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Numerical Evaluation of Modal Properties Change of Railway Bridges during Train Passage

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Abstract

During the passage of vehicles over a bridge, both systems (vehicle and bridge) are coupled together. This coupling is generally accounted for in vehicle-bridge interaction analyses. It is also commonly acknowledged that this coupling leads to changes in modal properties of the bridge. However, this aspect has rarely been investigated in detail. Therefore, the goal of this study is to explore numerically the evolution of the modal properties (natural frequencies and modes of vibration) of the coupled system during the vehicle passage. In particular, special attention is given to railway bridges traversed by trains. For this purpose a numerical model is developed that correctly accounts not only for the train and bridge, but also for the railway track. This Train-Track-Bridge-Interaction model is used to explore the effects on modal properties for a range of typical railway bridges. The numerical results indicate that the variations in natural frequencies depend greatly on vehicle to structure frequency ratio and mass ratio. In some conditions, significant variations in modal properties are observed. However, the relation is not straightforward and some counterintuitive results are reported here, indicating that the phenomenon cannot be explained considering exclusively the added mass of the vehicle.

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1. Introduction

In the study of dynamic systems, it is generally well understood that the modal properties of coupled systems are different to the modal properties of the uncoupled subsystems. The natural frequencies and mode shapes of the

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subsystems change when merged together into a coupled configuration. The amount of change depends on their relative masses and frequencies.

In bridge engineering, the study of the bridge response under traffic loading has to be interpreted also as the coupling of separate subsystems. Separately, the vehicles and the bridge have certain modal properties. During a crossing event, these subsystems are coupled together, which causes varying modal properties. In this case, not only the mass and the frequencies play an important role, but also the particular position of the vehicle on the bridge that effectively changes the degree of coupling between them. This coupling produces a non-stationary scenario that is generally correctly accounted for in Vehicle-Bridge Interaction (VBI) analyses, either iteratively solving the subsystems separately or directly solving the coupled system step-by-step [1]. However, the time-varying nature of the modal properties is rarely appropriately considered when interpreting the numerical results or the bridge response measurements. In most cases, it is acknowledged that the fundamental frequency of a bridge reduces when a vehicle is positioned over it [2] due to the contribution of the added mass, achieving larger (negative) frequency shifts for greater vehicle to bridge mass ratios. However, this offers only a partial explanation of the non-stationary problem. For a complete description, the relation between the frequencies of vehicle and bridge (i.e. frequency ratio) needs to be included. Furthermore, the change in modal properties is not limited to the natural frequencies only. In fact, the shapes of the modes of vibration do also change with the location of the vehicle.

Some recent studies have explored the frequency shifts in bridges considering both, the mass and the frequency ratios. In [3], the authors derive an approximate analytical expression of the change in fundamental frequency of a beam traversed by a vehicle modelled as a 1-DOF system. This has also been explored numerically in [4] clearly showing the non-stationary nature of the problem and highlighting the need of appropriate time-frequency tools to analyze the bridge response. The time-varying nature of the VBI phenomenon is empirically confirmed in [5,6] based on scaled laboratory experiments. In general, these studies support the idea that positive shifts of the bridge's fundamental frequency can occur and that both, mass and frequency ratios, play an important role in the degree of coupling. However, it is found that existing literature does not sufficiently explore the significance of these findings on full scale bridges. Furthermore, there is no study that explores the repercussion of the vehicle position on the shape of the mode of vibration.

Therefore, it is necessary to explore the effects of the time-varying nature of VBI problems on actual bridges subjected to common loading. In particular, this study investigates railway bridges loaded by a standard high-speed train. The analysis is done with a numerical model that also includes the contribution of the ballasted track. The scope of the paper is limited to the bridge's fundamental mode of vibration. Two aspects of the mode are evaluated, namely the frequency shift and change in the shape of the mode. The results are compared to the moving mass results.

The results in this study are interesting in general to achieve a better understanding of bridge dynamics under traffic loading in general. They confirm the inaccuracy of the stationary assumption for this problem, essential in classical output-only identification methods [7]. Furthermore, the results are particularly relevant for the fairly novel research line on indirect bridge health assessment [1], which aims at extracting bridge frequencies and modes of vibration [8] from the response of the traversing vehicle.

