Modal damping estimations of railway bridges under traffic excitation on InBridge4EU project

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Abstract. The European research project InBridge4EU (Enhanced interfaces and train categories for dynamic compatibility assessment for European railway bridges) intends to revise and propose methods to study the interface between railway bridges and rolling stock to harmonize standards across European and improve the design and maintenance of bridges in the context of interoperability. One work package of the project is focused on the study of the damping parameter since it is a key factor of dynamic behaviour of any structure.

This paper describes the methodology used to extract the modal damping ratio parameter for hundreds of train passages over about 90 European railway bridges.

Two methods were applied to extract damping data including a multi criteria and multi degrees-of-freedom optimization approach (MCO) and a covariance driven stochastic identification method (SSICOV). Complex bridge dynamics and interaction with train can involve several vibration modes, nonlinear patterns and noisy data which complicate damping estimation, so reliability of both methods has been studied on artificial test-cases and on real signals benchmarks.

The methodology applied to the project database is described and first results are presented and discussed. Additionally, two novel methods for automatic detection of the starting time of free-decay response is described.

Next stages of the InBridge4EU project will exploit these data to propose revisions of normative damping values for railway bridges.

Keywords: railway bridges, damping, InBridge4EU Project, Eurocode, multi-criteria optimization, SSI-COV method, dynamics, vibration

1 Introduction

The European research project InBridge4EU [1] aims to develop procedures to revise and enhance normative criteria for evaluating the dynamic performance of railway bridges, as stipulated in the Eurocodes and Technical Specifications for Interoperability (TSIs). These standards currently govern the design and assessment of railway infrastructure across Europe. A critical challenge lies in harmonizing methodologies for assessing parameters like damping, which significantly influence bridge-vehicle interactions and long-term structural integrity. Current damping ratio normative values specified in EN1991-2 [1] are conservative values as they were defined as lower bounds from the ERRI D214 damping ratio study in 1999 [3].

Despite its importance, extracting reliable damping ratios from real bridge responses remains challenging. Estimation methods often struggle with noisy field data, non-stationary excitations (e.g., variable train loads or speeds), detection of the free-response and the coupling of multiple vibration modes. Additionally, extracted damping values from several passages on a same bridge can lead to a significant scatter.

To address these challenges, this paper describes and evaluates reliability of a multi degrees-of-freedom and multi-criteria optimization approach (noted MCO) for damping identification, alongside a covariance-driven stochastic subspace identification (SSI-COV) method for cross-validation. This task within the In-Bridge4EU project granted damping ratio estimations for about 90 bridges in 5 countries (Portugal, Spain, France, Germany and Sweden) based on about 1450 train passages. Damping values are evaluated from the free response of the bridge after the train passage and two methods to automatically detect the train exit time are presented.

2 Viscous damping hypothesis

Damping plays a key role in determining the bridge dynamic response to train-induced excitations. In the common linear viscous damping hypothesis, an excited structure (e.g., by a passing train) returns to its equilibrium state after a free-decay response over its excited natural frequencies which can be modeled as a sum of exponentially decaying sinusoids. This response is described by Eq. (1):

$$s(t) = \sum_{i=1}^{Ndof} A_i \, . \, \exp\left(-\omega_i \cdot \xi_i \cdot t\right) \, . \sin\left(\omega_i \sqrt{1-\xi_i^2} \cdot t + \phi_i\right) \quad (1)$$

Where s(t) represents the time-domain signal of the structural response for example in acceleration (m/s²). The term N_{dof} denotes the number of degrees of freedom in the signal, while A_i corresponds to the amplitude of the i-th mode (initial modal amplitude). The natural frequency of the i-th mode is given by ω_i, and ξ_i represents the damping ratio (as a percentage of critical damping). Additionally, ϕ_i is the phase shift, and t represents time. Both MCO and SSI-COV methods are based on the linear viscous damping hypothesis.

Nevertheless, some bridges can feature a non-linear behavior in terms of frequency (the sudden mass change after train exit causing a frequency shift along the response) and/or in terms of energy dissipation (the free decay is not exponential) so the behavior of the MCO and SSI-COV has been qualified on artificial benchmarks and on real signals with non-linear features as presented in §4.

