

COVER LETTER TO THE REVIEWERS

Manuscript ID: sensors-1937098
Title: Train-track-bridge dynamic interaction on a bowstring-arch railway bridge: advanced modeling and experimental validation
Authors: Diogo Ribeiro, Rui Calçada , Maik Brehm , Volkmar Zabel

1. Initial Considerations

- 1.1 We would like to start by expressing our gratitude to the Reviewers for the relevant remarks addressed in their reports about the manuscript referenced above. These comments and suggestions helped us to improve the manuscript.
- 1.2 This letter serves as a guide in the identification of all the changes introduced into the reviewed version of the manuscript and provides a point-by-point response to all the pertinent remarks of the Reviewers. The most relevant changes in the manuscript are identified by the track changes mode of MS Word in the file “Revised_Manuscript_with_Track_Changes”.

2. Specific Answers to the Reviewers’ Comments

Reviewer 3

The authors acknowledge the positive evaluation made by the Reviewer. Concerning the pertinent remarks raised by the Reviewer (*italic*), the following changes were introduced into the manuscript, or alternatively the following clarification comments are made:

- 1) *The authors conduct a study to validate a 3D dynamic interaction model of the train-track-bridge system on a bowstring-arch railway bridge based on experimental tests. The model sub systems are modelled based on finite element model previously calibrated based on experimental data and the authors found the model results to be in a very good correlation. This study holds good efforts and contributes to the literature. However, there are some issues that the authors should consider in the revision round.*

The authors acknowledge all the positive feedback addressed by the Reviewer related to the technical contents of the manuscript.

- 2) *Limitations of the previous studies should be discussed.*

The authors acknowledge the pertinent observation addressed by the Reviewer.

Concerning the validation of the train-track-bridge dynamic system several limitations of the previous studies were already pointed/discussed in the Introduction section.

Despite of that, the authors decided to include some specific insights about some of the limitations of the previous studies.

Therefore, in the points below, the authors present the identified limitations and the parts of the manuscript in which they are addressed, including some punctual insights:

- a. Most of the studies are focused on bridges belonging to high-speed lines, while a by far smaller number of publications envisages bridges on conventional lines.

“1. Introduction

... between both records. Most of the studies are mainly focused on bridges belonging to high-speed lines, while a by far smaller number of publications envisages bridges on conventional lines. Several...”

- b. Most of the existing bibliography do not consider calibrated numerical models of the train, track, and bridge subsystems. Normally, the existing studies consider calibrated models of some of the subsystems but not for all of them. Also, in the case of the track and vehicles subsystems, authors resort to calibrated models of lesser complexity.

“1. Introduction

... vehicle. Most of the existing bibliography do not consider calibrated numerical models [31-33], particularly in case of the track and vehicles, and normally resort to calibrated models of lesser complexity [32]. Furthermore...”

- c. In the bibliography, few works were focused on the simultaneous validation of the dynamic response in the bridge, track, and vehicle subsystems. Even in situations where the response of the bridge and train were evaluated, the number and type of measurements was limited.

“1. Introduction

...In the bibliography, few works were focused on the simultaneous validation of the dynamic response in the bridge, track, and vehicle subsystems. Even in situations where the response of the bridge and train were evaluated, the number and type of measurements was limited...”

- d. Typically, the validation is performed in terms of the dynamic response of the bridge (displacements, accelerations, and strains) and there are still only few studies that include the dynamic responses of vehicles.

“1. Introduction

... Typically, the validation is performed in terms of the dynamic response of the bridge (displacements, accelerations, and strains) and there are still only few studies that include the dynamic responses of vehicles. Among the...”

- e. In most of situations the track irregularities profiles are randomly generated from power spectral density functions proposed by railway administrations. The evaluation of the track irregularities based on direct measurement of the track geometry is reported in a scarce number of works.