2. Numerical model

This study investigates the evolution of the bridge's fundamental mode using a numerical model that describes the dynamic properties of a vehicle, track and bridge system (Fig. 1). The train convoy is represented as a series of successive 10-DOF systems, which include the properties of the main vehicle body mass, the primary and the secondary suspensions. The ballasted track is modelled by a beam resting on a 3-layer spring and dashpot configuration, which captures the behavior of the main components of the infrastructure. The bridge is described as a simply supported Euler-Bernoulli beam formulated in a finite element framework. This model, originally developed for solving the dynamic interaction in [9], generates the equations of motion of the coupled system for a vehicle located anywhere on the track. In this study, the eigenvalue analysis of the coupled mass and stiffness matrices, while varying the location of the vehicle, leads to varying modal properties. The reader is referred to [9] for a more detailed description of the numerical model.

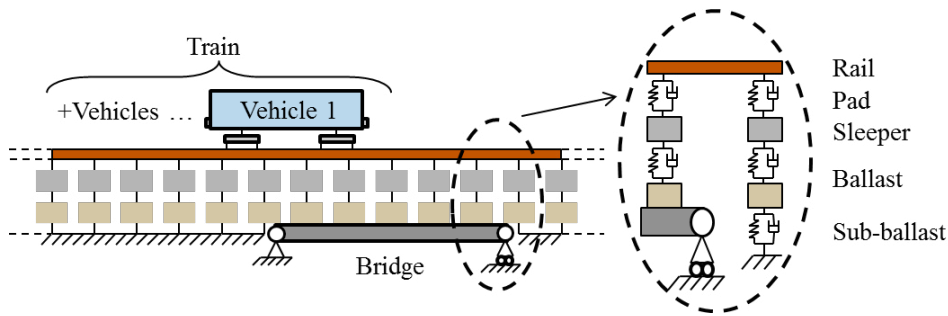


Fig. 1. Schematic representation of numerical model.

In this numerical study, only the locomotive of the high-speed train ICE-2 is considered. The geometry and mechanical properties of this vehicle are taken from [10]. The numerical values to describe the railway track are taken from [11] considering a separation between sleepers of 0.6 m. The numerical properties of a simply supported beam for a given span can be defined in terms of its fundamental frequency and total mass. The goal of this study is to provide results of railway bridges in general. Therefore, the numerical values are taken from two sources. The fundamental frequency (Fig. 2a) is the average value between the upper and lower limits allowed according to the Eurocode [12]. Whereas the mass (Fig. 2b) is taken as the average value of the maximum and minimum values proposed by Doménech et al. [13], which derive from the statistical analysis of a large number of railway bridges.

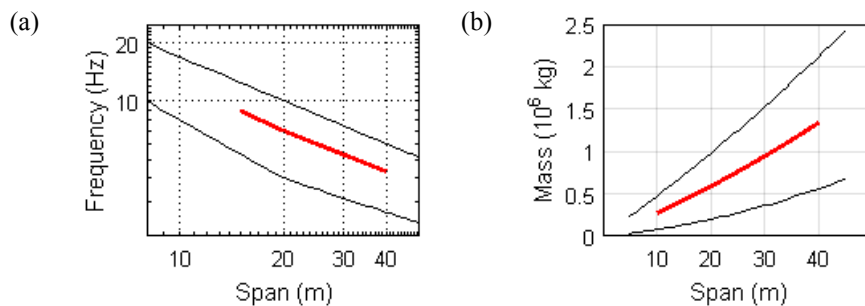


Fig. 2. Properties of bridge; (a) Frequency limits (thin black line) as defined in [12] and considered fundamental frequency (thick red line); (b) Total bridge mass limits (thin black line) [13] and considered values (thick red line).