3 Estimation methods

3.1 Multi-Criteria Optimization Method (MCO)

The multi-criteria optimisation method is based on the reconstruction of an analytic multi-degrees of freedom function matching the measured signal in both time and frequency domains according to Eq. (1). This model allows to evaluate the superposition of several modes at once and does not require to heavily filter signals.

It uses the matlab multi-objective optimisation toolbox GODLIKE (abbreviation for Global Optimum Determination by Linking and Interchanging Kindred Evaluators) shared by Oldenhuis & Vandekerckhove [4] which implements the combination of 4 metaheuristics (solving procedures) to find a global optimum of a problem involving several constrained input variables and several objective functions. The 4 metaheuristics are: Genetic Algorithm (GA), Differential Evolution (DE), Particle Swarm Optimization (PSO) and Adaptative Simulated Annealing (ASA). The multi-evaluator step is followed by the use of second unconstrained optimization with the Nelder-Mead algorithm (matlab's fminsearch) in order to help converging towards a local minimum. The objective function ϵ, mixing time domain and frequency domain estimators, is written as Eq. (2).

$$\epsilon = h_{tmp} \cdot \frac{\int (s_{init}(t) - s_{calc}(t))^2 dt}{\int s_{init}(t)^2 dt} + h_{fft} \cdot \frac{\int (p_{init}(f) - p_{calc}(f))^2 df}{\int p_{init}(f)^2 df} \quad (2)$$

Where s_{init} & s_{calc} are time-domain signals (measured and synthesized respectively), p_{init} & p_{calc} are frequency-domain signals, h_{tmp} and h_{fft} are possible weighting terms of time-domaine and frequency-domain estimators.

The reliability of results is evaluated by the quality of the fit of measured signals by analytical estimates. The user's expertise is required for the validation step since usual error indicators can be biased by a lack of fit in parts of signal which are not essential for the current purpose (high frequencies for instance).

3.2 Covariance Driven Stochastic Subspace Identification Method (SSI-COV)

The Covariance Driven Stochastic Subspace Identification (SSI-COV) method was adopted by another team to estimate damping in parallel. This methodology is based on the identification of a state-space model of the recorded response and can also be adapted to extract modal parameters from the free response of a bridge after train passage based on correlation matrices. A detailed description of the theoretical background of the SSI-COV method and the definition of the contribution of each mode for the measured decay can be found in Pimenta et al. [5]. This implementation of SSI-COV method estimates an equivalent viscous damping ratio per mode and controls the reliability of the estimate through stability diagrams.

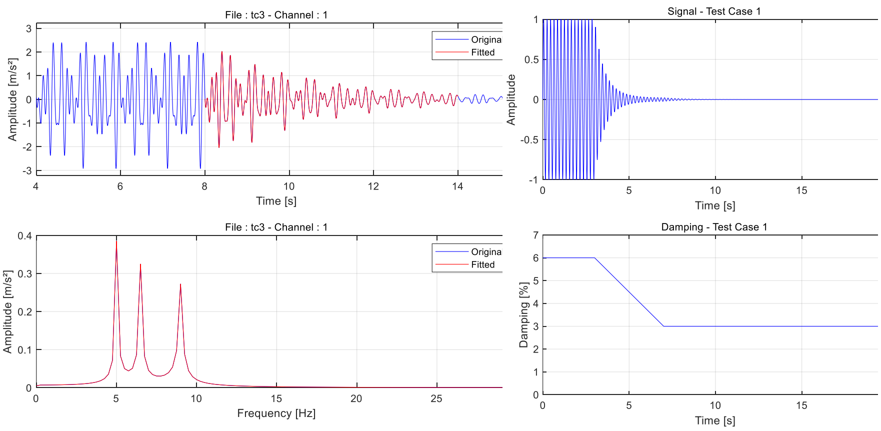
4 Benchmarking of methods

To ensure the reliability of the damping estimation method, a three-step validation process was implemented, encompassing synthetic and real-world datasets.

