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Windbreak protection for road vehicles against crosswind

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ABSTRACT

In this study, wind tunnel experiments and a Large Eddy Simulation (LES) model were used to investigate the protective effect of porous windbreak on road vehicles against crosswind. The model prediction of the side force and lift coefficients compared favorably with the wind tunnel experiments of vehicles on the ground. The simulation results of the wake flows behind porous windbreaks were verified by the results of wind tunnel experiments. Then the validated numerical model was used to inspect the effect of porous windbreaks for the protection of vehicles on a bridge. The flow conditions included four different windbreak heights (0, 1, 2 and 3 m) and three different porosities (0, 0.233 and 0.485). The numerical results showed that the porous windbreaks could significantly reduce the side force coefficient of the vehicle, and the side force experienced by the vehicles on the windward lane of the bridge is smaller than that on the leeward lane because of the impermeable concrete barrier and windward windbreak. In addition, the shielding effect of the windbreak height of 2 m plus the barrier of 0.8 m height is sufficient to protect the vehicles of 3.6 m height.

1. Introduction

The effect of crosswind on ground vehicles has become a research topic due to its importance in regard to vehicle safety (Gawthorpe, 1994). The lateral aerodynamic force on moving vehicles could cause vehicles to deviate from their original path or even to rollover. The strong winds of typhoons have led to several traffic accidents in the exposed locations, like on river bridges or viaducts in Taiwan. Therefore, bridge and transportation engineers are interested in reducing the crosswind loading on the vehicles.

The time-averaged aerodynamic loadings on the vehicle can be calculated as (Blevins, 1984):

$$F_S = C_S \frac{1}{2} \rho V_R^2 A \quad (1)$$

$$F_L = C_L \frac{1}{2} \rho V_R^2 A \quad (2)$$

where F_S is the side (lateral) force, F_L is the lift force, C_s is the side force coefficient, C_L is the lift coefficient, V_R is the time-averaged relative wind speed, ρ is the density of the air, and A is the side area of the vehicle. This study only considered the time-averaged forces, the time dependent fluctuating loading were not discussed. The time-averaged force coefficients are functions of vehicle shape, attack angle and Reynolds number (Blevins, 1984).

Previous studies used wind tunnel experiments and numerical simulations to determine the force coefficients of various types of vehicles. For example, Coleman and Baker (1990) used wind tunnel experiments to measure the surface pressure and forces of a stationary tractor-trailer model in smooth and turbulent flows. These parameters were needed to assess the risks of vehicles to rollover and to slide. Their results showed that the side force coefficient C_s increased steadily with the yaw angle (angle between the wind direction and the vehicle moving direction) and the maximum value of C_s occurred when the yaw angle was around 80–90 deg. On the other hand, the maximum lift force coefficient was C_L=0.5 when the yaw angle was 40–50 deg.

Kramer et al. (1991) described the parameters influencing the aerodynamic loading on a road vehicle under crosswind condition, and derived the relationship between crosswind speed V_W, and vehicle speed V_V:

$$V_R = \sqrt{V_W^2 + V_V^2 + 2V_W V_V \cos\alpha} \quad (3)$$

where V_R is the relative wind speed and α is the yaw angle (see Fig. 1). When a vehicle moves in a straight line, the angle θ between the vehicle direction and the relative wind speed V_R is

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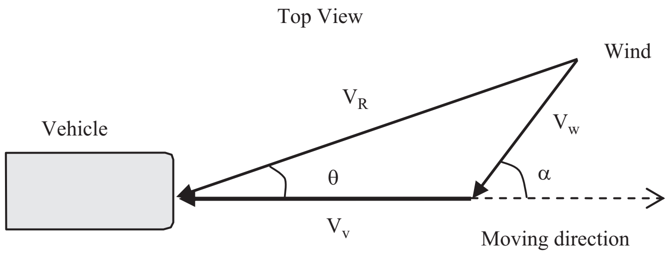

Fig. 1. Schematic diagram of wind speed and vehicle speed.

related to the yaw angle α:

$$\tan\theta = \frac{V_w \sin\alpha}{V_v + V_w \cos\alpha} \tag{4}$$

The overturning moment M_s caused by the crosswind can be calculated as:

$$M_s = F_s h_s \tag{5}$$

where h_s is the distance from the ground to the location of the side force F_s. It can be calculated from the pressure distribution on the vehicle surface:

$$h_s = \frac{\int_A p(z) z dz}{\int_A p(z) dz} + h_o \tag{6}$$

where p is the surface pressure on the vehicle, z is the distance from the vehicle underside, and h_o is the height of the vehicle underside.

Baker and Humphreys (1996) reviewed the side force coefficients on lorries and railway containers of different wind tunnel experiments. They found that the side force coefficient can be accurately determined by the scale model tests. However, the lift coefficients from different studies have large scatter, because the lift coefficient is dependent on the vehicle shape, free-stream turbulence level and the nature of the wind tunnel test. They suggested that using a moving model is necessary to obtain accurate results for the lift coefficient. Sigbjörnsson and Snabjörnsson (1998) used reliability analysis to develop a probability model which considered the effects of wind speed, friction coefficient and radius of road curvature. Their model can be of use in evaluating preventive measures to improve traffic safety in windy environments.