3. Detailed example

It is convenient to study first one particular example in more detail, namely, one bridge and one vehicle at various locations along the track. The results highlight how differently the modal properties change for coupled, un-coupled and moving mass cases. In this example the locomotive of the ICE-2 high-speed train is positioned along various locations over a 19.8 m long simply supported bridge. The properties of the bridge are defined according to the average of the limits in (Fig. 2) giving a fundamental frequency of 7.10 Hz and a total mass of 583 t. The vehicle's total mass is 80 t (mass ratio = 13.72%) and has multiple frequencies, one of which (7.05 Hz) is close to the bridge's fundamental frequency (frequency ratio = 0.99). Fig. 3 shows the evolution of the bridge's fundamental frequency for three distinct modelling scenarios. When the vehicle and bridge are coupled together, the fundamental frequency not only changes significantly but the frequency shift is positive. This is, the frequency rises up to 7.50 Hz. If the systems are uncoupled, the fundamental frequency remains constant regardless the position of the vehicle. On the other hand, if the vehicle is modelled as a moving mass, the frequency of the bridge reduces (as expected) to values as low as 6.62 Hz. The magnitude of frequency shift varies depending on the number of axles and their particular location on the bridge.

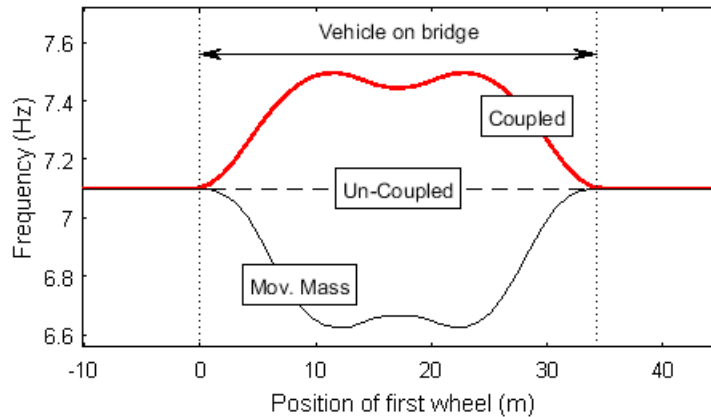


Fig. 3. Evolution of fundamental frequency of a 19.8 m bridge traversed by ICE-2 locomotive.

It is interesting to look also at the evolution of the mode shape. Fig. 4a shows the mode shape associated to the fundamental frequency of the bridge for different locations of the vehicle. It shows that the bridge's mode shape remains constant while the vehicle is at the approach. As soon as the vehicle is on the bridge the magnitude of the mode varies. Fig. 4b shows the variation in magnitude of the fundamental mode compared to the one at the approach. Furthermore, theoretically the mode shape changes also in shape. In order to assess the amount of change in shape of the mode shape the Model Assurance Criterion (MAC) [14] is calculated. Note that the MAC index solely reflects changes in shape between two given modes (Fig. 4c). The comparison of two modes only different by a scaling factor would render a unit value. Here, the shape of the mode for each vehicle position is compared to the mode obtained when the vehicle is off the bridge. A MAC value exactly equal to one indicates that the mode and the reference mode are identical (in shape). On the other hand, any other MAC value indicates that differences in shapes exist between compared modes. Fig. 4c shows that the MAC values for this example are sometimes smaller than one. However, these MAC values are only marginally smaller than one, which indicates that the change in shape of the mode of vibration is negligible.

