Calibration of Numerical Models of Railway Vehicles Based on Dynamic Tests

Diogo Ribeiro, Rui Calçada, and Pedro Montenegro

Abstract The dynamic analysis of the vehicle-bridge system is a complex interaction problem which typically involves the development of advanced finite element (FE) models of the vehicles, track and bridge subsystems and their interfaces. The experimental calibration of the FE models of these subsystems is usually performed based on modal parameters, namely, the natural frequencies and mode shapes. This article describes the experimental calibration of 3D FE numerical models of railway vehicles, one for passenger and one for freight, based on modal parameters. The BBN vehicle is a tourist class vehicle that belongs to Alfa Pendular train and the vehicle Kbs is a freight railway wagon for transport of timber, both operating in the Portuguese railway network. The 3D FE numerical model of the vehicles consider the flexibility of the carbody/base floor and includes the suspensions and axles. The dynamic tests of the vehicles allowed the determination of the frequencies and modal configurations of several vibration modes involving rigid body and structural movements. The calibration was successfully performed through an iterative method based on a genetic algorithm, which demonstrated the stability of a significant number of numerical parameters estimates, and above all, a very good agreement between experimental and numerical modal parameters.

Keywords Railways vehicles · FE model · Dynamic tests · Calibration · Genetic algorithm

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1 Introduction

In recent years the railway traffic in Europe is rapidly developing, and an increasing number of railway operators are planning to increase the axle loads and speed of trains, in order to make the passenger and freight traffic on rails more competitive.

When interacting with the railway track, moving trains induce vibrations that can affect the structural stability of the infrastructure and rolling stock components. In case of bridges, this can lead to damages and can affect its performance and durability.

The analysis of the dynamic behaviour of the train-bridge system can be carried out through different methodologies, mainly analytical and numerical [1, 2]. For complex problems the use of numerical methodologies including the train-bridge interaction are common, and therefore there is the need of modeling the train, and inherently the knowledge of its geometrical and mechanical parameters is required [3–7].

Currently few works have been published about the experimental calibration of numerical models of train vehicles. From the works identified it should be highlighted the studies performed by Ribeiro et al. [3] and Jung-Seok et al. [8], for passenger vehicles, and Harak et al. [9] and Ahmadian [10] for freight vehicles.

In this paper some results of a calibration of the numerical model of a passenger vehicle and a freight wagon based on modal parameters are presented. The 3D FE numerical model of both vehicles considers the flexibility of the carbody and includes the suspensions and axles. The modal parameters of the vehicles were determined based on dedicated dynamic tests performed in rest position. The calibration methodology involved a sensitivity analysis and an optimization based on a genetic algorithm. The results revealed a very good correlation between experimental and numerical after updating modal parameters.

2 Calibration Methodology

The computational implementation of an iterative method based on a genetic algorithm involved the use of three software packages: Ansys, Matlab and OptiSlang [11, 12]. Figure 1 shows a flowchart that illustrates the computational implementation of the method, indicating the softwares involved in the different phases.

In ANSYS environment the FE numerical model is developed based on a set of initial parameter values $\theta_1, \theta_2, \ldots, \theta_k$, where k is the number of individuals in each generation. The pre-selection of the calibration parameters is performed based on global sensitivity analysis. The sets of parameter values of generation 1 are randomly generated in OptiSlang software by applying the Latin Hypercube method. The modal analysis is performed as well as the export of the numerical modal parameters.

