FSI Simulation of a Double-deck Bus Cornering under Crosswind Effects

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Abstract

Every road vehicle under motion experiences forces and moments caused by different sources. One of these sources is the wind. Several investigations have dealt with the effects of wind over road vehicles. Nowadays, it's a common practice to include also the dynamic characteristics of the vehicle. Particularly, high sided road vehicles (e.g., double-deck buses) are highly demanded and have its center of mass in a relatively high location, so in combination with moderate velocities may give rise to rollover instabilities.
In this work, an unsteady aerodynamics simulation of a simplified double-deck bus under the influence of crosswinds is performed, including the cornering scenario. The results obtained using ICFD/FSI capabilities in LS-DYNA® solver are compared with a theoretical quasi-steady analysis. The effects of crosswinds on the bus aerodynamics when cornering are evidenced as a key concept in the estimation of its rollover stability.

Introduction

Every road vehicle under motion experiences forces and moments caused by different sources. One of these sources is the wind. A number of investigations have dealt with the effects of wind over road vehicles. Particularly, several experimental and computational studies on the stability of vehicles under unsteady crosswind conditions have been conducted in the past 10 years [1-4]. Nevertheless, there is still a lack of research regarding computational simulations with coupled analysis of unsteady aerodynamics and vehicle motion and cornering. The cornering scenario plays an important role when the vehicle under study is a high-sided vehicle, like double-deck buses. Furthermore, the presence of crosswinds may affect the comfort of the passengers and even the stability of a vehicle.
The aim of this study is to make a comparison between the results obtained by computational simulation using LS-DYNA and OpenFOAM against a theoretical quasi-steady analysis. To achieve this, the target vehicle model is first presented and then the geometrical characteristics of the computational domain are described. Finally, the comparison with the results obtained by the theoretical equation formulated in this paper are compared against the simulations.

Vehicle geometry and mechanical characteristics

The vehicle of study in the present work is a simplified double-deck bus model, Figure 1. This model is based on the geometry of a real commercial bus, nevertheless its details are simplified to reduce the computational cost. The dimensions of the bus model are 14.0 m (length) x 2.5 m (width) x 4.2 m (height). The weight of the simplified truck is assumed to be 25000 kg considering passengers inside. The mechanical characteristics of the bus are reported in Table 1.
The bus model is assumed to move in a road curve at a constant speed of 80 km/h (22.22 m/s) in a cross wind region. Accordingly, the relative yaw angle of the vehicle with respect to the incoming flow changes in the curve. As a consequence of the aerodynamic forces caused by the crosswind and the centrifugal force due to the curve, the bus experiences a rollover moment that may overturn the bus on certain conditions.

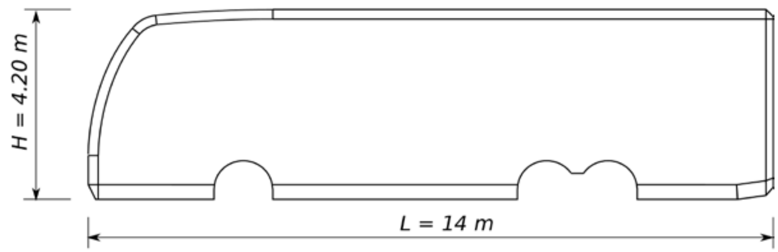

Figure 1: Main dimensions of the simplified double-deck bus model.

location of center of mass and axis of rotation mass mechanical characteristics	$z_O = 1.73\ m,\ z_T = 0.75\ m$ $m = 25000\ kg$ $k_1 = 193500\ N/m, k_{2-3} = 226000\ N/m$ $c_i = 3400\ Ns/m$

