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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF THE DYNAMICS OF THE FLOATING FLOOR AND PASSENGER SEATS OF A RAILWAY VEHICLE

Ivano La Paglia, Qianqian Li, Francesco Ripamonti *and* Roberto Corradi
Politecnico di Milano, Department of Mechanical Engineering, Milan, Italy
email: qianqian.li@polimi.it

In recent years, passenger comfort has gained greater attention from service providers and rail vehicle manufactures. Carbody vibrations perceived by the passengers mainly contribute in the low frequency range (i.e., below 50 Hz) and originate from the geometric defects of both wheel and track. The vibrations are then transmitted to the passengers through the suspension stages, and finally reach the carbody, the floor, and the seats. For an accurate estimation of the transmitted vibration, which is particularly important at the design stage, the dynamic behaviour of all the vehicle subsystems should be thoroughly studied and correctly modelled. Furthermore, the coupling effects of the assembled system should be appropriately accounted for. In the current work, the coupled dynamics of two vehicle subsystems, namely the floating floor and the passenger seat, is investigated. Laboratory tests are carried out to firstly determine the modal parameters and frequency response of the floating floor system. Then a test bench of the coupled floor-seat assembly is set up. The results demonstrate a strong effect of the floor-seat coupling on the assembly's frequency response. In parallel, FE models are developed based on the experimental results, and a satisfactory agreement between the simulated and the identified vibration modes is reached. Hence, the developed models are believed to be useful tools for the estimation of the vibration levels perceived by the passengers, and for the assessment of ride comfort. Moreover, the proposed methodology relying on both labora-tory tests and numerical models proves to be a promising approach towards the design and optimization of rail vehicle subsystems.

Keywords: railway vehicle, ride comfort, floating floor, passenger seat, experimental modal analysis.

1. Introduction

For railway vehicles the wheel/rail contact along the vertical plane relies on a geometric coupling, so that the rail roughness excites the vehicle vertical dynamics. As a consequence, the vibrations are transmitted through the suspension stages to the carbody, which typically results in the excitation of the flexible carbody vibration modes up to 50 Hz [1]. In their turns, given the dynamic coupling between the carbody structure and the floor, also the vibration modes of the seats can be excited, with consequences on the passenger comfort. Most of the related works focus on the effect of the suspension stages and carbody [2, 3], while much less attention has been paid to the floor and the seats. However, for an accurate estimation of the vibration perceived by the passengers, also the floor and seats should be thoroughly studied and correctly modelled [4].

In this respect, this paper presents an investigation of the dynamics of the floating floor and passenger seats of a railway vehicle. A full-scale laboratory test bench of the floating floor is realised to identify its dynamic properties (frequency response and modal parameters). The test bench allows the installation of the seats through the actual connections, and the dynamic response of the floor-seat coupled system is also investigated. In parallel, detailed FE models of the floor and seat subsystems are developed. Special attention is paid to the values assigned to the model parameters. Experimentally characterised material properties of the modelled components are used, and a satisfactory agreement between the experimental and numerical results is reached.

2. Experimental investigation

The laboratory tests are performed at the Department of Mechanical Engineering of Politecnico di Milano. In the current section, the test bench containing only the floor of a real vehicle is firstly described and the results of the experimental tests are presented; secondly, the floor-seat coupled system is presented together with its frequency response.

The reference vehicle is equipped with a floating floor system that is connected to the carbody through isolators. For a single coach, the system contains 5 identical modules repeated in the longitudinal direction. The test bench, shown in Fig. 1, reproduces one module of the reference floor in full scale. It consists of floor panels, extruded aluminium profiles and isolators (between the previous components and the ground, not visible in the figure). The dimensions of the test bench are 2.8 m in width (lateral direction) and 4 m in length (longitudinal direction).

Figure 1: floating floor full-scale test bench.

An Experimental Modal Analysis (EMA) test campaign was carried out. Given the symmetry of the system, a portion of one quarter of the floor is tested by adopting a roving hammer procedure: accelerometers were positioned along to the perimeter of the portion under test, and impact dynamic loads are applied by a dynamometric hammer. A regular grid of 10 cm is considered to carry out the test.