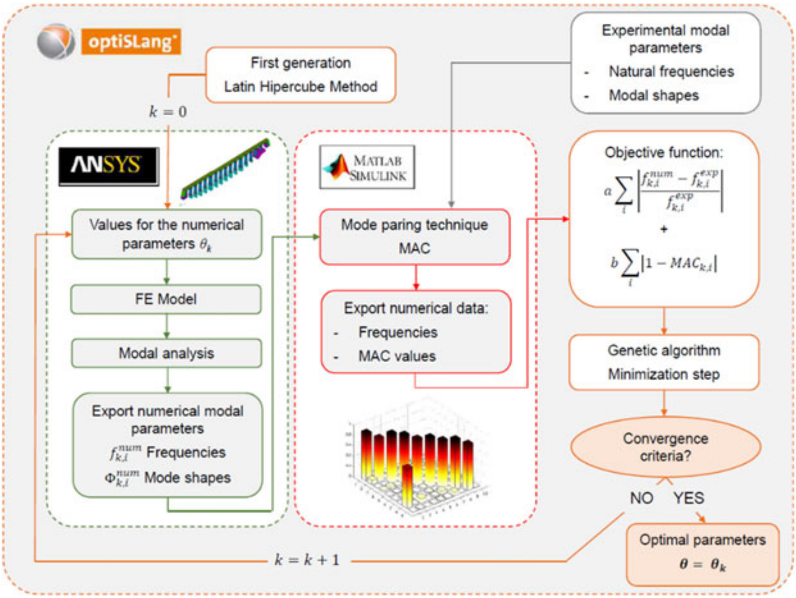


Fig. 1 Flowchart of the calibration methodology

In Matlab software, based on the experimental modal information, the mode pairing between numerical and experimental modes based on MAC (Modal Assurance Criterion) parameter is performed. The values of the natural frequencies and the corresponding MAC values are exported in text format.

Finally, the OptiSlang software, based on an objective function and on the application of an optimization technique supported by a genetic algorithm, estimates a new set of parameters focused on the minimization of the objective function residuals. The objective function includes two terms, one relative to the residuals of the frequencies of vibration and other related to the residuals of modal configurations. This procedure is repeated iteratively until the maximum number of generations is reached.

3 Passenger Railway Vehicle

3.1 Description and Numerical Model

The BBN vehicle, Fig. 2a, is a tourist class vehicle of the Alfa Pendular train [3]. The total mass of the vehicle, including the bogies, achieve 52.2 t, in running order, and 55.0 t, in normal load conditions. The length of the vehicle is 25.9 m, the distance between the bogie pivots of the vehicle equals 19.0 m and the wheelbase


a) b)

Fig. 2 Passenger railway vehicle BBN: a) perspective view, b) FE numerical model

equals 2.7 m. The carbody is formed by a tubular structure made of aluminum alloy consisting of 20 alveolar extruded panels longitudinally welded.

The modal analysis of the BBN vehicle was performed using a three-dimensional finite element model developed in the ANSYS software. The use of a finite element formulation allows considering the influence of the deformability of the carbody, bogies and axles. Figure 2b presents a perspective of the numerical model.

The carbody was modeled by shell finite elements while the bogies were modeled by beam finite elements, with the exception of the suspensions, the connecting rods and the tilting system which were modeled by spring-damper assemblies. Additionally, the passenger-seat system was modeled, in a simplified manner, by a 1-DOF system composed of a mass over a spring-damper assembly.

3.2 Experimental Tests

The dynamic test of the carbody was conducted at EMEF facilities, in Porto, in order to identify the natural frequencies and vibration modes of the carbody involving rigid body and structural movements. The carbody was instrumented with 14 piezoelectric accelerometers (A0 to A13), PCB's model 393A03, in the vertical direction, and placed on the base of the carbody next to the intersection with the side walls, according to the scheme of Fig. 3a. The accelerometers located within the area of the seats were positioned by means of metallic angles fixed to the structure of the seat with magnetic disks. Attending to the high damping of the vibration modes of the vehicle, it was necessary to use an external excitation, through people jumping, in order to increase the vibration levels. The modal identification was carried out through the application of the stochastic subspace identification method based on the time series of acceleration (SSI-DATA). Figure 3b shows the stabilization diagrams that were estimated based on state models of order between 1 and 160. The alignments highlighted in the figure correspond to the five vibration modes of the carbody with natural frequencies ranging from 1.01 Hz to 12.26 Hz. These modes are associated with rigid body (modes 1 to 3), torsion (mode 4) and bending (mode 5) movements of the carbody.