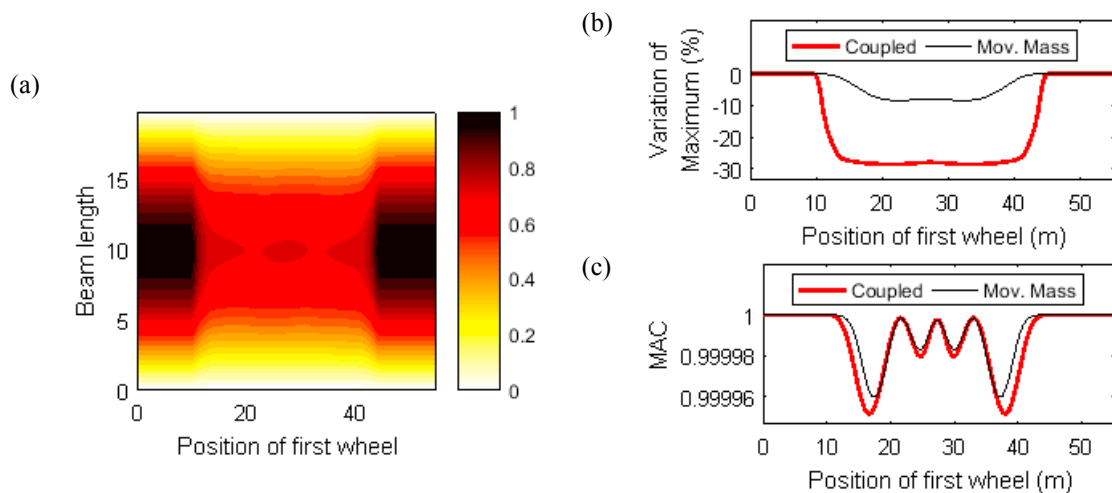


Fig. 4. Evolution of mode shape of the bridge's fundamental mode; (a) Spatial variation of mode; (b) Relative magnitude variation; (c) Shape variation in terms of MAC.

This study performs multiple eigenvalue analyses of the coupled train-track-bridge system; one for each vehicle position. As a result, for each location there are as many modes and frequencies as degrees of freedom in the model.

For simplicity, only the fundamental bridge mode is presented and analyzed in this study, since it is generally the dominating mode of the response. However, not reported here, the vehicle modes and higher bridge modes also change in magnitude and shape depending on the particular position of the vehicle. It is important to note that the extracted fundamental mode has not been mass normalized; its magnitude corresponds to the unaltered result from the eigenvalue analysis of the coupled model. In this case, broadly speaking, the magnitude of the mode indicates the relative importance of that mode to the total dynamic response. Therefore Fig. 4a and Fig. 4b show that the bridge's fundamental mode reduces its relative importance when the vehicle is traversing the bridge.

4. Parametric study

In this section the study of bridge's fundamental mode change is extended to study the influence of different bridge lengths. More in particular, a discrete number of spans are considered, ranging from 15 m to 40 m in 0.3 m increments. The numerical properties for the bridge models are taken as those deemed representative of railway bridges in general, defined in Fig. 2. Fig. 5a shows that the larger frequency shifts occur when there is a close match between un-coupled bridge and vehicle frequencies. Therefore, when the fundamental frequency matches any of the vehicle's frequency we can expect some large variation in modal properties. The actual magnitude in frequency shift depends on the mass of the vehicle and the actual mode of the vehicle that matches the bridge frequency. The frequency shift of the coupled system is compared to the one of the moving mass in Fig. 5b. The results clearly show that the frequency shift can be positive or negative in a coupled system. The abrupt changes in the frequency shift trends in Fig. 5b correspond to situations where one of the vehicle frequencies matches the bridge's frequency. The trend is clearly different to the one obtained for the simpler moving mass situation.

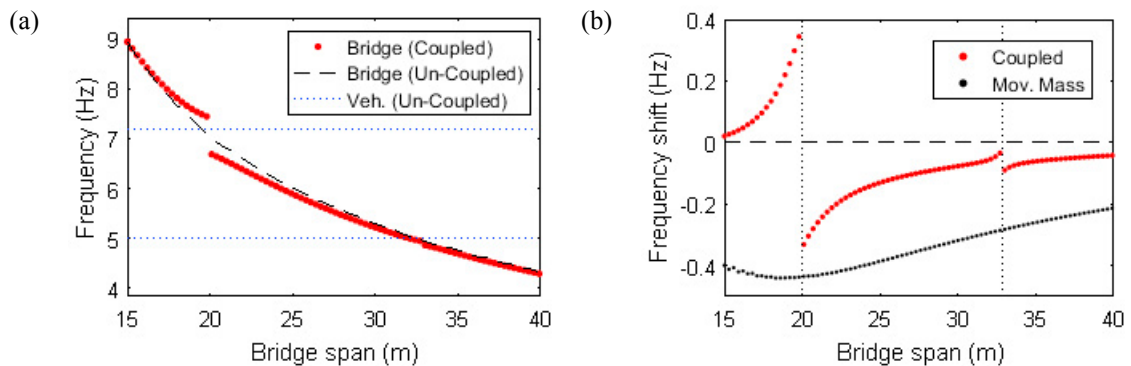


Fig. 5. Influence of bridge span on its fundamental frequency; (a) Vehicle and bridge frequencies; (b) Frequency shift.