Linear test cases: 10 synthetic signals were generated using the linear free-decay response equation (Eq. 1) to validate the method under idealized linear viscous damping conditions. A noise term has been added to the analytic formula for 2 cases. MCO and SSI-COV methods obtained near-perfect estimations of the synthetic data (3% error on the test with most noise). This confirmed both method's accuracy in linear regimes. An example of linear test case with 3 modes and MCO fitting is presented in Fig 1a.

Nonlinear Test Cases: To address nonlinearities, 4 synthetic signals were designed with damping ratios decreasing over time ($\zeta = \alpha \cdot t + \beta$) during the decay phase on the [3% - 6%] and [1% - 3%] ranges. The goal is to identify whether algorithms have a tendency to obtain a lower or a higher estimate of damping. An example of test signal is presented in Fig 1b.

From results over 20 combinations of signal portions, a general trend of overestimation of the theoretical mean of damping is highlighted for both MCO and SSI-COV methods. Both methods appear to be more likely to be sensitive to the first cycles of oscillation with higher damping values instead of averaging on the full considered decay duration. The two methods are generally consistent with one another with less than 0.5 percentage-point of difference in their estimations.



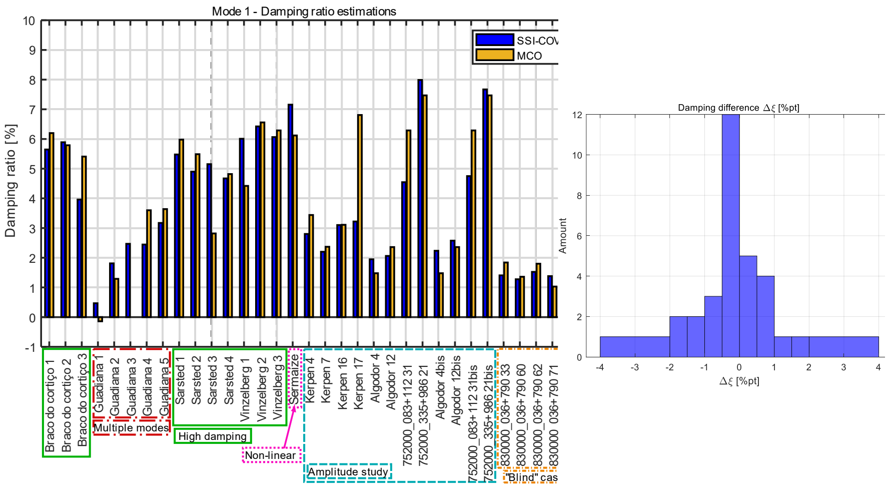
a) b)

Fig 1. a) Example of MCO estimation on a linear test case, b) Example of non-linear test signal and its damping values over time.

Real Signal Comparison: Field-acquired signals introduce complexities such as noise, transient phenomena, and distorted decay patterns, which impacts the quality of the damping coefficient estimations. Consequently, several passages from the database were selected to compare the reliability of SSI-COV and MCO methods on the same input data. Several rounds of benchmarks have been fulfilled in order to explore the following scenarios:

- Signals involving multiple low-damping modes.
- Signals involving high damping ratios: Estimating high damping ratios is more complex due to fast amplitude changes over a short period of time, especially if several modes are contributing.
- Signal showing non-linear behaviour: The chosen bridge displays a non-linear dynamic behavior in terms of frequency and amplitude as the frequency of oscillations evolves along the decay from about 16Hz to 20Hz.
- Study of the amplitude parameter: modal amplitude is an important aspect because of a plausible dependence of damping values to amplitude on some bridges.
- “Blind” benchmarks with non-fixed time parameters: starting and ending values were not communicated between the teams using SSI-COV and MCO methods in order to check if tendencies are equivalent with “user dependent” input parameters.

Damping ratio estimations of both methods (SSI-COV and MCO) for the benchmarks are compared in Fig 2a (bridge names on the x-axis are grouped according to benchmarks categories) and an histogram of methods gaps is presented in Fig 2b.



a) b)

Fig 2. a) Damping estimation results for MCO and SSI-COV, b) Histogram of gaps Δξ in damping ratio between the two methods

Gaps between estimations and their histogram show that most test cases present a margin $\Delta\xi$ of 0.5 %pt in absolute values. Moreover, with a most occurring gap falling in [-0.5 %pt, 0], it can be noticed that MCO has a tendency to estimate higher damping values as compared to SSI-COV. It can be noted that few test cases present low damping values (< 2%) on the first mode, limiting the interpretation of the error margin in such case. A long resonant free response is more likely to result in relevant estimations like in linear test cases.

