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IMPROVED METHODOLOGIES FOR THE ANALYSIS OF THE CROSSWIND STABILITY OF RAILWAY VEHICLES

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1 INTRODUCTION

Over the last years, the analysis of the crosswind stability of railway vehicles has established its position in the research community. However, the topic is still conflicting because of the different actors and interests involved: on the one hand, simplicity of robustness of the analysis tools and methodologies are required for the definition of norms which have to meet demands of railway operators and safety bureaus from different countries. On the other hand, high accuracy and closeness to reality is aimed to achieve safety without falling back to exaggerated – and thus uneconomical and unsustainable – safety limits.

In this paper three of the most controversial topics are discussed and improvement proposed. The first issue concerns the overall approach: a probabilistic one, based on well established *reliability techniques*, offer many advantages with respect to the almost universally adopted deterministic approach. The second issue refers to the modeling of the turbulent crosswind: even though deterministic models based on ideal (mean) gusts are very simple and efficient, the benefits of models based on *stochastic processes* cannot be ignored. Possibly, both models have to be used in an appropriate framework for an efficient risk assessment. The third topic refers to the modeling of the *unsteady aerodynamic* loads on the vehicle: even though the central role of the vehicle's aerodynamic admittances has been unanimously accepted, the importance of the indicial functions for the ideal gust case still is almost disregarded.

It is easy to recognize that these three topics, which are addressed in the following sections, are intrinsically linked and strongly influence each other.

2 RELIABILITY ANALYSIS AND RANDOM PROCESSES

2.1 Probabilistic Risk Assessment

Reliability techniques, [7], are a common tool in many fields including wind engineering, [10]. A framework for the application of such techniques to the crosswind stability of railway vehicles was recently proposed, [2]. The goal therein is to manage uncertainties and/or variabilities in the parameters of the computational models in an efficient way. These uncertainties are mainly due to the lack of information (e.g. unknown/variable crosswind boundary conditions), to systematic errors in the determination of the model parameters (e.g. wind tunnel experiments based on simplified models) and intrinsic parametric randomness (e.g. ideal gust amplitude and duration). The field of reliability analysis is, in general, well established but still bustling and new methodologies are continuously being proposed.

The reliability framework in [2] is based on the ideal gust model, which can be efficiently handled by stochastic variables. Actually, the reliability based approach can in principle also cover the crosswind as a stochastic process, which is a desirable purpose indeed and has been discussed in many circumstances. It follows that reliability methods capable to handle with stochastic processes, usually denoted as *time dependent reliability*, [7], must be looked at.

2.2 Analysis based on random process models

The first problem in the time dependent reliability approach is to evaluate the system response, usually the wheel unloading, due to the crosswind loads. Typically, the computational model consists of a nonlinear multibody model and a time integrator. Thus, the wheel unloading is computed by integration of the equations of motion set up by the chosen multibody formalism. It follows that the wheel unloading can be easily computed only as a time history corresponding to a specific realization of the crosswind input process. Even though the integration can be repeated many times for different realizations of the wind process, a complete statistical description of the wheel unloading response process is not directly available.

A possible circumvention of this problem consists in the linearisation of the multibody model, which seems to be an admissible practice if some precautions are taken. For the resulting linear system a statistical description of the wheel unloading can be found using the usual tools from linear system theory. A more appealing but challenging strategy is to tackle the nonlinear system. To this aim, methods based on the decomposition of stochastic processes through series expansion are tested in this work. Even though originally developed in the first half of the last century, only in recent times they could gain large attention, [4]. A formulation specifically tailored to multibody problems, [8], has been recently proposed, too.

Once the system response is known, the proper reliability evaluation has to be performed. Even in combination with the decomposition approach, this step is in general non-trivial. The Rice's formula in its commonly used approximation, [7],

$$p_F(T) = 1 - \exp\left[-\int_0^T \nu_{Q_L}^{+} \mathrm{d}t\right] \tag{1}$$

seems to be acceptable, considering that other more substantial simplifications have to be made during the analysis. In Eq. 1, $\nu_{Q_L}^{+}$ is the upcrossing rate of the wheel unloading limit Q_L and $p_F(T)$ the probability of failure (i.e. of overturning) for the time interval $(0, T)$.

In the present work the adequacy of random processes decomposition techniques for the crosswind stability analysis in a reliability framework is investigated, showing that the approach is feasible and offers a valid alternative to the time consuming Monte Carlo.

3 UNSTEADY AERODYNAMICS

3.1 Aerodynamic loads

In recent times, *unsteady* aerodynamic loads have been accepted as an essential part of the crosswind stability analysis, whereat ideal gusts could establish as the computational model of the wind. The use of an ideal gust is mainly motivated by the time domain approach on which the analysis is based and by the fact that such a gust can conveniently be codified in norms. Moreover, physically sound models of ideal gusts have recently been developed for the analysis of wind turbines and then become universally available, [1].

