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Performance analysis of wind fence models when used for truck protection under crosswind through numerical modeling

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ABSTRACT

This paper is focused on truck aerodynamic analysis under crosswind conditions by means of numerical modeling. The truck was located on the crest of an embankment during the study. In order to analyze the performance of three wind fence models, the truck's aerodynamic coefficients were obtained and compared in two different situations either with or without the wind fences installed. In addition, the effect of both height and porosity of wind fence models on the aerodynamic coefficients acting on truck with respect to separation distance between the truck and the wind fence, was analyzed. A finite volume (or computational fluid dynamic) code was used to carry out the numerical modeling. The Reynolds-averaged Navier–Stokes (RANS) equations along with the $k-\omega$ SST turbulence model were used to predict the behavior of turbulent flow. With respect to the results, the influence of the distance on the rollover coefficient is soft for all height values studied except for the lowest value (1 m of fence height), where the maximum value of rollover coefficient was obtained for the truck position closer to the fence. Regarding fence porosity, its effect on rollover coefficient is stronger for truck positions on road closer to the wind fence model.

1. Introduction

Under strong crosswind conditions, vehicle stability is adversely affected and as a consequence the risk of having an accident is increased. This issue has motivated the development of wind warning systems (Hoppmann et al., 2002; Delaunay et al., 2006) and new guidelines/regulations (Tielkes et al., 2008; Imai et al., 2002) in order to safeguard crosswind safety. With this goal, wind fences have also been used in bridges and embankments as in Imai et al. (2002). Another aspect is that blowing snow hinders driving because the drivers' visibility is reduced and ice formation is caused (Tabler and Meena, 2007; Matsuzawa et al., 2005). Thus, in exposed windy and snowy locations, wind fences have been adopted as control measures for protecting roads. In different locations around the world several accidents due to crosswind and blowing snow have been registered and analyzed (Imai et al., 2002; Shao et al., 2011; Matsuzawa et al., 2005).

There are many works on wind fence performance within other fields of application apart from traffic safety. Bitog et al. (2009) analyzed the effect of different building parameters of wind fences on preventing the generation and diffusion of dust from sandy land. In open storage yards, the stockpiles are often eroded by the wind and as countermeasures are needed to avoid the dispersion of particles, wind fences are used in many locations (Yeh et al., 2010; Santiago et al., 2007; Park and Lee, 2001). Trees may also be used as windbreaks to prevent odour dispersion in places like livestock farms (Lin et al., 2007). Another application of wind fences is aimed at improving external comfort in urban open spaces such as parks, playgrounds and recreational fields (Li et al., 2007).

Some studies have focused on optimizing different parameters of the snow fence geometry to improve its performance. Dong et al. (2007) studied the influence of porosity on the fence's shelter efficiency, measuring wind velocity and analyzing streamline patterns behind the fence. This research found that the optimal porosity was around 0.2 or 0.3, since for higher values of porosity, bleed flow dominates and for lower values of porosity, reversed flow becomes significant. Other parameters such as wind fence height and gap between the ground and the fence have been also studied. Kim and Lee (2002) investigated the flow field behind porous fences for four values of gap ratios, and the best protection against the wind was found for a gap ratio of 0.1H (H being the height of the fence). Imai et al. (2002) obtained the aerodynamic coefficients of a vehicle through wind tunnel test for several values of the

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height and porosity of the fence. The result indicated that for higher height of fence, keeping the porosity constant, the possibilities of overturning diminished. The influence of the distance between the vehicles and a wind fence model consisted of boards on the aerodynamics coefficient of rail and road vehicles, was studied in Zhu et al. (2012) for four positions of vehicle along the cross section of bridge. Also, Guo et al. (2015) estimated the aerodynamic coefficients acting on rail vehicle with different wind fence configurations installed on a bridge for two positions of vehicle on the bridge (windward and leeward). In both studies, the aerodynamic coefficients of vehicles diminished with the distance between the vehicle and the wind fence.

So far, wind fence performance has been evaluated by different techniques such as numerical simulation (CFD), wind tunnel test and field experiments. Wind tunnel tests were carried out to investigate how the wind fence improves vehicle stability under cross wind conditions when a vehicle passes through the wake of a bridge tower (Argentini et al., 2011; Bocciolone et al., 2008). For instance, Santiago et al. (2007) used numerical simulation in addition to wind tunnel tests in order to determine an optimum porosity for sheltering effect of an isolated windbreak. While other research such as Tuzet and Wilson (2007) and Torita and Satou (2007) performed field studies about the wind shelter provided by natural windbreaks.

In this paper, shelter efficiency of three wind fence models installed on an embankment is analyzed by obtaining the aerodynamic coefficients acting on the truck. Particularly, the first aim of this research consists in analyzing the influence of the geometry design of wind fences on truck aerodynamics. The second aim is to demonstrate the use of CFD codes to solve this kind of problems, being validated with experimental data. On the other hand, the first part of the paper describes the methodology applied to carry out the numerical simulations and the second section indicates and discusses the main results of the study. The last section specifies the main conclusions based on the results obtained.