“1. Introduction

... Furthermore, in most cases the irregularities of the track are randomly generated based on dedicated power spectral density functions proposed by railway administrations...”

- f. In most of the existing literature, the estimates of damping coefficients are based on ambient responses obtained for vibration levels significantly lower than those verified under traffic.

“1. Introduction

...In most of the existing literature, the estimates of damping coefficients ~~is~~are based on ambient responses obtained for vibration levels significantly lower than those verified under traffic.”

- g. Typically, the dynamic tests performed for the validation of the train-track-bridge system do not guarantee the time synchronization of the measurements on the bridge and vehicles subsystems.

“1. Introduction

...used an integrated dynamic monitoring system that guarantees the synchronization of the measurements on the bridge and vehicles by means of precision GPS systems. This level of detail in terms of time accuracy is normally not reported in the bibliography.”

- 3) *Outcomes and limitations of the present study regarding the validated model calibrations should be discussed. May this model validate out of the limitations?*

The authors acknowledge the relevant aspects pointed by the Reviewer.

Concerning the limitations of the validated train-track-bridge dynamic model, the authors would like to emphasize the following points:

- a. The model may present constraints in capturing the local dynamic behavior of the bridge, particularly on specific critical details of the arches' connections. The characterization of this local behavior would require the adoption of refined local FE models based on submodelling strategies. The merge of these local models within a global FE model using a multiscale methodology for local stress analysis would be particularly useful for fatigue investigations.
- b. Since the modal superposition method uses a limited number of modes to calculate the bridge-track subsystem, the local dynamic behavior of the track components is not adequately captured. This is because the track components response is greatly influenced by high frequencies modal contributes that are not being included the present study. By the way, this high frequency contributes would never be efficiently included in the dynamic responses using a modal superposition approach.
- c. The dynamic model does consider the eventual non-linear incursions of the train-track-bridge system during the train passage over the bridge. Typically, in this type of bridge it is relevant to consider the eventual non-linear behaviour: i) at the support bearings, ii) at the track-deck interface due to the longitudinal shear stresses transmission between the rail and deck through the ballast layer, and iii) at semi-rigid connections between elements of the arches.

Thus, out of the circumstances pointed before the model would be able to give a reliable prediction of the dynamic responses of the train-track-bridge coupled system.

In relation to the main outcome of the present study, it should be highlighted the development of a highly complex dynamic model of the train-track-bridge system able to reliable capture the global dynamic behavior of the train and bridge subsystems under real operational scenarios.

Some other specific outcomes/contributes of this work were already depicted at the end part of the Introduction section of the manuscript in a point-by-point discussion. Therefore, the authors performed the following correction in the revised manuscript:

“7. Conclusions

...

...movement of the carbody.

Thus, as main outcome of the present study, it should be highlighted the development of a highly complex dynamic model of the train-track-bridge system able to reliable capture the global dynamic behavior of the train and bridge subsystems under real operational scenarios.

Despite the efficiency of the validated model in predicting the train-track-bridge global dynamic responses, it should be pointed out some of its limitations, especially in capturing: i) the local dynamic behavior of the bridge, particularly on specific critical details of the arches, which would require the adoption of a submodelling approach; ii) the local dynamic behavior of the track components, which is greatly influenced by higher frequencies modal contributes not considered in this study, and iii) the eventual non-linear incursions of the bridge subsystem namely at the support bearings, at the track-deck interface and at the semi-rigid connections between arch elements.

Finally, as ongoing and future works...”

- 4) *In last bullet of page 6, please replace “estimations” with “estimates”.*

The authors acknowledge the correction addressed by the Reviewer and performed the following correction in the revised manuscript:

“1. Introduction

...

...passage. In most of the existing literature, the ~~estimation~~estimates of damping coefficients is based...”

- 5) *There are some typos. They should be revised. For instance, in page 7, pay attention “length”.*

The authors acknowledge the comment addressed by the Reviewer and performed a full and detailed review of the typos on the manuscript, including the term “length” that was replaced by “length”.