3.3 Calibration

The calibration process based on a genetic algorithm involved 7 design variables, particularly, the stiffness of secondary suspension—front (K_{S1}), stiffness of secondary suspension—rear (K_{S2}), stiffness of base panel (RMI_b), stiffness of side walls panel (RMI_p), additional mass—base (ΔM_b), additional mass—side walls (ΔM_p) and additional mass—cover (ΔM_c). Ten modal responses were considered, in particular 5 natural frequencies and 5 MAC parameters. Figure 4 presents the ratios of the values of four parameters of the model, in relation to the predefined limits of variation, as well as the optimized values, for four independent optimization runs (GC1 to GC4). A 0% ratio means that the parameter coincides with the lower limit. A ratio of 100% means that it coincides with the upper limit. The analyzed parameters present a very good stability with variations below 10%.

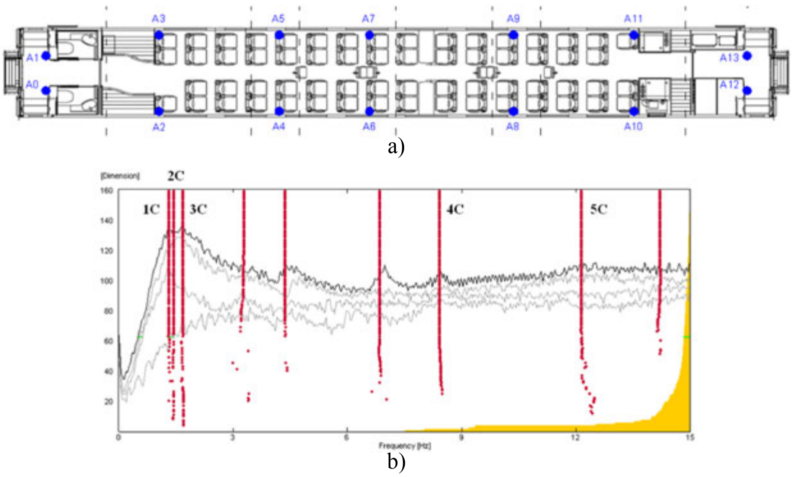


Fig. 3 Dynamic test: a) experimental setup (plan view), b) SSI-DATA: stabilization diagrams

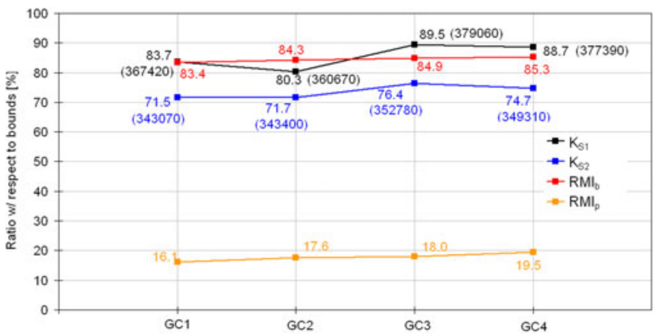


Fig. 4 Values of four numerical parameters for optimization cases GC1 to GC4

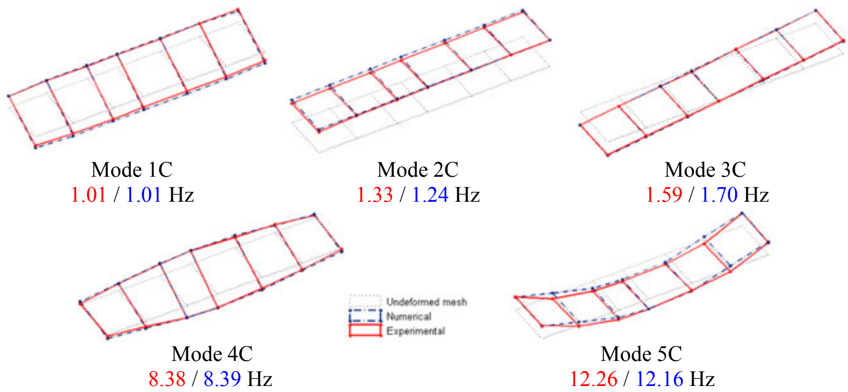


Fig. 5 Comparison between experimental (red) and numerical after updating (blue) modal parameters of the passenger vehicle

Figure 5 shows the comparison between experimental and numerical after updating modal parameters. The average error of the frequencies decreased from 20.3% before calibration to 2.9% after calibration. In turn, the average value of the MAC parameter increased from 0.927 before calibration to 0.937 after calibration.