The experimental Frequency Response Functions (FRFs) relating the input force and the measured accelerations are evaluated by means of the H1 estimator, considering time averaging to reduce the noise effect. The modal parameters are then identified, by making use a software specifically developed to this task (described in [5]) that provides natural frequencies, nondimensional damping ratios and modes of the system. Some examples of the results of the EMA campaign are reported in Fig. 2, in terms of natural frequencies and associated vibration modes (shown only for the floor section considered during the tests).

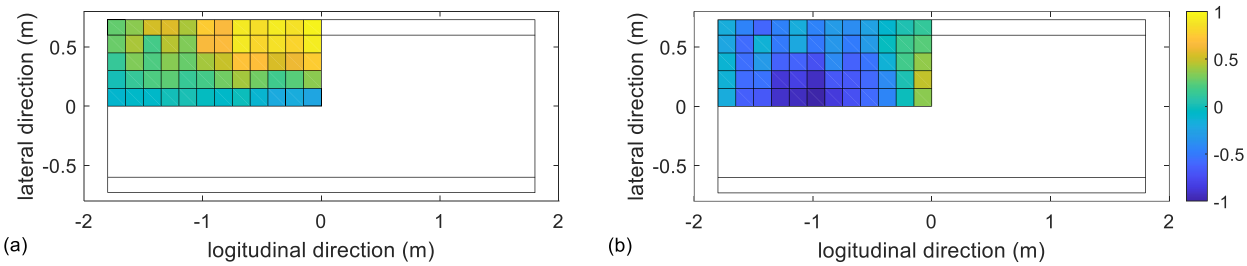


Figure 2: example of experimentally identified natural modes, whose natural frequencies are (a) 51.1 Hz; (b) 53.7 Hz.

The floor-seat coupled test bench is developed by installing a seat on the floor through the same connections adopted on the vehicle, that is shown in Fig. 3. Tests are performed for two purposes. At first, accelerometers are attached on the floor to verify the effect of the seat on the dynamic response of the coupled system. To excite the system, an electrodynamic shaker (as visible in Fig. 4, nearby the seat) is used, that follows a slow sine sweep input signal in the 10-60 Hz frequency range.

Figure 3: test bench including a pair of a seats.

Figure 4 shows the FRFs measured on the floor without (Fig. 4a) and with the seat installed (Fig. 4b) for comparison. A strong coupling between the floor and seat subsystem can be observed. For the same measurement position, the peaks of the FRF magnitude shift significantly towards lower frequencies. This preliminary results confirm the need to experimentally characterize the dynamic response of the floor-seat coupled system. To this aim, more tests are carried out, that allow identifying the vibration modes of the seat installed on the test bench. The results are presented in the following section, being compared to the those numerically predicted by means of the FE model.

