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# A vehicle-based infrastructure monitoring system using an inverse dynamic model approach

**J.A. Neto[1], P.A. Montenegro[1] and R.B. Calçada[1]**

**[1]Construct, Department of Civil Engineering, Faculty of Engineering, University of Porto, Portugal**

## Abstract

This paper presents an inverse dynamic model approach as an indirect way to obtain the wheel/rail contact forces. Therefore, a numerical model of a passenger vehicle is developed taking into consideration a multibody formulation. The model is used to perform a numerical simulation where the train-track interaction problem is considered. The resultant contact forces time-histories are used to evaluate the capacity of the inverse algorithm to replicate the vehicle dynamic behaviour. At the same time, the acceleration responses obtained from the simulation are fed to the inverse dynamic model. The comparison between the contact forces from the simulation and from the algorithm reveals that the inverse model has high accuracy and it is capable of catching even the abrupt changes in the system. When evaluating the Prud'Homme criterion results, the method can reproduce the simulation outcomes. Hence, the method can be considered as robust and accurate.

**Keywords:** condition monitoring, inverse dynamic model, wheel/rail contact forces, numerical analyses.

## 1 Introduction

For the last two decades, the railway transport system has been considered the key to solving the enormous increase in demand for mobility of people and goods, mainly because of its high transport capacity and its reduced environmental impact. However, this put pressure on railway companies in terms of punctuality, comfort, reliability, and safety. Therefore, condition-monitoring systems have been seen as a crucial contributor to meet these growing needs. They are usually categorized as either wayside or on-board systems, being the latter the focus of this work. The on-board systems are commonly used for monitoring the railway infrastructure or they can be applied with fault detection and isolation (FDI) techniques for the rolling stock, with a growing interest in implementing inertial sensors, due to their great performance and their low cost.

The purpose of the present work is to present an inverse dynamic model that is capable of quantifying the wheel/rail contact forces through the acquisition of signals from inertial sensors attached to the train. Henceforth, a numerical model of the Alfa Pendular train is developed and numerical simulations are carried out, taking into account the train-track interaction problem. The simulated acceleration results are fed into the inverse dynamic model and the obtained wheel/rail contact forces compared with the ones from the simulations. The comparison shows a good match for both the lateral and the vertical forces, which means that the presented inverse dynamic model has high levels of accuracy.

## 2 Methods

This work consists of the development of an inverse dynamic model capable of determining the wheel/rail contact forces through vehicle acceleration measurements. The algorithm is based on a multibody formulation and is written considering the equilibrium state of each body, which means that even though it is applicable to any railway vehicle, it always depends on the geometrical and mechanical characteristics of each individual train. For this paper, the passenger train AP is considered and its numerical model is outlined in Figure 1.