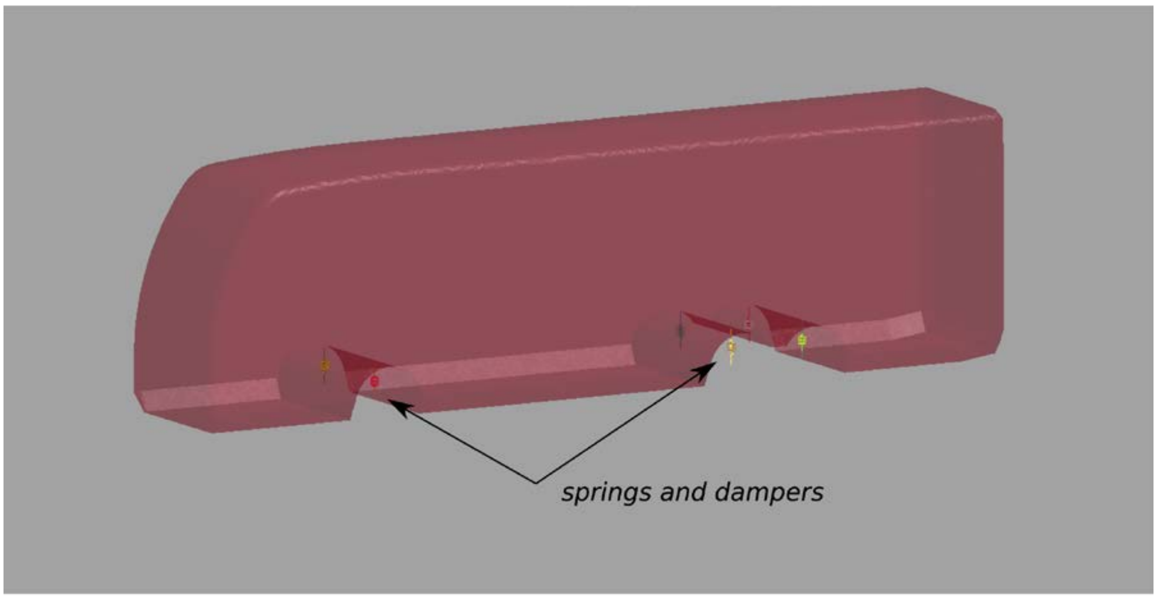

Figure 2: Mechanical model in LS-DYNA.

Analytical solution of the quasi-steady problem

The equation of equilibrium relative to the axis of rotation (*T*):

$$F_w\ z_{TO} + W\ y_{TO} = 2\phi \sum_{i=1}^{3} \frac{y_s^2}{4} k_i = k_s\ \phi, \tag{1}$$

being k_i and y_s the stiffness coefficient and transversal separation of the springs, respectively; F_W the crosswind force over the bus, *O* the mass centre, z_0 the height of the mass centre, y_{T0} and z_{T0} the separation between the mass center and the rotation axis at *y* and *z* directions, respectively. *W* is the weight of the bus (without consideration of the vertical aerodynamic force) and k_s is the stiffness of the bus system. Then, assuming a small-angle approximation and that the unstable equilibrium state would be reached once the reaction force R_z tends to zero,

$$
\begin{aligned}
R_z\ y_R =& W(y_R/2 - y_{TO}) - F_w\ z_O \to 0 \\
& W(y_R/2 - z_{TO}\ \phi) - F_w\ z_O = 0
\end{aligned} \tag{2}
$$

and considering the aerodynamic crosswind force,

$$F_w = \frac{1}{2}\rho U^2 A, \tag{3}$$

it is possible to obtain the following equation:

$$U = \left[\frac{W\ y_R}{\rho A}\ \frac{k_s - W\ z_{TO}}{W\ z_{TO}^2 + z_O(k_s - W\ z_{TO})}\right]^{1/2} \tag{4}$$

being *U* the crosswind velocity at which the bus model reaches an unstable equilibrium, *A* is the cross-reference area and ρ the air density.
In this case, with $A = 50.65\ m^2$ then $U = 63.22\ m/s$ which is a particularly high velocity to achieve in an open road (under normal conditions). Nevertheless, if another force acting laterally on the vehicle is included in the analysis, like for example the centrifugal force arising in a cornering situation, then Equation (4) may be rewritten as:

$$U = \left[\frac{W\ y_R}{\rho A}\ \frac{(k_s - W\ z_{TO})}{W\ z_{TO}^2 + z_O(k_s - W\ z_{TO})} - \frac{2F_c}{\rho A}\right]^{1/2} \tag{5}$$

where $F_c = \frac{W\ v^2}{g\ R}$, being *v* the velocity of the vehicle and *R* the cornering radius. Considering, for example, if $v = 80\ km/h = 22.22\ m/s$ and $R = 100\ m$, then the estimated maximum crosswind velocity is $U = 9.86\ m/s$.

Computational domain and mesh configuration

The dimensions of the computational domain adopted in this work are: *16.4 B = 82 m* width (normal or lateral direction *Y*), *7.6 H = 32 m* tall (vertical direction *Z*) and *8 L = 112 m* depth (longitudinal direction *X*, following the flow direction), see Figure 2. These geometric dimensions are adopted in order to eliminate the interference effects caused by the bus model over the inlet and outlet boundary conditions.