For simplicity, the changes were marked directly on the manuscript with track changes, and exceptionally not detailed point by point.

- 6) *Version of ANSYS should be given.*

The authors acknowledge the pertinent note of the Reviewer.

The version of ANSYS software used in this work was version 12.0. The indication of the version of ANSYS software is included in the correspondent reference at the References section.

The authors performed the following correction in the revised manuscript:

“2.2. Numerical modelling

...three-dimensional finite element model, including the track, developed in the ANSYS software version 12.0...

...

3.2. Numerical modelling

The numerical model of the BBN vehicle was developed in the ANSYS software version 12.0...”

7) Please give full form of MAC.

The authors acknowledge the comment addressed by the Reviewer.

The full form of **MAC** is **Modal Assurance Criterion**.

Thus, the authors performed the following correction in the revised manuscript:

“2.2. Numerical modelling

...

...and the values of the parameter MAC (Modal Assurance Criterion) ~~parameter~~, indicating...”

- 8) In Table 1, the optimal values based on the calibration process were given. If the values in Tables are not obtained based on the experimental data, the optimization procedure should be discussed. How did the authors search these parameters and conclude the optimal values? However, the authors should discuss the equifinality problem of the parameters.*
- 9) What is the sensitivity of the parameters given in Table 1? Please address the sensitivity of each parameter value. The changes in parameter values given in Table 1 may affect the results of Figure 3. What about the reliability of the model outputs?*

The authors acknowledge the pertinent observations addressed by the Reviewer.

The objective of this article is focused and restricted to the validation of the train-track-bridge dynamic model of the São Lourenço railway bridge.

As background of this article, three other articles from the same authors and already published were specifically focused on the calibration processes of the bridge, track and train subsystems.

Thus, the details of the calibration process of the bridge and track subsystems respectively, can be found in the following references:

[47] *Ribeiro D, Calçada R, Delgado R, Brehm M, Zabel V. Finite element model updating of a bowstring-arch railway bridge based on*

experimental modal parameters. Engineering Structures. 2012;40:413-35. DOI: 10.1016/j.engstruct.2012.03.013

[48] *Ribeiro D, Calçada R, Brehm M, Zabel V. Calibration of the numerical model of a track section over a railway bridge based on dynamic tests. Structures. 2021;34:4124-4141. DOI: 10.1016/j.istruc.2021.09.109*

Due to space limitations and avoid repetition of information with the already published articles, the authors decided to keep to the essential the aspects related to the calibration of the bridge and track FE models.

Anyway, as an overall perspective of the calibration procedure of each specific FE model:

- The calibration strategy consisted in the application of an iterative methodology based on a genetic algorithm and resorting on experimental modal parameters (natural frequencies and mode shapes).
- The calibration involved a sensitivity analysis and an optimization stage.
- A global sensitivity analysis using a Spearman correlation matrix and a stochastic sampling technique was performed. In case of the bridge, the most sensitive numerical parameters were the modulus of elasticity modulus of concrete and steel, the density of concrete, the density of ballast and the vertical stiffness of supports. Also, the parameters associated with the initial stress of the hangers and diagonals, as well as the stiffness of the connections between these elements and the deck and arches, presented high sensitivity values. A brief of all sensitivity values is presented in Figure 16 of reference [47]. In case of the track, the most sensitive parameters were the ballast elasticity modulus, Poisson's ratio and density, as well as the additional height of the ballast. The sensitivity values are presented in Figure 17 of reference [48].
- The optimization stage was based on the results of several independent optimization runs with different initial populations. In case of the bridge, the optimal parameters' values presented variations usually below 10%, while in case of the track the estimates were practically identical. The optimal values refer to the optimization run that presented the lowest residual of the objective function.