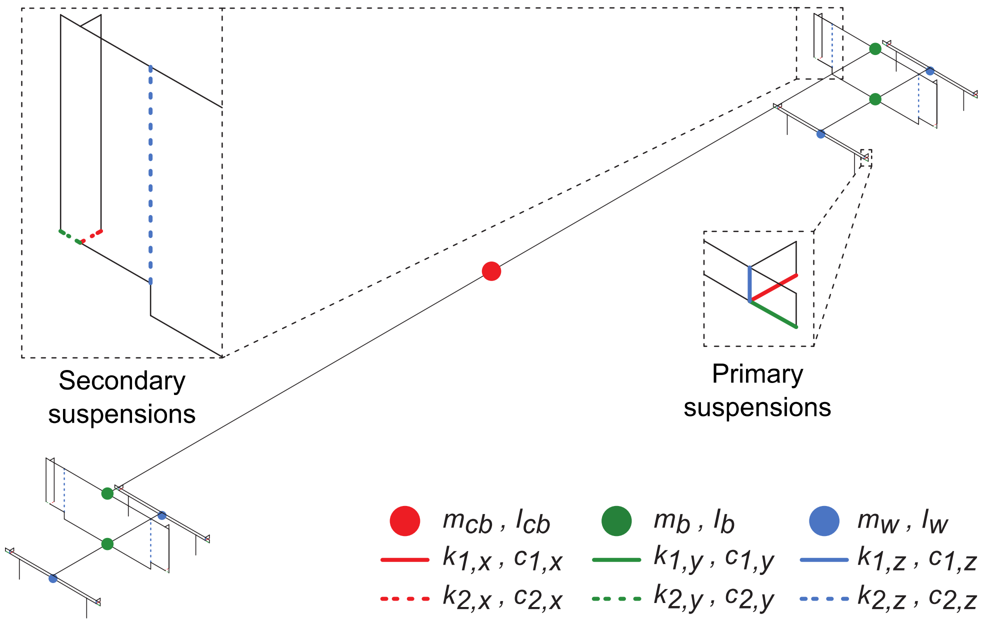



Figure 1: Numerical model of the AP train

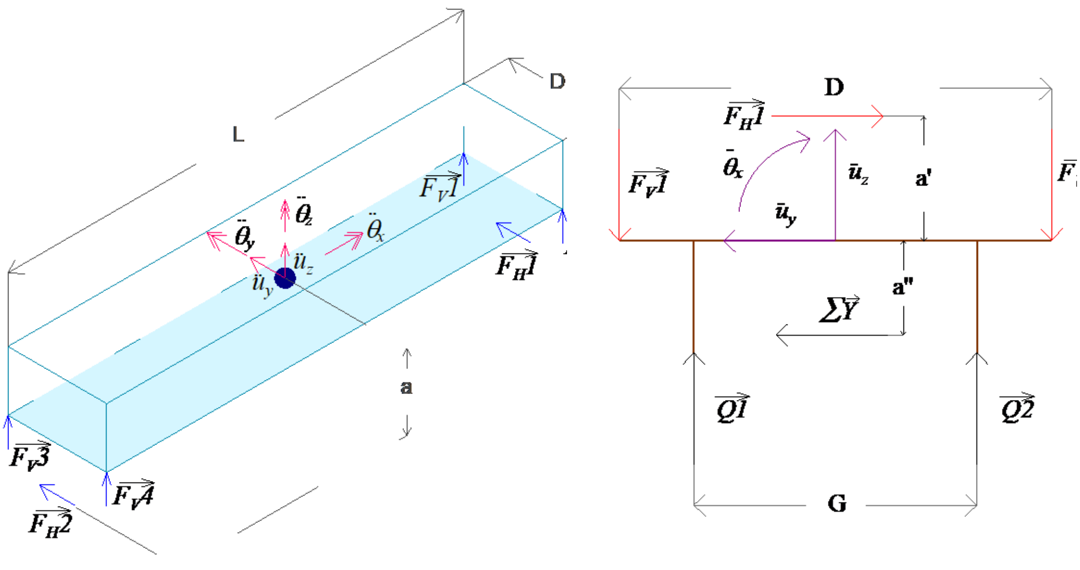
The vehicle is divided into three levels (the carbody, the bogie, and the wheelsets) that are linked by the primary and secondary suspensions. Therefore, it is necessary to solve three equilibrium equation systems, one for each linked structure to obtain the contact forces. The process starts from the top body, i.e. the carbody, from which five inertial measures are taken as the input variables (see Figure 2 a)). The first step is to solve the lateral equilibrium by considering the sum of the y forces and the sum of the z moments equal to zero, as it is defined in equation (1).

$$\begin{Bmatrix} \overrightarrow{F_{H1}} \\ \overrightarrow{F_{H2}} \end{Bmatrix} = \underline{T_H}^{-1} * \mathrm{diag}\left(\mathrm{m}, \frac{2 * I_z}{L}\right) * \begin{Bmatrix} \overrightarrow{\ddot{u}_y} \\ \overrightarrow{\ddot{\theta}_z} \end{Bmatrix} \quad \text{with} \quad \underline{T_H} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{1}$$

Then, the second step is to solve the vertical equilibrium by considering the sum of the z forces, the sum of the x moments and the sum of the y moments equal to zero. Since there are only three equations for four variables, it is required a fourth equation related to the rigid body formulation (see equation (2)).

$$\begin{Bmatrix} \overrightarrow{F_{V1}} \\ \overrightarrow{F_{V2}} \\ \overrightarrow{F_{V3}} \\ \overrightarrow{F_{V4}} \end{Bmatrix} = \underline{T_V}^{-1} * \mathrm{diag}\left(1, \mathrm{m}, \frac{2 * I_x}{D}, \frac{2 * I_y}{L}\right) * \begin{Bmatrix} 0 \\ \overrightarrow{\ddot{u}_z} + g \\ \overrightarrow{\ddot{\theta}_x} \\ \overrightarrow{\ddot{\theta}_y} \end{Bmatrix} \quad \text{with} \quad \underline{T_V} = \begin{bmatrix} +1 & -1 & -1 & +1 \\ +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ -1 & -1 & +1 & +1 \end{bmatrix} \tag{2}$$

Once the six equations are solved, it is possible to step down for the next level to continue the process. When it reaches the wheelset body level, three input variables are considered instead of five (see Figure 2 b)), the lateral equilibrium is already solved and the vertical one is reduced to only two equations, the sum of z forces and the sum of the x moments. The algorithm is applied for each time-step.

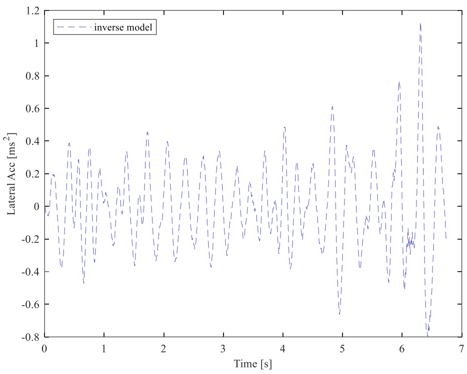



a) b)

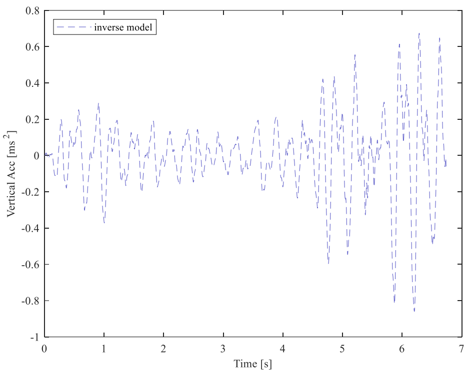
Figure 2: a) Sketch of the parameters definition for the carbody and bogie; b) sketch of the parameters definition for the wheelset.