Bettle et al. (2003) used a computational fluid dynamics (CFD) model with constant turbulent viscosity to calculate the aerodynamic forces experienced by a truck traveling on a highway bridge. They simulated a truck traveling at speeds of 0 ~ 120 km/h on the windward and leeward lanes under wind speed of 120 km/h of different wind directions. Their results showed that the value of the side force coefficient on the windward lane is larger than that on the leeward lane. They also discovered that the most serious limitation of their model was the inadequate representation of free stream turbulence, which is important in simulating the aerodynamic forces.

Sterling et al. (2010) compared the wind tunnel experiments, CFD simulations with the full-scale field measurement of the aerodynamic forces and moments of a high sided lorry. They found that all three methods can correctly simulate the mean side force coefficient. However, the lift coefficients obtained from the CFD simulations were larger than the values from the other two methods, their result can be attributed to the difficulty in simulating the near ground flow.

Cheli et al. (2011a, 2011b) conducted a series of wind tunnel experiments to measure the aerodynamic loadings on the vehicles caused by the crosswind. It included various types of vehicles (truck and tank truck) traveling on flat terrain, bridge and embankment, viaduct and double viaduct. They found that at large yaw angles ($\alpha > 50$ deg) the risk of rollover is higher for the single viaduct due to its narrow width. On the other hand, at small yaw angles, the rollover risk is higher on the embankment and double viaduct.

In view of the above studies, there was a need to protect moving vehicles against crosswind, especially in exposed sites and/or in strong wind areas. There are two approaches to mitigate the crosswind effects on moving vehicles: one is to regulate the vehicle speed, and the other is to install windbreaks on these sites. The impermeable and porous windbreaks have been widely used to reduce the crosswind effect on pedestrians and buildings (Good and Joubert, 1968; Ranga Raju et al., 1988; Lee and Kim, 1999). The force coefficients from the above vehicle studies could not be used to evaluate the vehicle safety at locations with windbreaks. Therefore, the object of this study was to investigate the protective effects of porous windbreaks on road vehicles. This study combined a Large Eddy Simulation (LES) model and a canopy model to simulate the flow field around the porous windbreaks and the vehicle. A series of numerical simulations was carried out to determine the side force and lift coefficients of vehicle with windbreaks of different heights and porosities.

2. Numerical model

In this study, the authors used a three-dimensional Large Eddy Simulation (LES) model to simulate the velocity field around a vehicle on a bridge, and calculate the aerodynamic loading on the vehicle. The governing equations can be expressed as (Pope, 2000):

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{7}$$

$$\frac{\partial \rho \overline{u_i}}{\partial t} + \frac{\partial \rho \overline{u_i u_j}}{\partial x_j} = -\frac{\partial \overline{P}}{\partial x_i} + \rho g \delta_{i3} + \frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right)\right] + f_d \tag{8}$$

where the subscripts i, j=1, 2, 3 represent x, y, z directions, respectively, t is the time, $\overline{u}$ and $\overline{P}$ are grid filtered velocity and pressure (Germano et al., 1991), respectively; ρ is the fluid density; δ_{ij} is the Kronecker delta; g is the gravitational acceleration; f_d is the drag force induced by the porous windbreak; and μ_{eff} is the effective viscosity, defined as:

$$\mu_{eff} = \mu + \mu_{SGS} \tag{9}$$

where μ is the dynamic viscosity of the air, and μ_{SGS} is the viscosity of sub-grid scale turbulence, its definition is expressed as:

$$\mu_{SGS} = \rho (C_{sm}\Delta_s)^2 \sqrt{2\overline{S}_{ij}\overline{S}_{ij}} \tag{10}$$

where C_{sm} is the Smagorinsky coefficient (Smagorinsky, 1963), S_{ij} is the rate of strain, and $\Delta_s = 2(\Delta x \Delta y \Delta z)^{1/3}$ is the characteristic length of computational cell. In this study, the value of the Smagorinsky coefficient C_{sm}=0.15 was chosen after comparing the simulation results with the experimental data. In addition, the projection method (DeLong, 1997) was used to solve the pressure Poisson Equation (PPE):

$$\frac{1}{\rho}\nabla^2 P = -\frac{\partial^2 u_i u_j}{\partial x_i \partial x_j} \tag{11}$$

The wall function suggested by Cabot and Moin (2000) was used to calculate the velocity near the solid wall:

$$\frac{\mu_{SGS}}{\nu} = \rho \kappa z_w^+ (1 - e^{-z_w^+/a})^2 \tag{12}$$

$$z_w^+ = \frac{z_i u_*}{\nu} \tag{13}$$