Therefore, considering all the above referenced aspects, the authors performed the following inclusion in the revised manuscript:

"2.2. Numerical modelling

... of the deck or arches [47,48]. In references [47, 48] are also detailed the results of the sensitivity analysis and optimization, and therefore for simplicity and avoid repetition of information, those aspects are here kept to the essential. Table 1 presents the values..."

10) *If the authors could add legend in Figure 3, the deformations may be easily detected.*

The authors acknowledge the comment of the Reviewer.

Figure 3, as well as Figure 10, already include a legend identifying the colors/patterns associated to the "undeformed mesh", "numerical mode shapes" and "experimental mode shapes".

For simplicity and avoiding unnecessary repetitions, this legend was strategically positioned only close to the first two mode shapes.

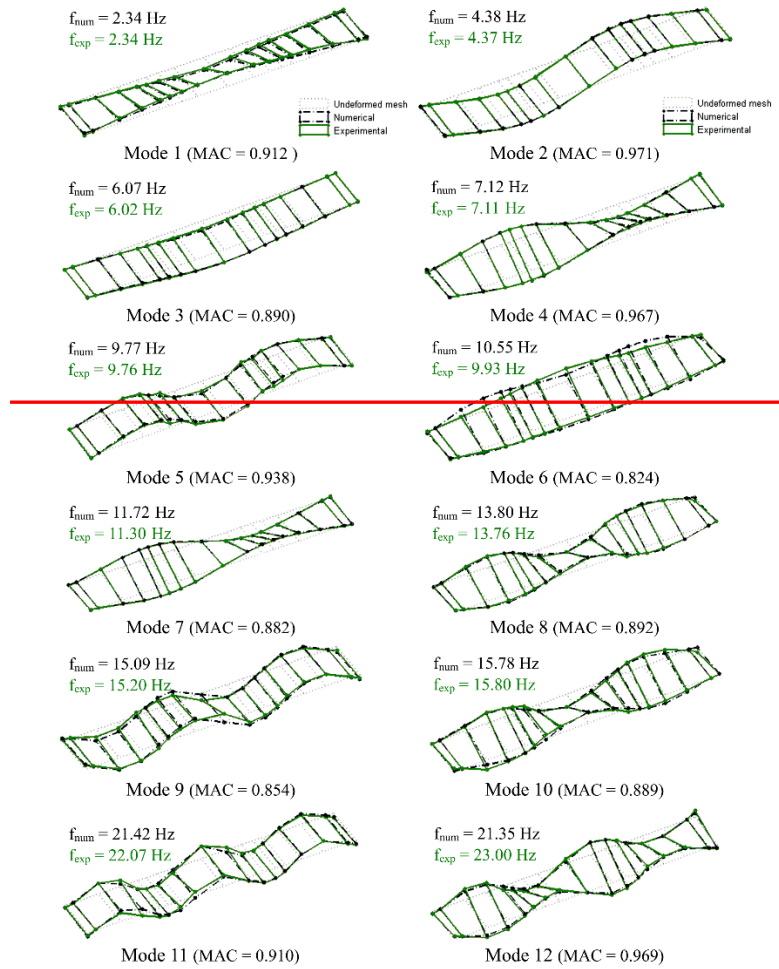
However, to increase the visibility of the mode shapes, as well as to enhance the differences between the numerical and experimental mode shapes, the authors

decided to change the colors of the experimental modal configurations, from green color to orange color.

Thus, the authors performed the following modifications in the revised manuscript:

“2.2. Numerical modelling

...