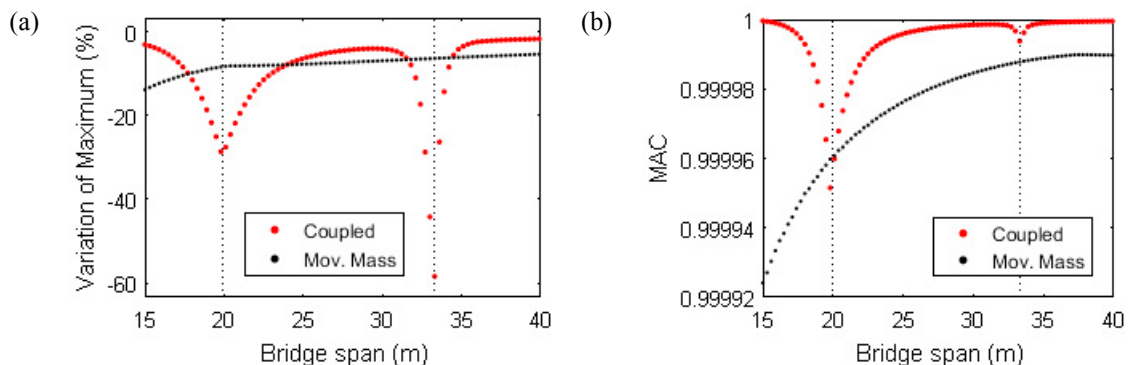


Fig. 6. Changes in mode shape; (a) Relative magnitude variation; (b) Minimum MAC

Finally, the changes in modes of vibration are evaluated using the two indicators used in the example in Fig. 4. The relative variation magnitude of the mode shape is evaluated in Fig. 6a for the range of bridges considered. Large variations in the mode's magnitude are observed when one of the vehicle frequencies matches the bridge fundamental frequency. Again, the change in shape of the mode is evaluated in terms of MAC values. The results in Fig. 6b show that lower MAC values are obtained in a coupled system when any of the vehicle frequencies match the bridge's frequency. But in general, the moving mass modelling approach seems to give smaller MAC values. Nevertheless, the reduction in MAC values can be regarded as insignificant. The results indicate that there is indeed a small change in the shape of the mode but this is effectively negligible.

5. Conclusion

This study has explored the changes in modal properties of a coupled vehicle-bridge system. In particular, the analysis focuses on the changes in the fundamental mode of railway bridges in general due to the passage of a common high-speed train locomotive. The results clearly show that the frequency shift can be either positive or negative and that the magnitude of this shift can be important. The comparison of the coupled model results to the moving mass scenario indicates that the vehicle cannot be simply considered as an additional mass on the bridge. In other words, not only the mass ratio is important, but also the vehicle-to-bridge frequency ratios are important when evaluating the frequency shift. Furthermore, this study evaluated the effects of the vehicle and bridge coupling on the shape of the mode of vibration. Even though the shape of the mode does change with the vehicle's position, it was found that these changes are insignificant and can be neglected. In summary, the vehicle-bridge interaction of railway bridges should be regarded as non-stationary due to the possibility of significant frequency shifts. Therefore, any analysis of signals during the vehicle passage should use tools that appropriately account for the time-varying nature of the response.

The results from this study cannot be generalized to any train and bridge configuration. This study investigated only one particular vehicle but, on the other hand, attempted to cover a wide range of bridges by using typical mechanical properties. Nevertheless, because of the complexity of the problem, larger frequency shifts and even significant changes in the shape of the modes can be expected for other train and bridge configurations. Additional numerical investigations and field experiments are required to gain a complete understanding of the nonstationary nature of VBI.

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