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Procedia IUTAM 13 (2015) 98 – 107

Procedia IUTAM

www.elsevier.com/locate/procedia

IUTAM Symposium on "Dynamical Analysis of Multibody Systems with Design Uncertainties"

Influence of Uncertainties on Crosswind Stability of Vehicles

Carsten Proppe*, Xiaoyu Zhang

Institute of Engineering Mechanics, Karlsruhe Institute of Technology, Kaiserstr. 10, Bdg. 10.23, 76131, Karlsruhe, Germany

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Abstract

Crosswind stability is an important criterion for the modern design of railway and road vehicles. In the past, most of the studies on the influence of crosswind on vehicles are based on deterministic models. This paper investigates the crosswind stability by a stochastic model, in which uncertainties are taken into account. A wind model with nonstationary wind turbulence is developed. As the excitation of the vehicle is a stochastic process, a risk analysis has to be carried out and failure probabilities have to be calculated. The proposed method has been utilized to analyze the crosswind stability of road vehicles and railway vehicles on both straight and curved tracks. Besides, in order to find the most influential parameters, a sensitivity analysis has been undertaken.

Peer-review under responsibility of organizing committee of Institute of Engineering and Computational Mechanics University of Stuttgart.

Keywords: Nonstationary; Crosswind stability; Vehicle; Stochastic; Risk analysis

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1. Introduction

Sufficient crosswind stability is an important criterion for the approval process of railway and road vehicles. In the past, many wind-induced accidents of railway vehicles have been reported around the world. Accidents of road vehicles under strong crosswind conditions are also frequent. For these reasons, there is a need to investigate the crosswind stability of vehicles by computational simulation[1].

Simulation models for crosswind stability can be basically classified into two groups, namely deterministic models and stochastic models[2].

Most of the studies on crosswind stability of vehicles are carried out based on deterministic models, with the aim to compute the critical wind velocity for a certain type of vehicles at a given vehicle speed. The underlying assumption for this method is that all parameters (such as aerodynamic coefficients, gust amplitude, gust duration and so on) are specified as deterministic values. Critical wind speeds are calculated with respect to a given gust shape. However, wind is always a stochastic process due to the existence of turbulent fluctuations. Realistic assumptions on the nature of crosswind gusts have to take its nonstationary character into account.

Recently, stochastic models have attracted a lot of attention. They take uncertainties into account and yield failure probabilities for the evaluation of crosswind stability. In this regard, a gust model with random amplitude and duration

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* Corresponding author. Tel.: +49-721-608-46822 ; fax: +49-721-608-46070.
E-mail address: carsten.proppe@kit.edu

Peer-review under responsibility of organizing committee of Institute of Engineering and Computational Mechanics University of Stuttgart.
doi:10.1016/j.piutam.2015.01.006

has been taken into consideration in this paper. In addition, the strongly nonlinear aerodynamic coefficients, which highly depend on the vehicle shape as well as the relative wind angle, are modeled as random variables. The nonstationary turbulent fluctuations of the wind velocity can be described by an evolutionary power spectrum density, from which the auto-correlation function is obtained. Based on this knowledge, a nonstationary auto-regressive model[3] is proposed and developed in this study.

Based on the nonstationary crosswind process and the nonstationary vehicle state (acceleration or deceleration)[4], the combined wind-vehicle system is modeled and simulated. The nonstationary aerodynamic force produced by the nonstationary crosswind excitation can be analyzed by means of the Hilbert-Huang transform (HHT)[5,6]. This allows for a decomposition of the force into a small number of intrinsic mode functions and instantaneous frequencies which provide important information on the excitation process and the corresponding system response.

As the excitation on the vehicle is a stochastic process, a risk analysis has to be carried out and failure probabilities must be computed. They can be obtained either conditioned on a certain mean wind speed and direction or in a certain topographical scenario. They are based on limit states for the safe operation of the vehicle. Typical performance functions take the ratio between the dynamic and the static vertical wheel force into account. For road vehicles, failure conditions for lateral displacement and yaw angle must also be considered. Computation of failure probabilities can be either based on Monte Carlo simulation with variance reduction (e.g. line sampling[7] or subset simulation[8]) or on analytical methods (e.g. FORM and SORM[9]).

The proposed method has been applied to both railway and road vehicles. The influence of various design and track/road parameters can be analyzed. Moreover, based on sensitivity analysis, the most important parameters for crosswind stability can be identified. Finally, the effect of counter-measures such as wind fences and vehicle speed reduction can be judged on an objective basis.

2. Modeling aspects

2.1. Wind model

Due to the existence of turbulence, natural wind is a stochastic process. For a given point at height z in space, the wind speed can be considered to consist of two parts, i.e. the mean part and turbulent part.

$$u(t) = u_0 + u'(t) \tag{1}$$

where $u(t)$ is the time-varying wind speed, u_0 is the mean wind speed and $u'(t)$ is the wind turbulence.

The turbulent wind speed can be described by the von Karman power spectral density (PSD) which is expressed as follows[10]:

$$S_{u'u'}(f) = \frac{4\sigma_{u'}^2 L_{u'x}}{u_0\left(1 + 70.8\left(\frac{fL_{u'x}}{u_0}\right)^2\right)^{\frac{5}{6}}} \tag{2}$$

where $S_{u'u'}(f)$ refers to the wind spectrum, $L_{u'x}$ is the longitudinal length scale, $\sigma_{u'}^2$ is the variance and f is the frequency.

The above wind spectrum considers the wind turbulence at a fixed point. For a moving point, the mentioned wind spectrum has to be modified. Based on Taylor's frozen turbulence hypothesis, Cooper derived the wind spectrum relative to a moving vehicle as follows[11,12]:

$$\frac{fS_{u'u'}(f)}{\sigma_{u'}^2} = \left[\frac{4fL_{u'}}{\bar{V}_r\left(1 + 70.8(fL_{u'}/\bar{V}_r)^2\right)^{5/6}}\right]\left[\left(\frac{u_0}{\bar{V}_r}\right)^2 + \left(1 - \left(\frac{u_0}{\bar{V}_r}\right)^2\right)\frac{0.5 + 94.4(fL_{u'}/\bar{V}_r)^2}{1 + 70.8(fL_{u'}/\bar{V}_r)^2}\right] \tag{3}$$

where $\bar{V}_r$ is the mean relative wind speed, $L_{u'}$ is the compound turbulence length scale which can be calculated by the following equation

$$L_{u'} = L_{u'x}\sqrt{\left(\frac{u_0}{\bar{V}_r}\right)^2 + 0.353\left(\frac{u_0}{\bar{V}_r}\right)^2} \tag{4}$$