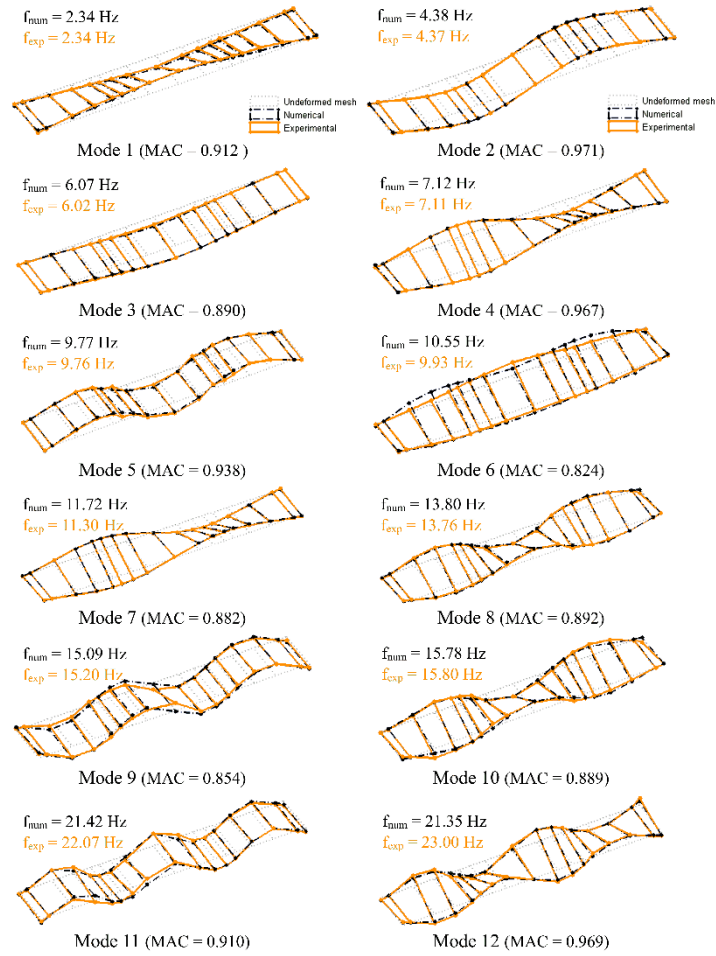
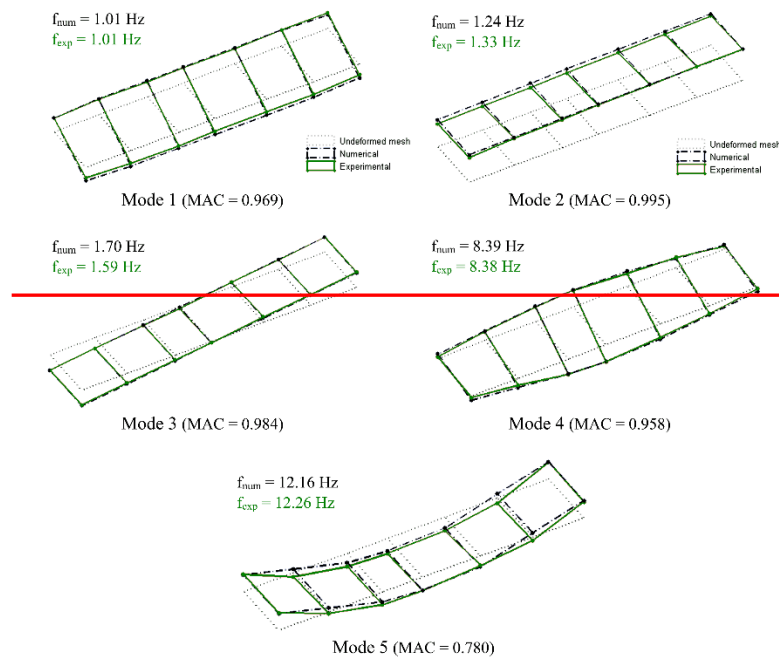


Figure 3. Comparison of the global vibration modes of the bridge obtained experimentally and numerically

...



