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Railways modelling toolbox: Open source finite element models for rail pads and track optimisation.

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Abstract

In Europe, with the growing population and the need of an environmentally friendly way of transportation, the traffic of train increase and therefore its impact on the society. Research on reducing those impacts are studied worldwide from decades. Our project is aligned with this vision and aim to develop a new rail pad. This pad has to reduce the noise emissions of the track and the ballast solicitations, thanks to its geometry and materials. To design this rail pad, 3D finite element models have been developed using the open source software Code_ASTER [1] and will be published as an open-source modelling toolbox.
The toolbox is composed of five models:

1. A three sleepers model in the frequency domain.
2. A pad level model.
3. A semi-analytic model.
4. A three sleepers model in the time domain.
5. A large scale FE model of the track using dynamic substructuring.

Those models are experimentally validated and aim to be as close as possible to the reality. They have been used successfully to develop a new rail pad. Compared to the current EVA pads used in Switzerland the new pad reduces the emission of >1 dB, while being significantly softer than those EVA pads to provide better ballast protection.

Keywords: Railpad, Modelling, finite elements, Acoustic.

1 Introduction

Railway is a common way of transportation in Europe. The noise emitted by trains can be a great discomfort; therefore, research on reducing the noise emission is on-going worldwide. Our project aim at developing a novel rail pad that both reduce the noise emissions of the track and reduce the ballast solicitations by using an optimized frequency dependent damping and stiffness response. Therefore, we had to study the impact of the rail pads on the track dynamic, especially the influence of the pads on the noise emission, the vibrations and loads transmission in the ballast.

Noise emissions are known to come from the wheel and track interactions [2]. Remington started to model these interactions. Its work has been further developed by Thompson et al. and many others which in the end led to the development of the TWINS model, "Track Wheel Interaction Noise Software" [3]. The TWINS model is used to evaluate the noise emission of given wheel and track profile. Despite its proven performance, the TWINS model does not represent the rail pads in great details as they are replaced by an equivalent stiffness and a hysteretic loss factor [3]. As 3D effects, such as vertical, lateral displacements profiles in the contact area, are important in the optimization of a rail pad, our project required a full 3D model to study and understand the in-situ loading of the pad.

A full 3D finite element (FE) model has been developed previously [4] and [5] to estimate the noise emissions of a track. This very detailed model has been validated on measurements and take into account the influence of the whole track, especially the ballast as well as complex acoustic radiation but the pads were replaced by an equivalent spring and dashpot.

In this project, a series of 3D FE models, simulation tools and graphical user interfaces have been developed using the open source software “Code-Aster” [1] in order to evaluate the response of a rail track as a function of the design and materials of the rail pads, under sleeper pads and ballast properties. Together, these developments form an open-source simulation toolbox to predict: the static, dynamic stiffness and damping of a rail pad (including rotation/moments), the static and transient response of a rail track under axle loading, the harmonic response (vibration and acoustic radiation) and TDR of a track based on the properties of its components.

2 Methods

The models developed during this project are based on a digital twin approach, where the modelling parameters are validated interactively based on an equivalent experimental set-up.

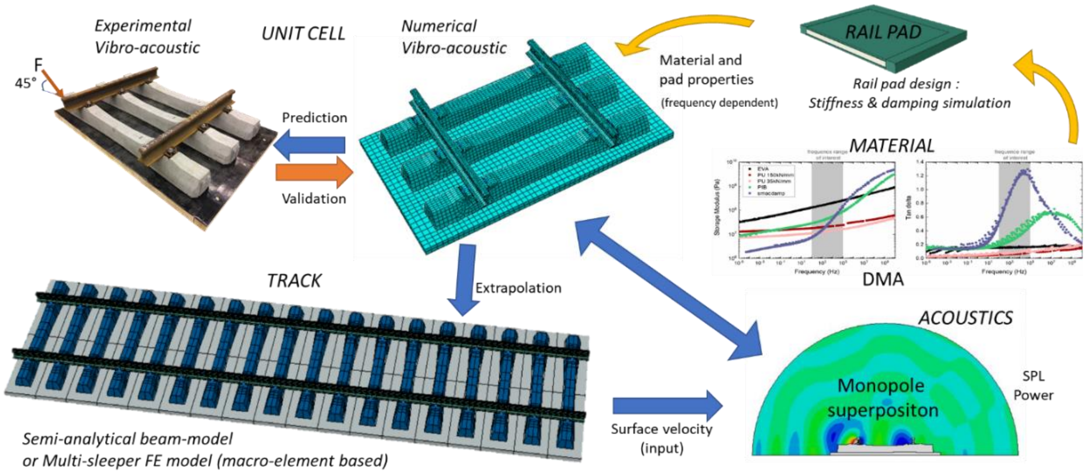


Figure 1 : modelling workflow and methodology.