Large discrepancies have appeared in the following situations:

- Non-linear behaviour,
- Complex signal: Some test cases are notably complex with very short or very long duration, large frequency content or noise level,
- Mode 1 is not predominant: The first mode is not always the main contribution in the response and is then more difficult to identify like in multiple modes case.

Frequency and modal amplitude estimations are not detailed in this paper but it has been observed that frequency estimation from both methods fall within a margin of 0.2 Hz except for the non-linear case with a 1 Hz gap (16 Hz vs 17 Hz).

Modal amplitude estimations on controlled and “blind” benchmarks are consistent between both methods although larger discrepancies were observed on test linked to a complex dynamic behavior with very close modes that cannot be captured equally by both methods.

5 Application to InBridge4EU train passages database

Processing the significant amount of train passages data (1450 passages selected) required a selection process based on the following criteria:

- Selecting passages according to their resonance profile,
- Selecting the appropriate channel to make the processing (sensor position),
- Pre-filtering the data to focus on low frequency modes,
- Checking the quality of results,
- Selecting the relevant damping values to input to the results database.

In terms of passage selection, passages that effectively induced resonance of the bridge were chosen, as these provided the most meaningful data for analysis. The validation of these resonant passages was conducted visually by analyzing the time signal and the Fast Fourier Transforms (FFTs) of train passages on the specified bridges.

The project focuses especially on the estimation of damping of the first bending mode since it is usually the one taken into account for bridge dynamic compatibility checks upon designing. Hence, ideally the sensors positioned midspan would be selected in most cases for estimation as they provide a maximal response from the first bending mode. However in practice, it was sometimes necessary to select alternative sensors due to the presence of excessive noise or saturation in the central sensor's data.

Additionally, a preliminary filtering of the signals is performed before estimations. The practice is similar to the one proposed in the EN 1991-2 [1]: apply a low-pass filter with a cutoff frequency 50% higher than the highest modal frequency to fit (with a minimal cutoff frequency of 30 Hz).

Fig 3 presents an example of the MCO procedure on a Spanish bridge called Guadiana. On this specific train passage, the most adequate signal for estimation came from accelerometer n°13 which is set midspan under the track being run by the train. The MCO method estimated modes at 9.72Hz and 10.92Hz which is consistent with identified modes in [6] with a first bending mode at 9.8 Hz and a first torsion mode at 11 Hz. In this example, damping ratios are estimated at 2.89% and 1.35% and modal initial amplitudes at 44.6 mm/s² and 53.0 mm/s² for respectively modes 1 and 2. The second mode is contributing more to the global response of the bridge.

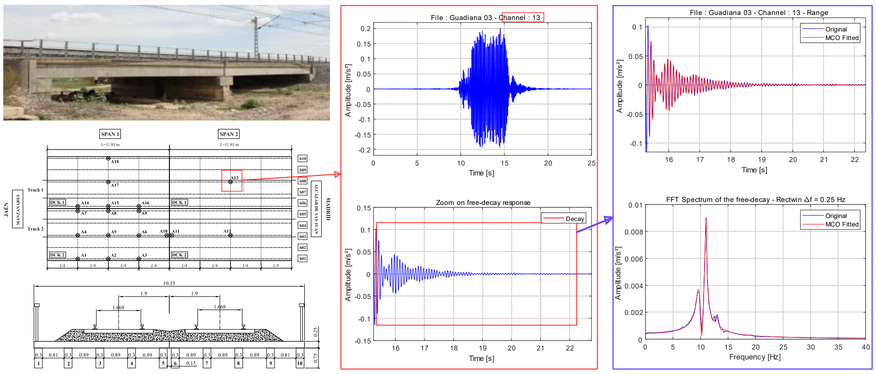


Fig 3. Example of data processing on a train passage over Guadiana bridge (Spain).