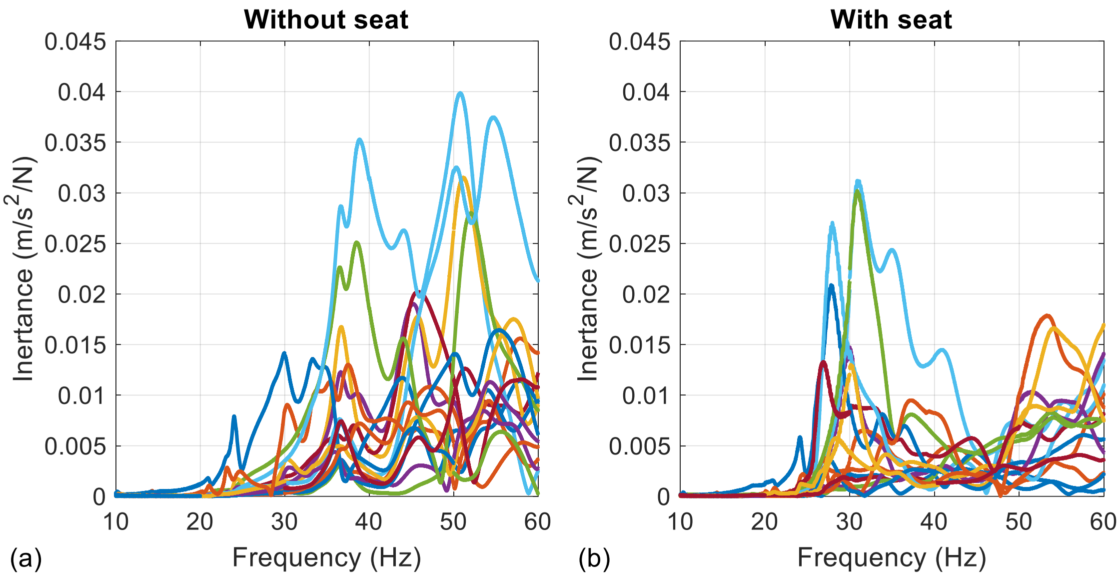


Figure 4: FRFs (inertances) measured on the floor perimeter (a) without and (b) with a pair of seats installed on the test bench.

3. Numerical investigation

FE models of the floating floor alone and of the floor-seat coupled system were developed according to the corresponding test bench layouts. In particular, the model containing only the floor is firstly developed. Then the model of the coupled system is realised by adding a seat model. Modal analyses are performed for both models and the results are compared to the ones experimentally identified.

The model of the floating floor is shown in Fig. 5.

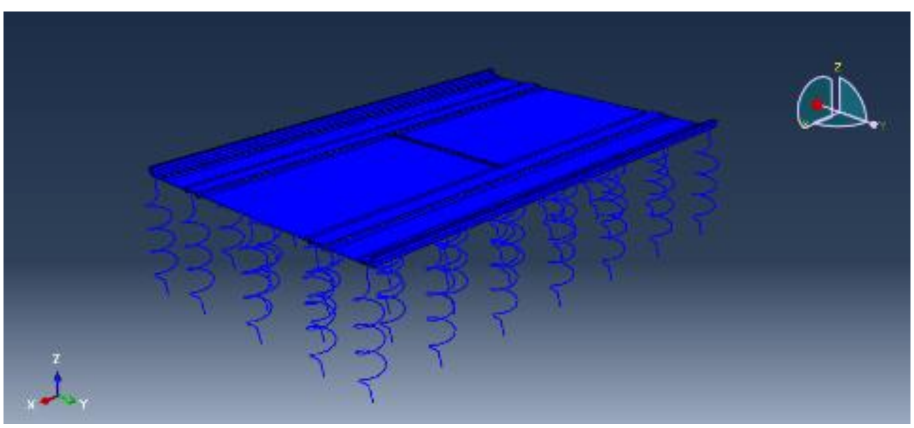


Figure 5: FE model of the floating floor.

The model layout is the same to that of the test bench (Fig. 1). Shell elements are used to model the floor panels and the aluminium beams, while the isolators are modelled as spring elements connecting the panel/beam components to the ground. Different from the aluminium beams, the floor panels are made of multiple materials, and have a layered structure. Therefore, it is necessary to choose an appropriate modelling strategy and to assign proper values to the material parameters. To this aim, an ad-hoc test campaign to characterise the frequency response of a single panel (in free conditions) was performed, and the natural frequencies and mode shapes are identified through an EMA. Based on the obtained results, it is verified that it is possible to model a single panel as an equivalent homogenous isotropic thin plate made out of a single material, and an equivalent Young's modulus is derived to match the EMA results. The same strategy and parameter values are subsequently adopted in the FE model presented in Fig. 5. In the same test campaign, the dynamic stiffness of the isolators was also characterised. The mode shapes computed by the FE model are presented in Fig. 6.

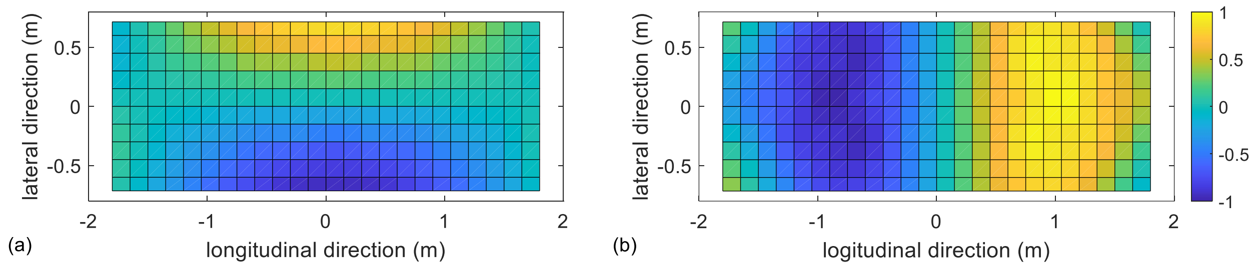


Figure 6: example of mode shapes computed by the FE model, whose natural frequencies are (a) 49.3 Hz; (b) 54 Hz.