The set-up used to validate the modelling is composed of three sleepers (type B91), two rails (type E61 of 1.8 m each), six pads and six set of clamping systems (Vossloh WK14). To ensure good repeatability, the ballast is replaced by wooden beams (10cm thick, spruce) with a comparable vertical stiffness. As the goal of this setup is mostly to compare different systems and validate the model, this equivalent ballast is considered sufficiently representative. This set-up is instrumented to record rail and sleeper vibrations and intensimetric acoustic measurements while the excitation is provided by an electrodynamic shaker.

Based on this set-up, a harmonic FE model in the frequency domain has been developed. The model represents the three sleepers with or without under sleeper pads (USP), the two rails, the rail pads and an equivalent ballast layer. All the parts are considered tied together. The material properties of the components are frequency dependant with hysteretic damping. As this model represents the small-displacement vibration response around the preloaded state of the track, the clamping system has been neglected as it is much more compliant than the pads. This digital twin model, once identified on the experimental data, provides a validated set of properties to upscale the simulation to a longer track using dynamic substructuring.

In parallel, a semi-analytical model, based on an expansion of the Thompson model, has been developed. This model allows to simulate an “infinite” track (200+ sleepers) in a very short time to compute the radiated acoustic pressure, the FRF and TDR (Track Decay Rate) of the system.

The semi-analytical model needs pad properties as input. Therefore, an FE based tool has been developed to simulate the pad stiffness and damping based on the pad geometry and the visco-elastic properties of its constituents. This model is validated on compression experiments and allow to compute the stiffness of a given pad in various directions (compression, shear, torsion).

To estimate the ballast loading during a pass-by and quantify its protection, a time domain model of a short track has been developed to simulate the response to an impulse loading corresponding to a bogie. The ballast protection is evaluated based on the mean stress below the sleeper at the peak force.

3 Results

Erreur ! Source du renvoi introuvable. shows a comparison of FRF (Frequency Response Function) between the model and experiment. The model captures well the amplitudes of the resonances, but a frequency shift is observed. It is mainly due the rail linear hexahedral mesh. Using quadratic elements would match the eigenfrequencies, but the increased calculation cost was considered not worth the effort as the main results of interest are the peak vibration amplitudes and the radiated acoustic power.

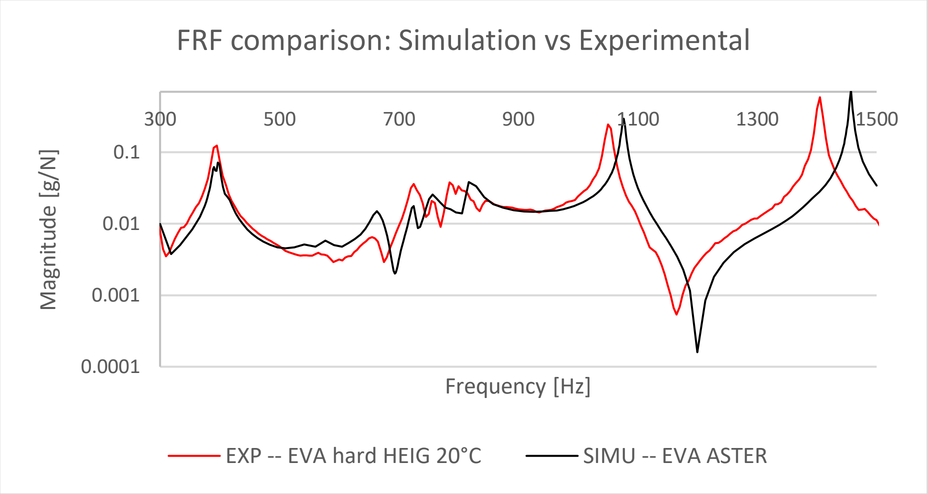


Figure 2 : Comparison of the experimental and simulated FRF.

The comparison of the vibration operational mode shapes between the model and experiment also shows a good match, Figure 3 a&b.