Overall Results: Damping estimations were performed using MCO and SSI-COV methods as described previously. The MCO optimization approach has been applied to bridges from France and Spain, and the SSI-COV method has been used for bridges in Portugal, Germany, and Sweden. First results on German bridges were presented in [1].

The resulting database includes damping estimates for up to two modes contributing to the total bridge response, along with the amplitude of each mode.

A global visualization of the obtained damping coefficients is presented in Fig 4, categorized according to bridge families specified in EN 1991-2 [1] (Filler beam bridges, prestressed concrete, steel and composite). Damping coefficients (ξ1) in these figures correspond to the first fundamental vertical bending mode when it is the one mostly contributing to the response. A significant scatter is observed even on a same bridge (constant span) showing the importance of the passage parameters such as train type and speed on the response. Most of the values significantly exceed the current normative limits specified in EN 1991-2. While these limits form accurate lower bounds for the damping values, some outliers remain below the curves and will be further studied in the next stages of the InBridge4EU project.

Additionally, no systematic influence of the amplitude parameter on damping values could be drawn for the current results.

It should be noted that damping estimation from bridge forced excitation (with an actuator) were also performed for comparison but on a much smaller data base and showed less scattering of results although some damping values could be near or below current normative limits. Next stages of the InBridge4EU project intend to evaluate possibilities of revisions of the normative damping values thanks to this new dataset, which is much larger than the ERRI D214 one [3] from which current normative values were based. New conclusions are likely to be drawn by, for instance, splitting bridge categories into more specific ones or focusing the analysis on cases where the first bending mode is resonant since it is the usual design case for bridge dynamics evaluation.

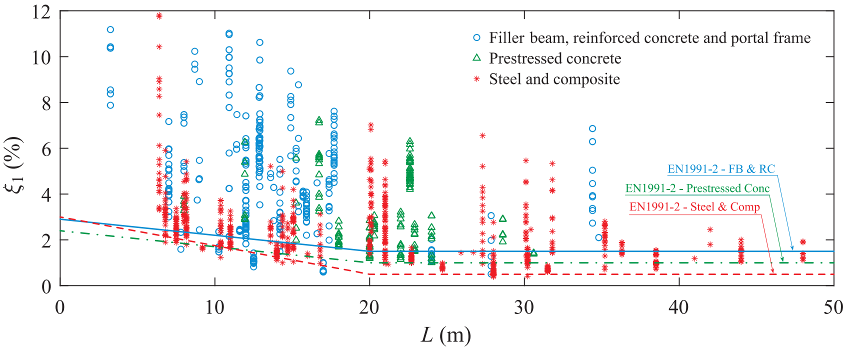


Fig 4. Damping coefficients related to the first fundamental bending mode as function of span and Eurocode bridge categories.

6 Complementary Study of the initial free-decay instant detection

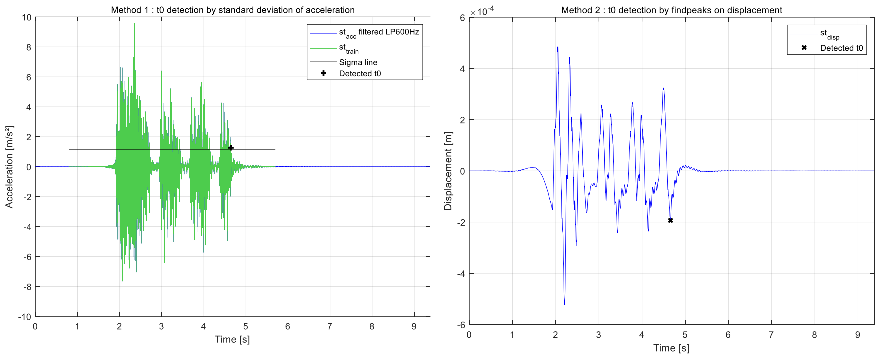
A study for ways to automatize the choice of the initial time (t0) to be considered for damping estimation (early beginning of free decay with maximum amplitude) has been performed with the help of the Portuguese dataset since it involves optical sensors to detect precisely the arrival and the departure of the train over the bridge. Two different methods, based on the acceleration response measured midspan, found fairly accurate match of the optically detected departure time:

Statistical sigma method. Computing the standard deviation ("sigma") of acceleration over a train passage and picking the last time it has been exceeded provides an estimate of the departure time.