# 3 Results

The inverse algorithm depends on the acceleration of the train to calculate and reproduce the contact forces. Therefore, both lateral and vertical accelerations of the carbody obtained from the numerical simulation are shown in Figure 3 a) and b).



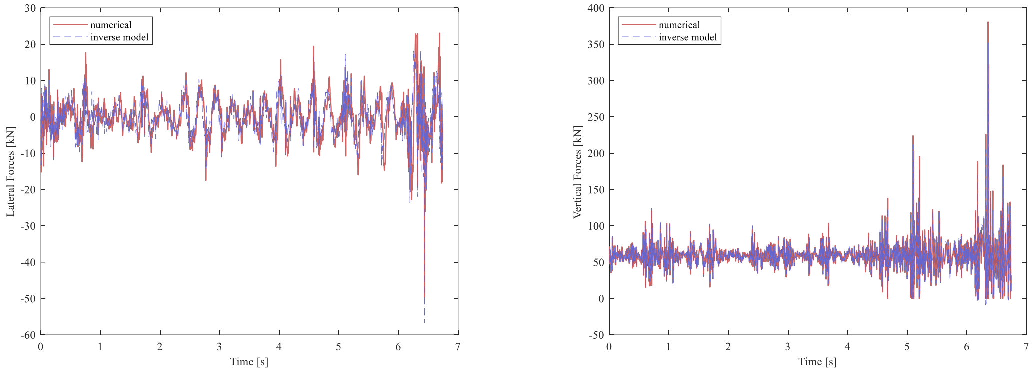

a)




b)

Figure 3: Dynamic responses of the carbody: a) lateral accelerations; b) vertical accelerations.

These dynamic measurements are fed into the inverse dynamic model and the results are compared with the ones from the numerical simulations. Figure 4 a) shows the two time-histories of the lateral forces of the fourth wheelset, both for the inverse algorithm and for the numerical simulations. As it is possible to see, the algorithm is extremely robust, with the capability of catching the hunting movement and the abrupt changes in vehicle behavior. However, the lateral forces of the right and the left wheels of each wheelset need to be considered as a sum, otherwise, the system of equations would not have a possible and determined solution. Figure 4 b) depicts the vertical contact forces of the right wheel of the 4th wheelset. Again, the method is able to replicate the vehicle contact forces successfully.




a) b)

Figure 4: Comparison between the numerical and the inverse results for the right wheel of the last wheelset: a) lateral contact forces; b) vertical contact forces.

To complete the validation process, the Prud'Homme criterion is computed and the time-histories of the factor are compared in Figure 5. The results reveal a good match.

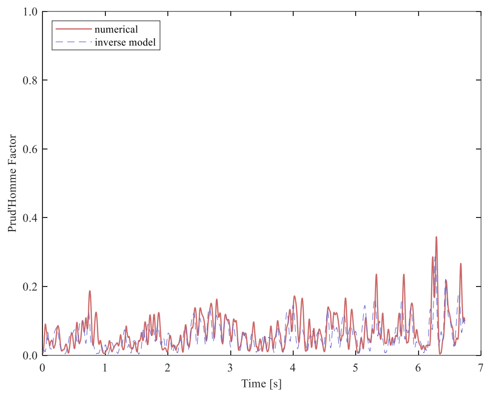



Figure 5: Prud'Homme factor for both the numerical and the inverse results.

# 4 Conclusions and Contributions

The present work focuses on the development of an inverse dynamic model, which represents an indirect method to obtain the wheel/rail contact forces. The results are compared with the ones derived from the dynamic analysis, revealing high levels of accuracy, with the inverse model being capable of reproducing the dynamics of the vehicle. Therefore, the first conclusion is that the algorithm is accurate and robust. Furthermore, when looking at the Prud'Homme factor, it is possible to say that the results are very much correlated, which means that the inverse dynamic model is able to distinguish good sections of the track from potential risky sites. The second conclusion is that the infrastructure managers can implement this method as part of a condition monitoring system, built-in operational trains. The advantage of such implementation is that the acquisition sensors are reliable and affordable, and instead of determining the track irregularities like most of the current researches do, it gives the contact forces. To conclude, the inverse dynamic model is numerically validated and can be seen as an alternative to the conventional inspection process. Moreover, it is possible to consider just the front half of the vehicle since the system of equations for one of the bogies is independent of the other bogie, and the same for the wheelsets.

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