The presented modes have highly similar shapes to those previously shown in Fig. 2, as well as the natural frequencies. The Modal Assurance Criterion (MAC) [6] is computed for the experimental and FEM modes as

$$\mathrm{MAC} = \frac{\left|\underline{\boldsymbol{\phi}}_{\mathrm{EXP}}^{\boldsymbol{T}}\underline{\boldsymbol{\phi}}_{\mathrm{FEM}}\right|^{2}}{\left(\underline{\boldsymbol{\phi}}_{\mathrm{EXP}}^{\boldsymbol{T}}\underline{\boldsymbol{\phi}}_{\mathrm{EXP}}\right)\left(\underline{\boldsymbol{\phi}}_{\mathrm{FEM}}^{\boldsymbol{T}}\underline{\boldsymbol{\phi}}_{\mathrm{FEM}}\right)} \tag{1}$$

where $\underline{\phi}_{\mathrm{EXP}}$ is a vector containing the experimentally identified mode shape values; $\underline{\phi}_{\mathrm{FEM}}$ is a vector containing the mode shape values computed by the FE model. The FE mode shape values are evaluated where the experimental ones are identified, and only a quarter of the model is taken into account. The MAC is 0.89 and 0.72 for the modes presented in Fig. 6a and Fig. 6b respectively. For most of the other modes in the frequency range of interest, the MAC values are larger than 0.5, which proves the capability of the model to correctly predict the dynamic properties of the floating floor.

The floor-seat coupled model is presented in Fig. 7.

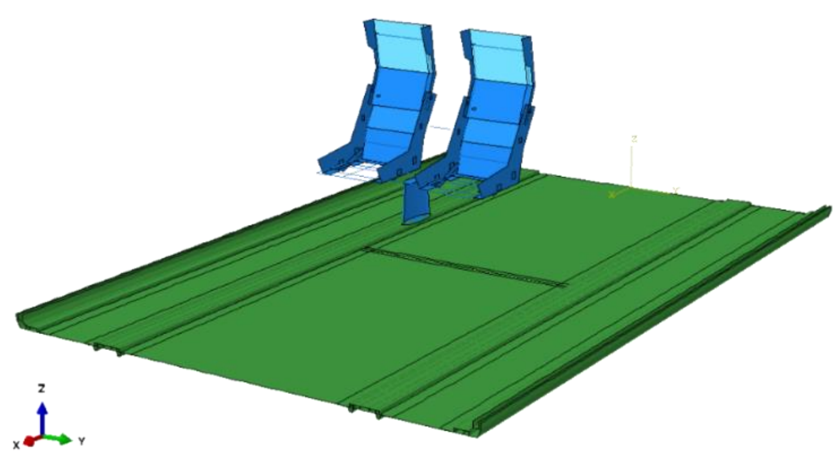
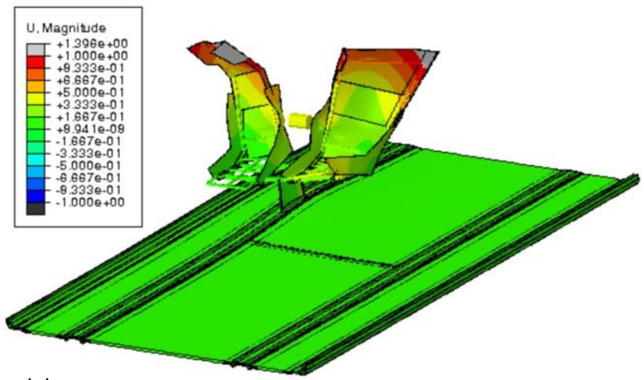


Figure 7: FE model of the floor-seat coupled system.