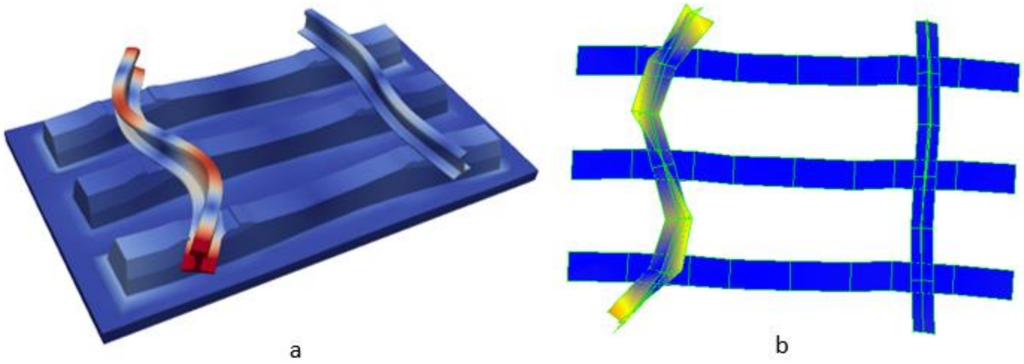


Figure 3 : Vibration pattern a) model at 396 Hz, b) measure at 385 Hz.

The three sleeper model is also used to estimate the radiated acoustic power by considering each finite element surface as an acoustic point source. Figure 4 shows the comparison of the acoustic power spectrum of the model and experiment. The peak and overall levels are well captured, but the frequency shift is still present as discussed previously.

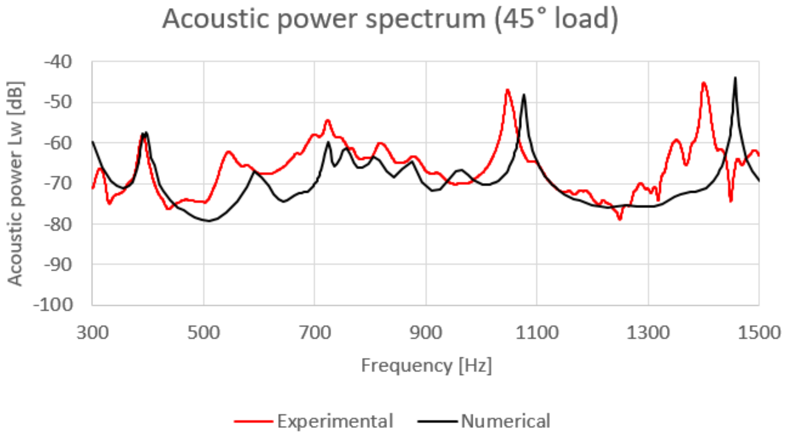
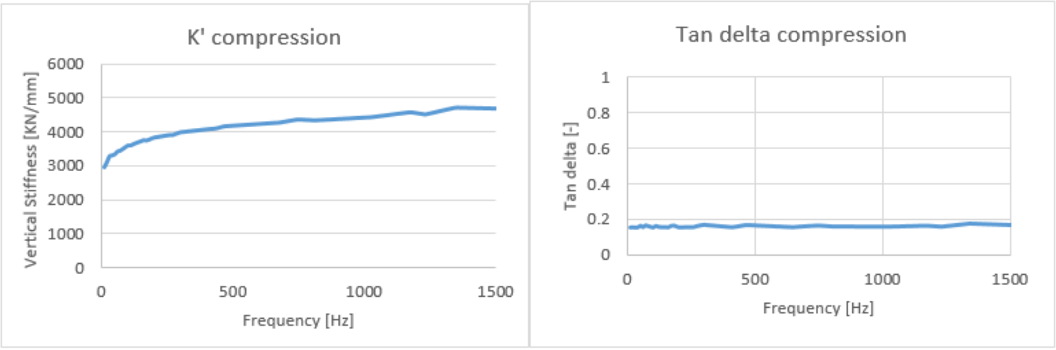


Figure 4 : Acoustic power emission, comparison between the model and the experimental data.

The toolbox provides a model to compute the frequency dependent complex stiffness & damping of rail pads in various directions based on its design and constituents. The Figure 5a&b show an example of the obtained vertical stiffness and tan(delta) of a plain EVA pad.



a b

Figure 5 : EVA pad a) Vertical stiffness (real part), b) Tan(delta).

Those data can be then integrated in the semi-analytical track model and compute, for example, the TDR (track decay rate). An example of TDR calculated with this model in presented in the Figure 6.

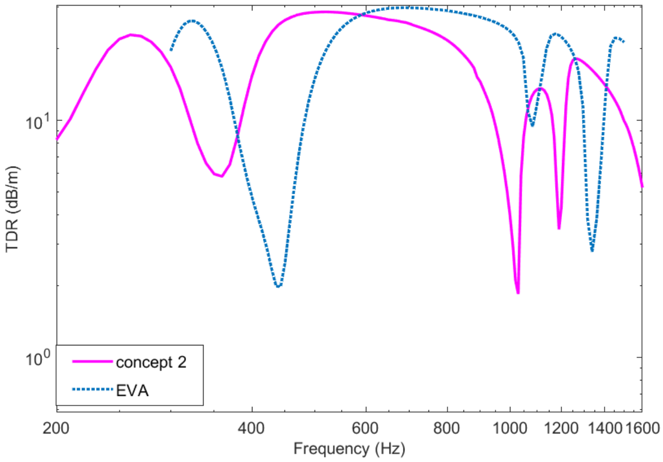


Figure 6 : TDR for two different pads from the semi-analytical model.