2. Numerical procedure

The ANSYS FLUENT Academic Research software version 15 was used for solving the fluid-structure interaction problem.

2.1. Formulation of the model

The CFD codes numerically solve the governing equations of a turbulent flow, which are the continuity equation and Reynolds average Navier-Stokes (RANS) momentum, equation indicated in Eq. (1) and Eq. (2) (Mathieu and Scott, 2000; Pope, 2000; Tu et al., 2008). In order to obtain these equations, the Reynolds decomposition was used.

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \overline{u}_i) + \frac{\partial}{\partial x_j}(\rho \overline{u}_i \overline{u}_j) = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \rho\overline{u\prime_i u\prime_j}\right] \tag{2}$$

The term $-\rho\overline{u\prime_i u\prime_j}$ is a turbulent stress or Reynolds stress and states the correlations among the fluctuating velocity components. This term depicts additional unknowns in the time-averaged Navier-Stokes momentum equation. Therefore, for closing the above system of equations, new expressions which model the Reynolds stresses are required. These expressions will be introduced by mean of called turbulence models.

The SST $k-\omega$ turbulence model (Menter, 1993, 1994) was used in the present work because it provides good performance when dealing with low Reynolds issues, adverse pressure gradients and separating flow regions. This turbulence model combines the standard $k-\varepsilon$ model and the $k-\omega$ model, which retains the properties of $k-\omega$ close to the wall and gradually blends into the standard $k-\varepsilon$ model away from the wall. Nevertheless, the numerical results were also obtained by using the standard $k-\varepsilon$ model in order to check the better performance of SST $k-$

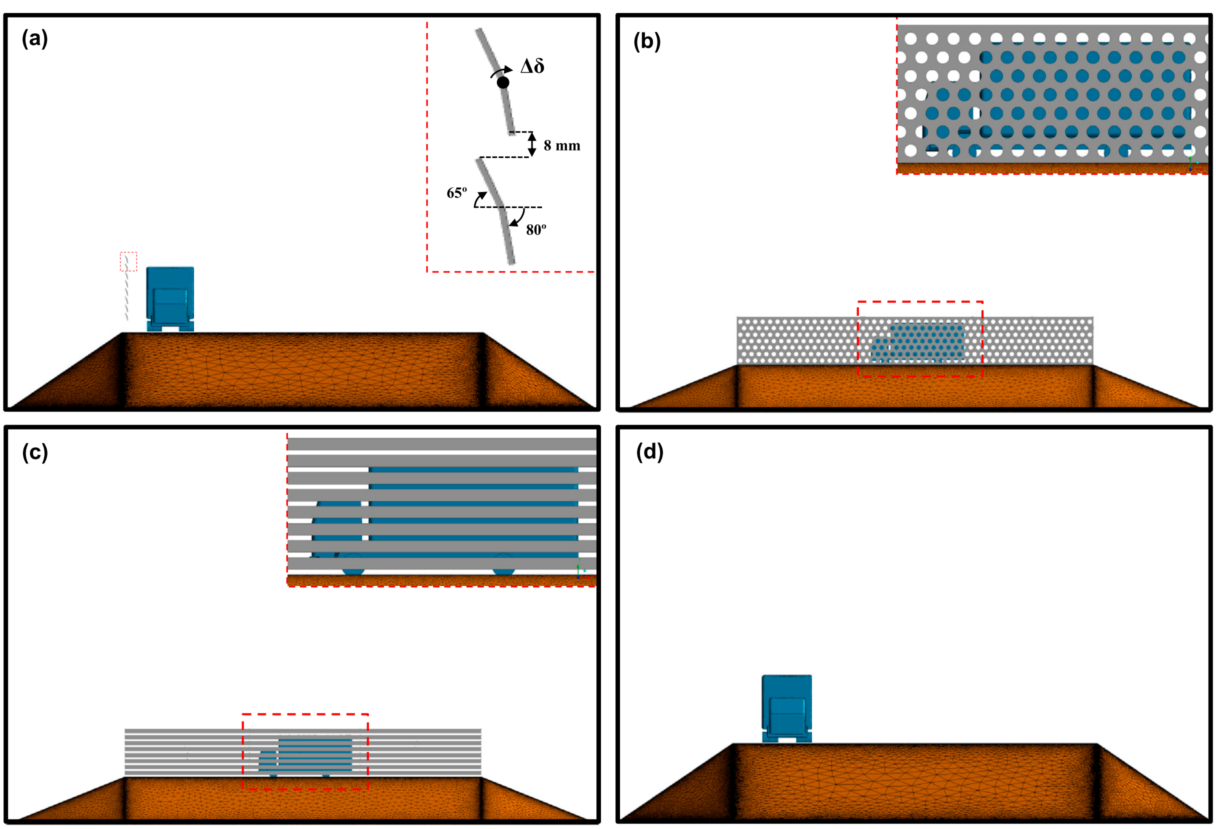

Fig. 1. Models studied (1:10 scale): (a) Wind fence model with plates; (b) Wind fence model with circular holes; (c) Wind fence model with rectangular slits and (d) Without wind fence model.