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CROSSWIND STABILITY OF HIGH-SPEED TRAINS: A STOCHASTIC APPROACH

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1 INTRODUCTION

The modern developments in railway engineering have been showing a trend to faster and more energy efficient trains with a higher capacity of passenger transportation. These efforts are directly leading to light-weight cars with distributed actuation. Unfortunately these developments are in contrast to a save use in strong crosswind conditions. Consequently, crosswind stability has become a crucial issue of modern railway vehicle design that cannot be solved easily, because counter-measures are very expensive.

This investigation is focused on a detailed quantification of the probability of overturning for a railway vehicle and applies a wind gust model that has been proposed for the fatigue analysis of wind turbines [1, 2]. Two wind scenarios are investigated: a train coming out of a tunnel immediately being hit by a gust and a train traveling on an embankment under constant mean wind load being hit by a gust, respectively.

In a second step, sensitivity analyses with respect to the stochastic excitation variables and with respect to deterministic design parameters are performed and the most crucial variables are accentuated.

Similar investigations have been carried out previously in [3]. However, this study differs from previous works by the environmental model, especially the gust model, the stochastic analysis techniques and the way the sensitivities are computed.

2 MODEL

The system can be divided into two separate parts: the environmental model and the vehicle model. The environmental model itself consists of two distinct components: the track and the aerodynamic forces and moments.

The railway vehicle is simulated in a commercial MBS-Software. Nonlinear spring and damper characteristics can be included without major problems and also the bump-stops, which have a great influence on the overturning behavior can be modeled very precisely. The wheel-

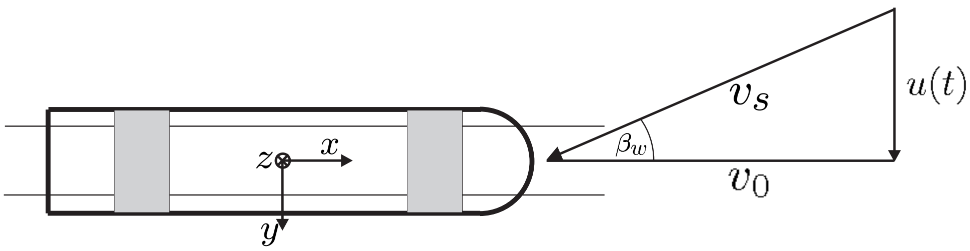

Figure 1: Schematic sketch of the vehicle with coordinate system and wind velocity vector.

rail contact forces are simulated using the implemented FASTSIM routine, which is a good compromise between speed and accuracy to calculate the resultant wheel-rail forces.

The crosswind model $u(t)$ consists of a superposition of the mean wind u_0 the gust wind $u_B(t)$ (corresponding to low frequency fluctuations) and the turbulence. Unsteady aerodynamics is accounted for by the aerodynamic admittance. Finally, the wind is a function of the track variable s and must be transformed into the time domain by the constant train velocity v_0 as a time integration of the differential equations has to be performed.

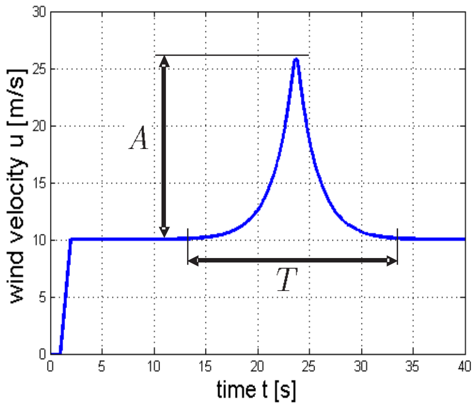

Figure 2: Crosswind characteristic with gust amplitude A and gust duration T.

The exponentially shaped gust characteristic (Fig. (2)) which is utilized in this investigations is often used in wind turbine design and has a strong theoretical foundation, [2, 1]. The gust amplitude A follows a half gaussian and the gust duration T follows a lognormal distribution as described in [4].

As the railway vehicle has a certain dimension in the horizontal and vertical direction the resultant wind forces have to be computed by an averaging process over the whole area of the carbody. In the time domain this integration transforms to a sliding mean procedure with the time interval $[t - \frac{L_t}{2v_0}, t + \frac{L_t}{2v_0}]$, where L_t describes the length of the carbody.

