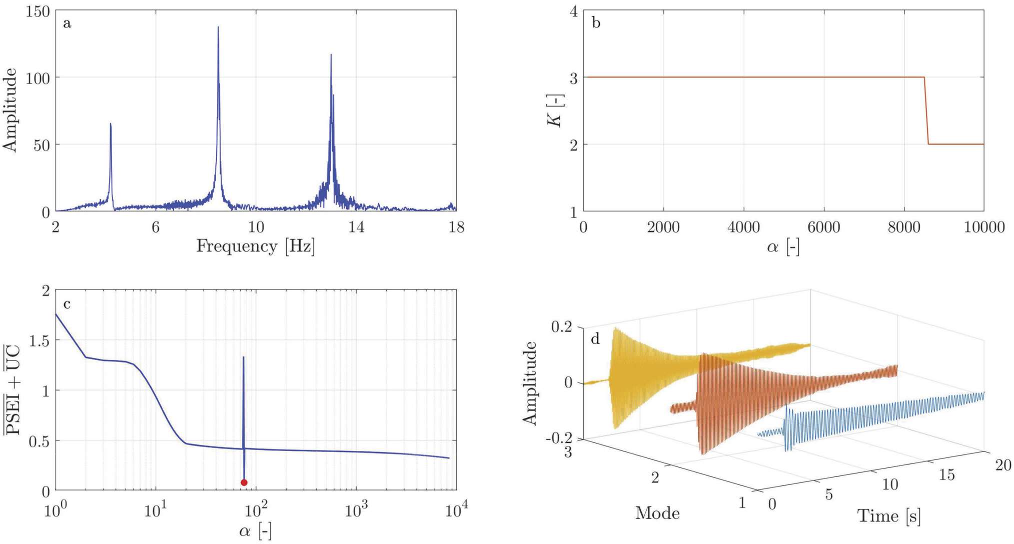

Figure 3. Elaborations on the signal V/V - Cable B in Rome direction: a) Fourier Transform, b) Stabilization diagram for K, c) Evaluation of optimal α and d) VMD of the signal with K=3 and α=76.

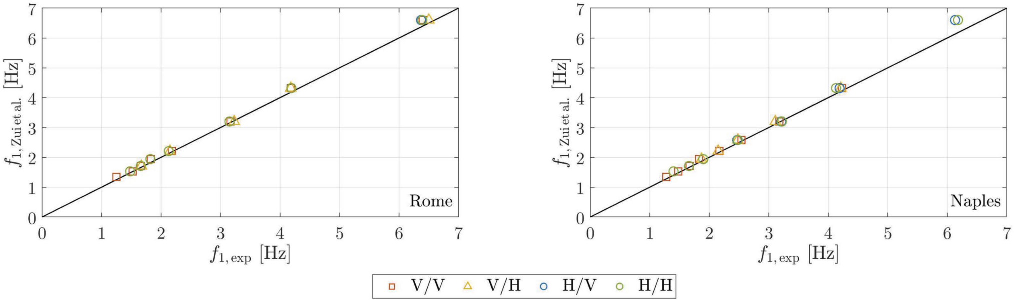

Figure 4. Comparison between experimental and predicted frequencies for the first mode of cables in both the road directions.

For each stay cable, the considered identification method also allows the estimation of modal damping ratios from the free vibration response (see Figure 5). All modal damping ratios fall within the range 0-0.8% with an average value of 0.25%; these results are consistent with literature studies on cable modal damping ratios in cable-stayed bridges (Chen et al. 2019).The estimations for the first mode are compared with results obtained interpreting ambient vibration tests executed on the same cables by means of the Natural Excitation Technique (James III et al. 1993) in Figure 6: consistent values can be observed between the two set of results obtained from two kind of vibration test with limited scattering.

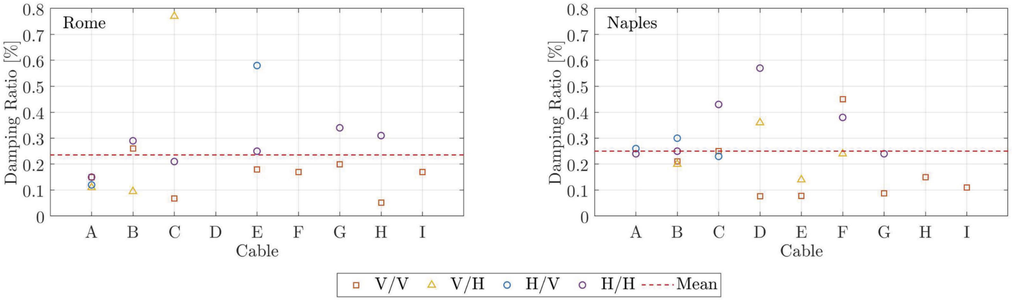

Figure 5. Identified Modal Damping Ratio for the first mode in both the road directions.

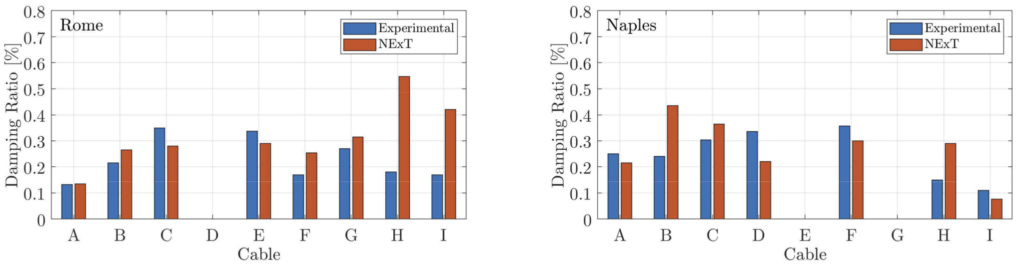

Figure 6. Comparison of modal damping ratios identified from free vibration tests (experimental) and ambient vibration tests (NExT).

4 CONCLUSIONS

In this contribution, the modal identification of cables in a stay-cabled bridge has been addressed. Using a tuned version of the VMD the modal acceleration components have been isolated and modal frequencies have been identified: comparing the latter to the ones obtained from theoretical formulations, good agreement has been achieved. Exploiting an area-ratio based approach, the modal damping ratio for the first mode of each cable has been evaluated. The estimations have been corroborated by the comparison with results from elaboration of ambient vibration data, showing good correspondence and reduced data scattering. The adopted decomposition method appears reliable also in case of cable-stayed bridges and the comparison between the parameters numerically identified and the theoretical ones may allow to make informed decisions for existing bridge structures in terms of eventual repair actions needed to ensure structural safety or serviceability.

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