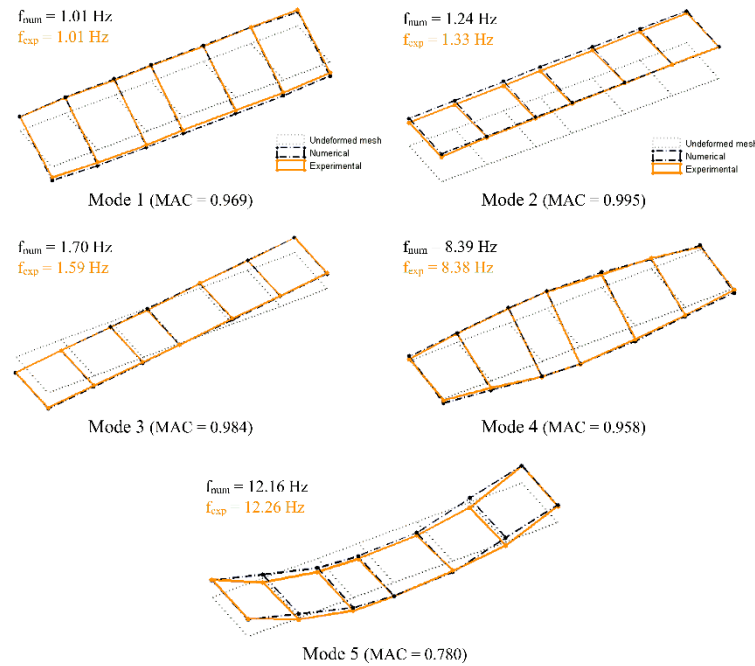


Figure 10. Comparison of the vibration modes of the BBN vehicle obtained experimentally and numerically

11) The similar problems may be discussed for the values given in Table 2 and the results presented in Figure 10. Authors may prefer including a new section to address this issue.

The authors acknowledge the pertinent observations addressed by the Reviewer.

The objective of this article is focused and restricted to the validation of the train-track-bridge dynamic model of the São Lourenço railway bridge.

As background of this article, three other articles from the same authors and already published were specifically focused on the calibration processes of the bridge, track and train subsystems.

Thus, the details of the calibration process of the train subsystem, can be found in the following reference:

[18] Ribeiro D, Calçada R, Delgado R, Brehm M, Zabel V. Finite element model updating of a railway vehicle based on experimental modal parameters. *Vehicle System Dynamics*. 2013;51:821-56. DOI: 10.1080/00423114.2013.778416

Due to space limitations and avoid repetition of information with the already published article, the authors decided to keep to the essential the aspects related to the calibration of the train FE model.

Anyway, as an overall perspective of the calibration procedure of this specific FE model:

- The calibration strategy consisted in the application of an iterative methodology based on a genetic algorithm and resorting on experimental modal parameters (natural frequencies and mode shapes).
- The calibration involved a sensitivity analysis and an optimization stage.
- A global sensitivity analysis using a Spearman correlation matrix and a stochastic sampling technique was performed. The most sensitive numerical parameters were the stiffness of the vertical secondary suspension, the corrective factor of

the moment of inertia base platform and side walls, and the additional masses at the base, side walls and cover. The sensitivity values are presented in Figure 32 of reference [18].

- The optimization stage was based on the results of several independent optimization runs with different initial populations. The optimal parameters' values presented variations between 1% and 25%, depending on the numerical parameters. The optimal values refer to the optimization run that presented the lowest residual of the objective function.

Therefore, considering all the above referenced aspects, the authors performed the following inclusion in the revised manuscript:

“3.2. Numerical modelling

... was also performed [18]. In reference [18] are also detailed the results of the sensitivity analysis and optimization, and therefore for simplicity and avoid repetition of information, those aspects are here kept to the essential. Table 2 presents the values...”

12) Equations should be given properly and written in equation in word.

The authors confirm that most of the equations were in image format and not in Word equation format.

Therefore, in the revised manuscript all the equations were properly written in Word equation format.

For simplicity, the changes were marked directly on the manuscript with track changes, and exceptionally not detailed point by point.

Thanks for your time and consideration.

Sincerely,

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