The last model, the impulse model, can be used to estimate the load in the ballast during a pass-by. During our project, we did use those results to calculate a “ballast index” which relates represents the relative number of loading cycles to achieve a critical ballast settlement based on Thom 2 model [6]. If this number is higher than one, then the ballast will last longer than our reference.

An acoustic index that represents the inverse ratio of noise radiation level with respect to the reference (plain EVA hard pad) is also computed based on the semi analytical rail track model.

4 Conclusions and Contributions

In the end, the two performance indexes computed by the toolbox can be used as a guide to optimize railway components such as the rail pads. When represented in a

Pareto diagram, Figure 7, it is possible to quantify the trade-off between ballast protection and noise reduction as well as identify the best pad for a given application. For example, the red triangle in Figure 7 shows the reference pad while the best prototypes developed in our project would show both in improved ballast protection and noise reduction. The green square represent the target area, the red line is the Pareto front.

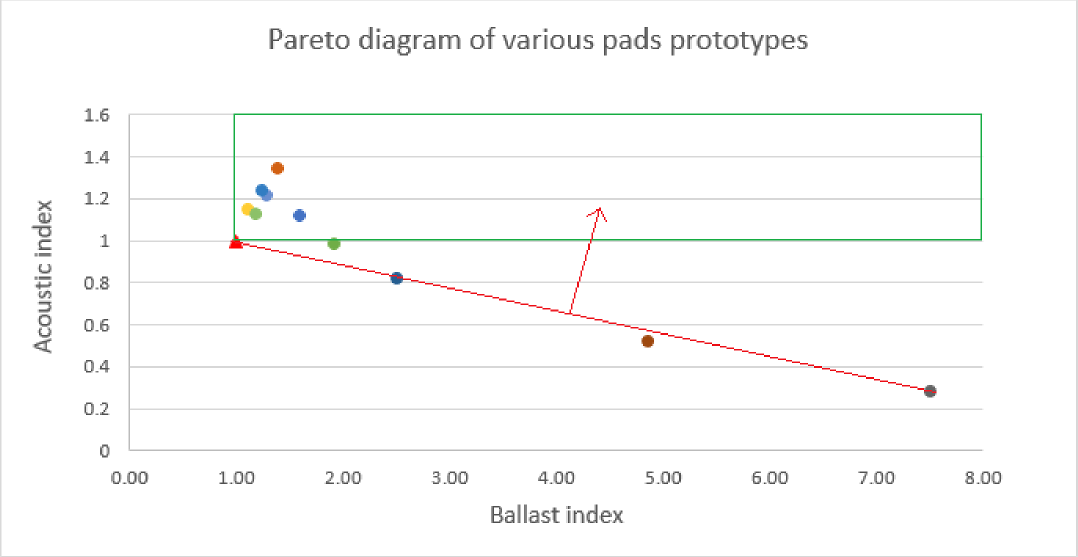


Figure 7: Pareto diagram of the acoustic index versus the ballast index; Triangle is the reference pad and dots are different design iterations.

In conclusion we can see that the developed open source toolbox can be used to efficiently design and optimize rail pads or other track components to match sometimes conflicting requirements in terms of noise and ballast protection for example. The tool box is composed of five models:

1. A three sleepers model in the frequency domain, that allows to compute the FRF of the system and the acoustic emission and validate modelling assumption on a small scale system
2. A pad level model that computes the dynamic properties of a pad from its design and materials.
3. A semi-analytic model that compute the TDR, FRF and acoustic pressure of a long track.
4. A three sleepers model in the time domain to compute the response impulse response of the system under axle loading.
5. A large scale FE model of the track using dynamic substructuring for detailed vibration and acoustic predictions

Those models are validated on experiments and aim to be as close as possible to the reality.

This toolbox will be published in open-source and is based on open-source solvers to allow anyone to use them or expand the capabilities. A set of simple graphical user interfaces make the system easy to use, but expert knowledge in Python, finite element modelling in Salomé / Code_Aster framework is recommended for developers.

Finally, those tools have been used successfully to develop a new rail pad that show improved noise reduction of >1 dB compared to the current EVA pads used in Switzerland, while being significantly softer than those EVA pads to provide better ballast protection.

Acknowledgements

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