A pivotal prerequisite of the ideal gust approach is the availability of a model of the unsteady aerodynamics, i.e. a relationship between the time dependent crosswind and the unsteady aerodynamic loads. But, in most cases, only the static aerodynamic coefficients of the vehicle are known, only allowing a quasi-steady description of the loads. This formulation is known to lead to exaggerated wind loads and very over-conservative results, Fig. 1. This impasse is usually bypassed, e.g. in the European norms [3], by the replacement of the absolute quantification of the crosswind stability with a relative one: the computed behavior of the vehicle being homologated is compared with that of a reference vehicle which is known from operative experience to be safe. Nonetheless, the approach based on the reference vehicle is very unsatisfactory because the comparability of completely different vehicles is questionable. Moreover, only very few vehicles are eligible for the role of reference.

A promising answer to the problem can be found in the application of unsteady aerodynamics tools from wind engineering, usually only considered in the context of turbulent/stochastic wind models, to the ideal gust case.

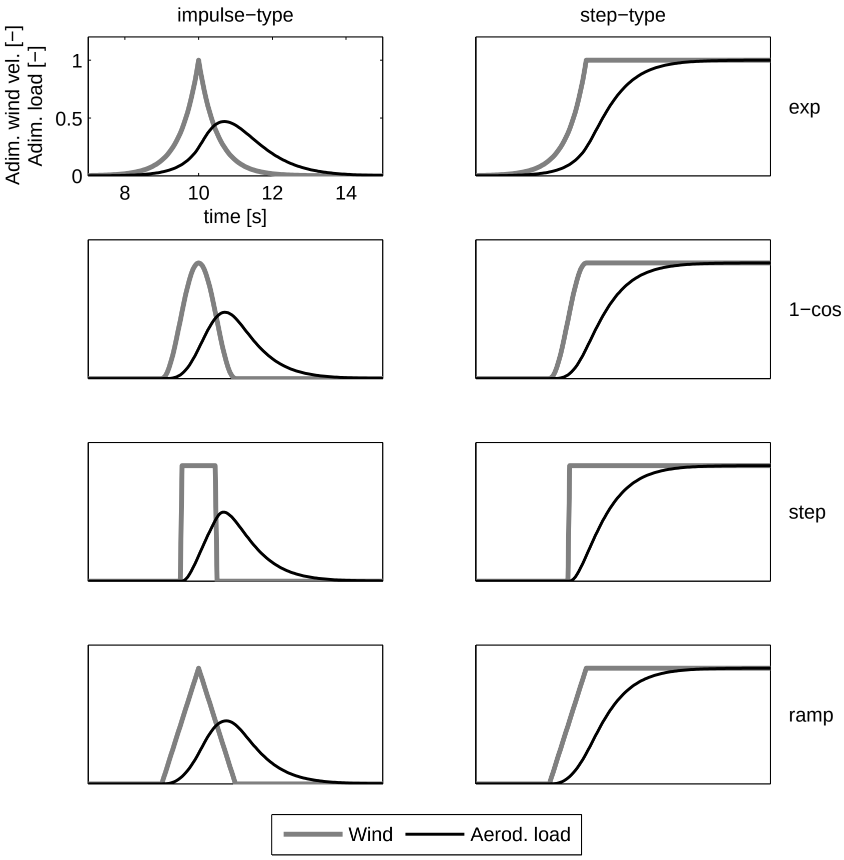

Figure 1: Adimensionalised time histories of different ideal gusts and corresponding *unsteady* aerodynamic load (side force). Qualitative results according to the experimental data in [6].

3.2 Aerodynamic admittances and indicial functions

The duality of aerodynamic admittances in the frequency domain and indicial functions in the time domain is a well established topic in aircraft aerodynamics but has also arisen interest in the field of bluff bodies, [9, 5]. From an aerodynamical point of view, caution is advised when concepts developed for moderately bluff bodies, like bridge sections, are applied to a railway vehicle in crosswinds, as the latter is characterized by very peculiar flow structures. Nonetheless, indicial functions offer an idoneous tool to embed unsteady aerodynamics in the framework of the crosswind stability analysis.

Additionally, some suggestions and guidelines for future wind tunnel tests can be issued on the basis of considerations gained from knowledge of the vehicle's driving dynamics. Apart from some obvious conclusions connected with the predominant influence of the roll motion of the vehicle (and thus the corresponding aerodynamic roll moment) on its stability, it is qualitatively shown that the analysis of the running behavior can significantly be improved if little information on the unsteady aerodynamics is available. Particular attention is given to the possibility of inheriting already existing experimental techniques from bridge aerodynamics for the set-up of the unsteady aerodynamic model of a railway vehicle.

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