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Error analysis of the application of combined subspace identification to the modal analysis of railway vehicles

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A B S T R A C T

This study is part of the development of a methodology for the application of the combined deterministic-stochastic subspace identification method for the identification of the modal parameters of railway vehicles. The proposed methodology employs the vertical accelerations measured on the axle boxes of one wheelset as excitations and the accelerations measured in the carbody and bogies as responses, which are registered when the vehicle is in circulation. With this aim, first the parameters that may affect the modal identification accuracy are identified. Then, they are grouped into three categories: parameters associated with the vehicle, parameters related with the excitation that the vehicle receives and parameters associated with the test execution. Next, an index named Modal Parameter Error Index (MPEI) is introduced. This index allows estimating the error that will be obtained in the identification of the natural frequency and damping ratio of the modes based on the knowledge of the parameters of the test. The terms that compose the index have been obtained applying the Monte Carlo method in numerical simulations for simple models. The availability of MPEI is a very powerful tool in the application of the combined subspace identification method for identifying modal parameters of railway vehicles. Also, based on MPEI and the expected variation range of the influencing factors, useful application guidelines are given.

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1. Introduction

Experimental modal analysis of railway vehicles is of interest for various reasons. First, modal parameters can be used for the validation of the numerical models that are employed in dynamic simulations [1,2], which is crucial for advancements in the virtual certification of vehicles. Moreover, new railway series are usually designed based on the models of previous series, which are modified to fulfil the client requirements. Such personalization implies that railway vehicles typically have a shorter experimentation and analysis phase than other types of vehicles. Modal analysis can be a useful technique to verify the design and, if necessary, obtain information to perform adjustments and corrections. Finally, modal analysis can be a useful tool for the resolution of problems that appear once the vehicles are in service. The investigation of problems related to comfort [3–5], vibrations [6], noise [7], fatigue of the structures [8], etc., becomes easier through the employment of modal analysis techniques.

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So far, the most commonly used excitation methods for the application of experimental modal analysis in the railway sector have been the relaxation method [9], the wedge method [10], and the use of shakers [11]. However, these methods have the disadvantage that the vehicle should be in stationary condition (parked) for their application. Hence, the excitation level is usually lower than that encountered during normal operation conditions, and in some cases, the application point of the forces differs from the actual application point of the excitations during normal operation conditions. Additionally, the boundary conditions are different from the circulation conditions because the wheel-track interaction associated with rolling is very different. Therefore, several modal parameters obtained when the vehicle is in stationary condition differ considerably from the modal parameters associated with the vehicle in circulation.

These limitations can be overcome through modal analysis techniques where data acquisition is performed when the vehicle is in normal operating conditions, known as Operational Modal Analysis (OMA). In addition, such techniques allow the test to be performed in parallel with other homologation tests or even during commercial circulation. Among the different methods developed to analyze data obtained during normal operating conditions, the subspace identification methods are outlined. These methods have provide satisfactory results in sectors such as aeronautic [12], automotive [13], and also in the study of structures [14–16]. There are two families of the subspace methods: the stochastic methods, in which the excitations are considered to be unknown; and the combined deterministic-stochastic methods, also known as Combined deterministic-stochastic Subspace Identification (CSI), in which only part of the excitations are considered to be known.

So far, in the railway sector, the application of OMA has been scarce and limited to output-only identification methods [17,18]. Many studies in other areas showed that the accuracy of the modal parameters identification increases considerably when the combined deterministic-stochastic method is applied in comparison with the results when the stochastic method is applied [19,20]. Moreover, one of the hypothesis of the stochastic method is that the excitations are white noise, which is incorrect for the excitations from the track, as will be described in Section 3. Hence, it is expected that the application of CSI methods in the railway sector will allow better identification of the modal parameters of railway vehicles than other methods. Under this consideration, this study is part of the development of a methodology for the application of the CSI method for the identification of the modal parameters of railway vehicles employing on-track measurements.

However, the application of CSI in the railway sector is not straightforward because of certain peculiarities that may result in difficulties in the application of the method and may lead to incorrect identification of the modal parameters. Some of the peculiarities are the frequency distribution of the excitation, the fact that the excitations in different wheelsets are the same but delayed in time and the presence of modes with high damping ratios. The aim of this study is to establish the principles of this methodology by evaluating the extent to which these peculiarities hinder the application of the CSI technique in the railway sector, as well as by providing the optimum value of test and analysis parameters. For this purpose, an index named Modal Parameter Error Index (MPEI) has been defined, which relates the identification error of the natural frequency and damping ratio of the modes to certain test parameters.

The text is structured as follows. Section 2 presents the basic principles of the CSI technique. Section 3 analyzes the peculiarities associated with the application of the CSI method in the railway field. In Section 4, the proposed index MPEI is defined. In Section 5, the relationship between the identification errors and the influencing factors is studied; which allows the parameters that compose MPEI to be determined. Section 6 presents the conclusions of the study.

2. Basic principles of combined subspace identification methods

The vehicle under study can be represented by a system with a finite number of degrees of freedom (d.o.f.), linear and time-invariant. The main source of excitation in railway vehicles is from the wheel-track interaction originating due to the wheel and rail irregularities; therefore, the vehicle can be considered as a support-excited system. Hence, the model can be expressed as a continuous-time state space model.

$$\begin{cases} \dfrac{\mathrm{d}\mathbf{x}(t)}{\mathrm{d}t} = \mathbf{A_c}\mathbf{x}(t) + \mathbf{B_c}\mathbf{u}(t) \\ \mathbf{y}(t) = \mathbf{C_c}\mathbf{x}(t) + \mathbf{D_c}\mathbf{u}(t) \end{cases} \tag{1}$$

where $\mathbf{u}(t) \in \mathbb{R}^m$ represents the m measured excitations applied to the system and $\mathbf{y}(t) \in \mathbb{R}^l$ represents the l measured responses. The meaning of matrices $\mathbf{A_c}$, $\mathbf{B_c}$, $\mathbf{C_c}$ and $\mathbf{D_c}$ and their relation with the parameters of the system is presented in [21]. $\mathbf{x}(t) \in \mathbb{R}^n$ denotes a vector of the states of the system. In this case, the states of the system are formed by the relative displacement and velocities of the d.o.f. employed to describe the system with respect to the displacement and velocities of the support. Considering this, the excitations can be measured as the absolute accelerations of the support and the responses can be measured as the absolute accelerations measured in the system. This formulation has been adopted because it is easier to perform the on-track experimental measurements in the form of accelerations instead of displacement or velocities when applying this method [22]. The state equations of the discrete system can be obtained by performing discretization in time using the zero-order hold model [23]. The relation between the matrices of the continuous state space model and the discrete one is presented in [21].

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