4 Freight Railway Wagon

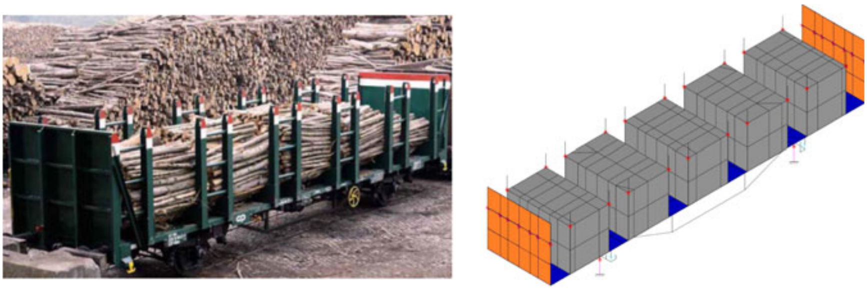
4.1 Description and Numerical Model

The vehicle Kbs, Fig. 6a, is a freight railway wagon for transport of timber (usually eucalyptus type) that operates in the Portuguese railway network. The wagon has a length of 12.8 m with a width of 2.7 m and the axles spacing is equal to 8 m. The wagon's structure is formed by a grid of steel beams and suspensions of the type UIC standard. The maximum axle load is equal to 23.7 t and its average tare weight is 16.3 t.

The 3D FE model of the wagon Kbs developed in ANSYS software is presented in Fig. 6b. The model includes beam elements for simulating the grid of girders of the base floor and lateral shafts, and shell elements, for simulating the base platform and extremities plates of the vehicle. The axles were modelled using rigid bars and are connected to the base platform by spring elements simulating the primary suspension system. The wheel-rail contact was represented by Hertzian spring element. The mass of on-board equipment was simulated based on mass elements. The towed load was also represented by means solid elements.

4.2 Dynamic Test

The dynamic test of the freight car allows the identification of the natural frequencies and modes of vibration of the freight car involving rigid body and structural movements. The test was performed in two different configurations, loaded and unloaded, in order to consider, the possible non-linear behaviour of the suspensions. The freight car was instrumented with 16 piezoelectric accelerometers, PCB's model 393B12. The response was evaluated in terms of accelerations in transversal (y) and vertical (z) directions in only one setup (Fig. 7a). The accelerometers are attached to the base platform using metallic plates fixed to the vehicle with magnetic disks. The identification of the vehicle modal parameters was carried out through the application of Enhanced Frequency Domain Decomposition (EFDD) method (Fig. 7b). Five modes of vibration with natural frequencies ranging from 5.10 Hz to 8.11 Hz were identified. These modes are associated with bending (modes 1 and 2), rigid body (modes 3 and 4) and torsional (mode 5) movements of the vehicle's platform.



a) b)

Fig. 6 Freight railway wagon Kbs: a) perspective view, b) FE numerical model

4.3 Calibration

The calibration process based on a genetic algorithm involved 7 design variables, particularly, the vertical stiffness of the suspensions (K_1 to K_4), modulus of elasticity of steel (E_s) and additional masses on the lateral shafts (M_{lat}) and extremity plates (M_{ext}). Five modal responses were considered, particularly 5 natural frequencies and 5 MAC parameters. Figure 8 presents the ratios of the values of each parameter of the model, in relation to the predefined limits of variation, as well as the optimized values, for four independent optimization runs (GA1 to GA4). The analyzed parameters present a good stability with variations below 10%, except for the modulus of elasticity of steel. Precisely, this is one of the parameters that the sensitivity analysis has shown to have a smaller influence over the numerical responses.

Figure 9 shows the comparison between experimental and numerical after updating modal parameters. The average error of the frequencies decreased from 8.5% before calibration to 3.2% after calibration. In turn, the average value of the MAC parameter increased from 0.911 before calibration to 0.950 after calibration.