The wind loads on the vehicle are modeled as concentrated forces and moments and so they are computed from the acting wind velocity $v_s(t)$ by means of experimentally determined aerodynamic coefficients:

$$F_{y/z}(v_0, u(t)) = C_{\text{side/lift}}(\beta_w)\frac{\rho_L A_t}{2}v_s^2, \tag{1}$$

$$M_{x/y/z}(v_0, u(t)) = C_{\text{roll/pitch/yaw}}(\beta_w)\frac{\rho_L A_t l}{2}v_s^2, \tag{2}$$

as the determination of reliable aerodynamic coefficients by means of computational fluid dynamics (CFD) is still an unsolved topic, [5]. The factors A_t and l are the related area and the length dimension of the railway car and ρ_L is the density of air. The wind forces and moments are therefore functions of the angle

$$\beta_w = \arctan\left(\frac{u_0 + u_B(t)}{v_0}\right) \tag{3}$$

and of the squared resultant wind velocity.

The aerodynamic coefficients $C_{\text{side/lift/roll/pitch/yaw}}$, the gust amplitude A and the gust duration T are assumed to be random variables. As not much information about the distributions of the aerodynamic coefficients exists they are fitted by a gaussian distribution with a standard deviation of 10%.

3 PROBABILISTIC ANALYSIS

3.1 Reliability analysis

To determine the probability of failure P_f it is necessary to evaluate the high dimensional integral

$$P_f = \int_{\Omega_f} p_{Z^*}(\underline{z}^*) d\underline{z}^* \tag{4}$$

over the failure domain Ω_f where $\underline{z}^*$ contains all stochastic variables of the system and $p_{Z^*}(\underline{z}^*)$ are the corresponding probability density functions. The failure domain Ω_f is separated from the safe domain Ω_s by the so called limit-state function $g(\underline{z}^*) = 0$ which is defined as:

$$g(\underline{z}^*) = 0.9 - \frac{\delta Q}{Q}. \tag{5}$$

From this definition the failure domain is characterized by $g(\underline{z}^*) \leq 0$ and the safe domain by $g(\underline{z}^*) \geq 0$. For the complex railway vehicle system where a numerical calculation of the function $g(\underline{z}^*)$ lasts about half a minute and where the limit-state function is not known explicitly but can only be evaluated pointwise the computation of the integral in equ. (4) is a demanding task. To simplify the calculations the law of conditional probability can be used and equ. (4) is reduced to

$$P_f = \int_{u_{0,d}}^{u_{0,t}} P(\underline{z}|u_0) p(u_0) du_0, \tag{6}$$

whereas $\underline{z} = [A, T, C_{\text{side/lift/roll/pitch/yaw}}]$ is the vector of the remaining stochastic variables. But still the conditional probability $P(\underline{z}|u_0)$ has to be calculated. In principle, this can be done by semi-analytical procedures such as FORM or SORM or by numerical methods like Monte Carlo Simulation and also response surface methods can be used [6].

Here, the following procedure has been employed: in a first step, a FORM result is obtained on a reduced set of random variables. In a second step, this result is improved by line sampling. Due to the precomputed design point, the computation of the conditional failure probability with line sampling is very efficient and accurate for the kind of problem under consideration [7].

3.2 Sensitivity analysis

Sensitivity methods are commonly classified in local and global methods and in qualitative and quantitative methods. In general the local and qualitative methods are less computationally expensive but the results gained from these methods are either only valid for a small local region or give only an indication how the dependency between input and output parameters is. On the other side the global and quantitative methods give either results which are valid over the whole parameter space or which show exactly how the input parameters affect the output, but these sensitivity methods require a much higher amount of computational effort.
In this work the sensitivity analysis is performed to deal with two different kinds of problems. The first one is the impact of the seven stochastic excitation variables on the crosswind stability of the railway vehicle and the second one is to investigate the influence of the deterministic design parameters.
In order to separate the unimportant excitation variables from the important ones and to determine the influence of design parameters a robustness analysis with latin hypercube sampling (LHS) has been undertaken. From the LHS linear and quadratic correlation coefficients and principal component values from a principal component analysis have been calculated. A comparison of these values show clearly how high the impact of a stochastic variable is. Another good method to decide which variable is important or not is to look at the response surface approximations and to search for high gradients.

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