The seat model (blue components) is coupled to the floor model in the same configuration of the test bench (Fig. 3). Only the metallic components (no cushions) are accounted for. The shell feature is used for the backrest and the seat support while the beam feature is used for the seat pan. The coupled model is then adopted for modal analysis. An example of the computed mode shape is presented in Fig. 8a, and the corresponding mode shape identified from experimental results is presented in Fig. 8b.



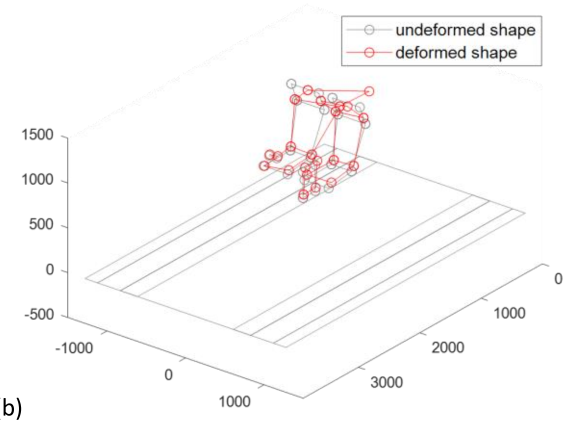


Figure 8: example of mode shapes (a) computed by the FE model and (b) identified from experimental results, whose natural frequencies are 22.3 and 22.7 Hz respectively.

The natural frequency predicted by the FE model is 22.3 Hz. The backrests vibrate more than the other components with a for-and-aft motion. Furthermore, the seat support vibrates in the vertical direction, indicating a strong coupling effect between the seat and the floor. The experimentally identified natural frequency is 22.7 Hz which is very close to the one numerically predicted. In addition, the identified mode shape suggests an obvious vibration of the seat support and the mode shape of the backrests are highly similar to the FE result. Hence, it is deemed that a good agreement is reached between the laboratory experiment results and the FE model.

4. Conclusions

The results of an experimental and numerical investigation of the floating floor and passenger seats of a railway vehicle is presented. A full-scale laboratory test bench of the floating floor is firstly realised and then the floor-seat coupled test bench is realised by installing a pair of seats on the floor. For both test benches the modal parameters are identified from the experimental frequency response. Detailed FE models are developed according to the corresponding test bench layouts and particular attention is paid to the model parameter values used. The mode shapes are computed and compared to the experimentally identified ones. A satisfactory agreement between the experimental and numerical results is reached.

The developed models are deemed as useful tools for the estimation of the vibration levels perceived by the passengers and can be combined with a complete FE vehicle model for the assessment of ride comfort. Moreover, the proposed methodology relying on both laboratory tests and numerical models is proved to be a promising approach towards the design and optimization of the floor-seat coupled system, also considering the seated passengers.

REFERENCES

1 Cheli, F., Corradi, R. On rail vehicle vibrations induced by track unevenness: Analysis of the excitation mechanism, *Journal of Sound and Vibration*, **330** (15), 3744–3765, (2011).

2 La Paglia, I., Rapino, L., Ripamonti, F., Corradi, R. A methodology for including suspension dynamics in a simple context of rail vehicle simulations, *in: WCCM-APCOM2022*. https://www.scipedia.com/public/Paglia_et_al_2022a, (2022).

3 Fu, B., Liu, B., Di Gialleonardo, E., Bruni, S. Semi-active control of primary suspensions to improve ride quality in a high-speed railway vehicle, *Vehicle System dynamics*, (2022).

4 Corbridge, C., Griffin, M.J., Harborough, P.R. Seat dynamics and passenger comfort, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **203** (1), 57–64, (1989).

5 Tania, S., La Paglia, I., Ripamonti, F., Corradi, R., Baro, S. A Theoretical Model for Investigating the Structural Dynamics of a Rolling Tyre, *Journal of Computational and Nonlinear Dynamics*, **17** (7), (2022).

6 Pastor, M., Binda, M., Harčarik, T. Modal assurance criterion, *Procedia Engineering*, **48**, 543–548 (2012).