The standard deviation of acceleration during train passage is computed on the 600 Hz low-pass filtered signal to include high frequency content linked to rail roughness for instance. The boundaries of the train passage are defined thanks to the 1s rolling-RMS or moving-std (Leq,1s) value and the time boundaries correspond to the moments when max(Leq,1s)-40dB is reached. The initial time the free-response (t0) is the time of last exceedance of the sigma value as depicted in Fig 5a.

Displacement analysis method. Train departure time is estimated thanks to the study of displacement signal. The last significant displacement peak matches with the optical sensor detection, as showed in Fig 5b, as it presumably manifests passages of each bogie.

The process involves the following steps: Double integration of acceleration to get displacement, applying a 1Hz high-pass filter to avoid drifting and detection of the last significant peak. The automated procedure to detect the last peak involves steps of normalization, peak detection, weighing and thresholding to remove spurious peaks.



a) b)

Fig 5. a) Detection of t0 with the sigma method, b) Detection of t0 with displacement peak method

Comparison to optical sensors data. Both methods were compared to the measured references from optical sensors on the Portuguese dataset (6 bridges). Fig 6 presents t0 estimations from the 2 methods difference to the reference. It can be observed that:

- The absolute error values are mostly inferior to 100 ms, despite bridges n° 2, 3 and especially 4 showing higher scattering,
- Standard deviation method (sigma method) shows better results on 5 out of 6 bridges with absolute median error values from 37.6ms to 0.488ms (bridge 4 excluded),
- Results on bridge 4 are notably worse than on other bridges and this is likely to be linked to the globally low speed of trains (often in the [20 60] km/h range),
- Bridge span is also likely to influence results as observed on bridge n°2 and n°3 which are about 11m-long where median errors reach about 30ms.

Consequently, the sigma method has been preferred to evaluate t0 in the database processing but keeping user's manual adjustment when automatic values were notoriously irrelevant.

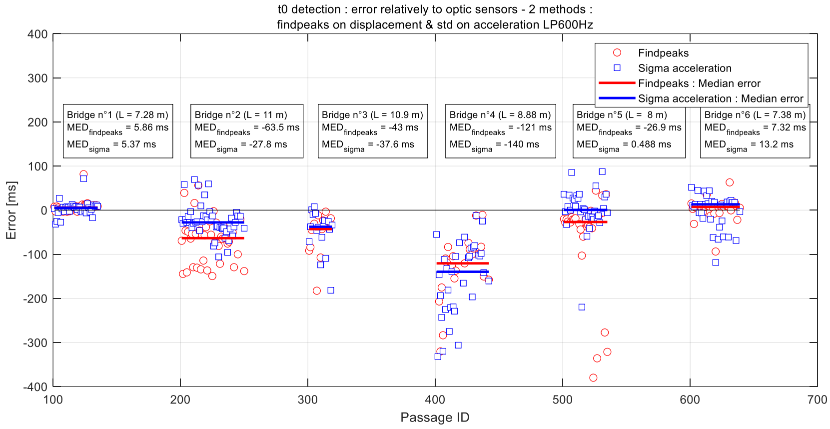


Fig 6. Estimation error between the 2 methods against optical sensor reference.

7 Conclusion

Evaluating damping of railway bridges from passing trains is a complex problematic because of parameters such as the actual resonance of the bridge, the detection of the starting time of the free-response when the train leaves the structure, the multiple modes contributing to the response and potential non-linear behaviour.

The presented task of the InBridge4EU project managed to evaluate damping on a large amount of bridges (90) and passages (1450) thanks to two methods which were methodically benchmarked in order to identify their weaknesses (non-linear dynamics, very close modes…) and evaluate their accuracy. Application of these methods to the project database led to consistent results on a data set much larger than what was available for the ERRI D214 study from which current normative damping values originate.

The first synthesis of results shows a large scattering of damping values, most of which largely exceeding normative values. Next stages of InBridge4EU project will focus on the lower damping values and outliers and on the bridge categorisation in order to evaluate potential revisions of the Eurocodes.

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