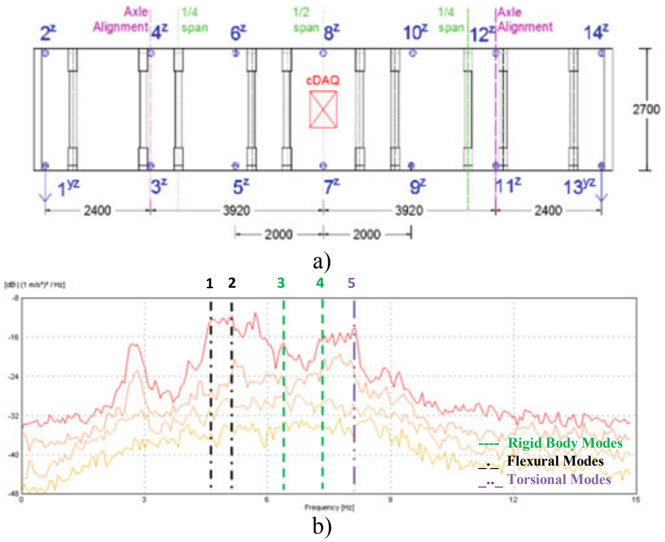


Fig. 7 Dynamic test: a) experimental setup (plan view), b) EFDD method: average and normalized singular values of the spectral matrix

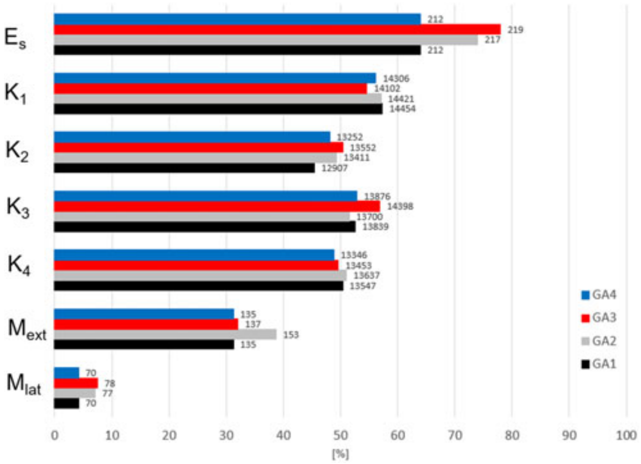


Fig. 8 Values of numerical parameters for optimization cases GA1 to GA4

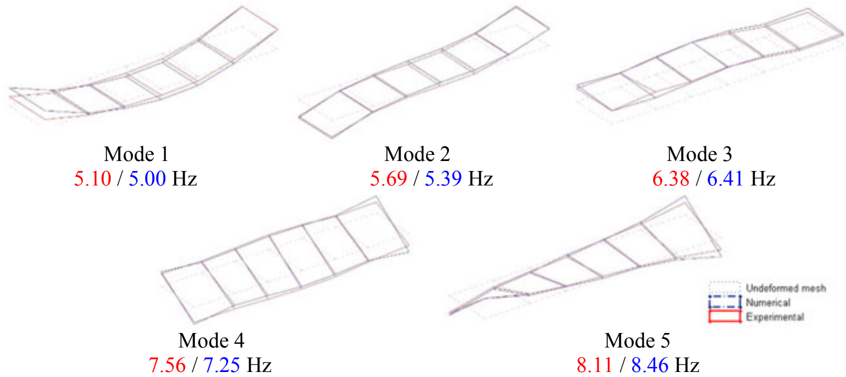


Fig. 9 Comparison between experimental (red) and numerical after updating (blue) modal parameters of the freight vehicle

5 Conclusions

This paper described the experimental calibration of the numerical models of a passenger and freight vehicles based on modal parameters. The dynamic tests allowed the identification of frequencies and modal configurations of several vibration modes involving rigid body and structural movements. The results show important differences in the dynamic properties of the passenger vehicles in comparison to the freight wagon, particular in what concerns the order of the rigid body and flexural modes of vibration.

The calibration of the numerical model was conducted through an iterative methodology based a genetic algorithm. The calibration process was successful which is demonstrated by the stability and consistence of the numerical parameters estimates and by the very good agreement between experimental and numerical modal parameters. In future studies, the calibrated models of the railway vehicles will be used for the dynamic analysis of the train-tack-bridge system in order to evaluate the integrity and safety of the railway infrastructures.

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