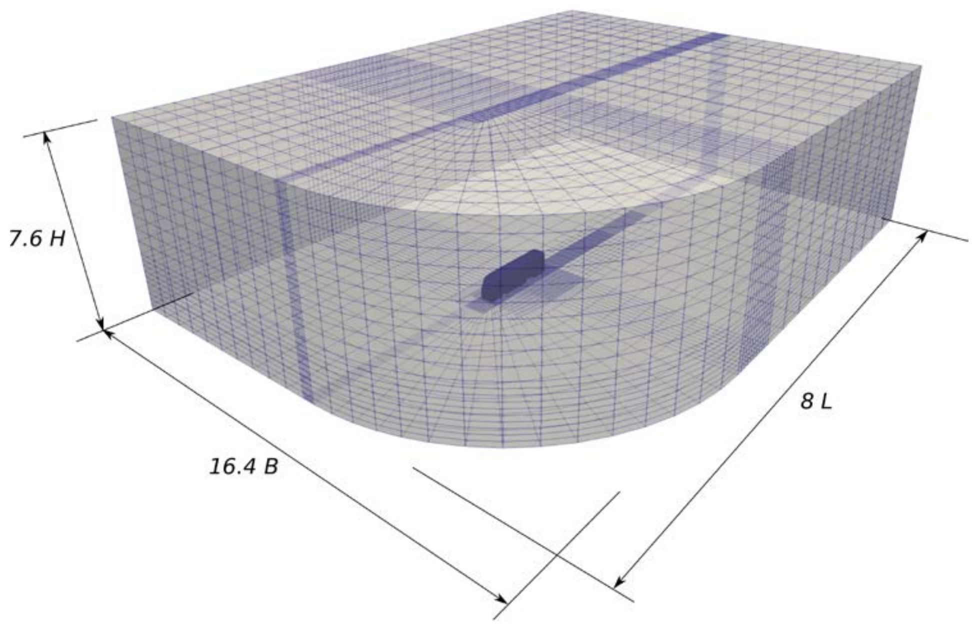

Figure 3: Configuration of the computational domain mesh (OpenFOAM).

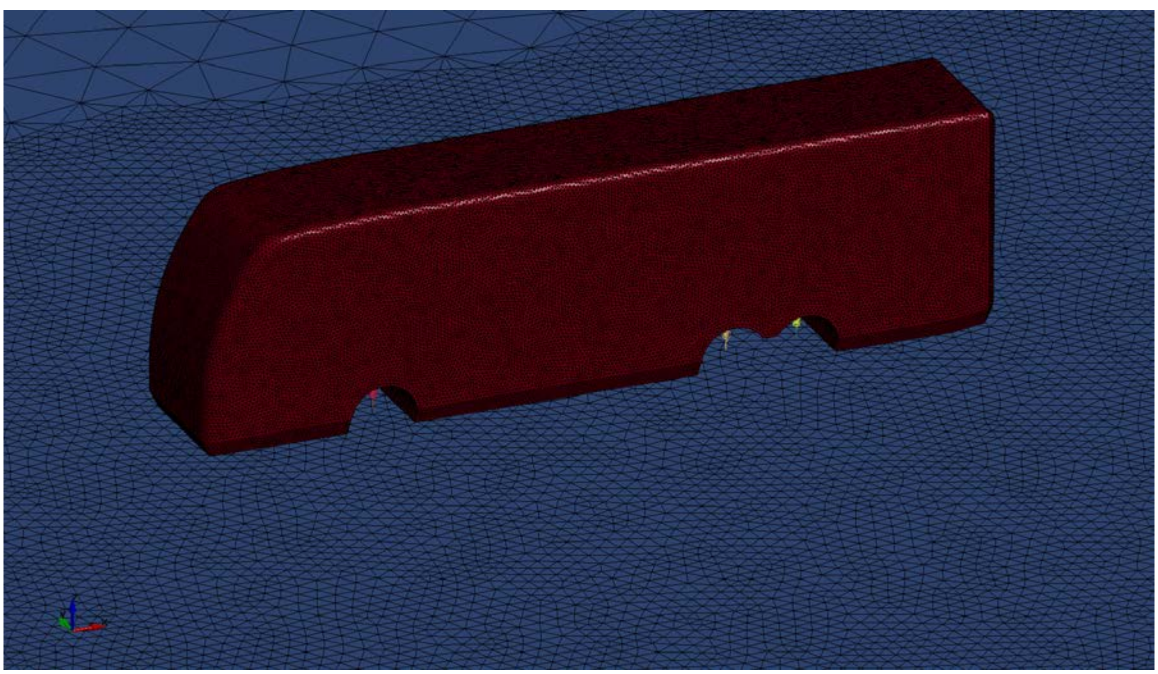

Figure 4: CFD surface mesh (LS-DYNA).

Synthetic turbulence flow generation in LS-DYNA

Based on the DSRFG technique [5], Castro and Paz [6] proposed some modifications to this methodology in order to improve its statistical characteristics. Accordingly,

$$u_i(x,t) = \sum_{m=1}^{M}\sum_{n=1}^{N} p_i^{m,n}\cos(\tilde{k}_j^{m,n}\tilde{x}_j + \omega_{m,n}\frac{t}{\tau_0}) + q_i^{m,n}\sin(\tilde{k}_j^{m,n}\tilde{x}_j + \omega_{m,n}\frac{t}{\tau_0}), \quad (6)$$

and

$$p_i^{m,n} = (r_i^{m,n})\sqrt{\frac{2}{N}S_i(f_m)\Delta f\frac{(r_i^{m,n})^2}{1+(r_i^{m,n})^2}}$$

$$q_i^{m,n} = (r_i^{m,n})\sqrt{\frac{2}{N}S_i(f_m)\Delta f\frac{1}{1+(r_i^{m,n})^2}},$$

where τ_0 is a dimensionless parameter to allow control over time correlation of the velocity fluctuations and Δ_f is the frequency bandwidth defined by the spectrum discretization. With these modifications, in [6] and [7] it is proved that this technique provide a velocity field at the inflow that preserves the statistical quantities irrespective of the resolution with which the target spectrum was discretized. Since this approach was based on the DSRFG technique, the authors called it as modified discretizing and synthesizing random flow generation (MDSRFG) method.

Preliminary Results and Symmary

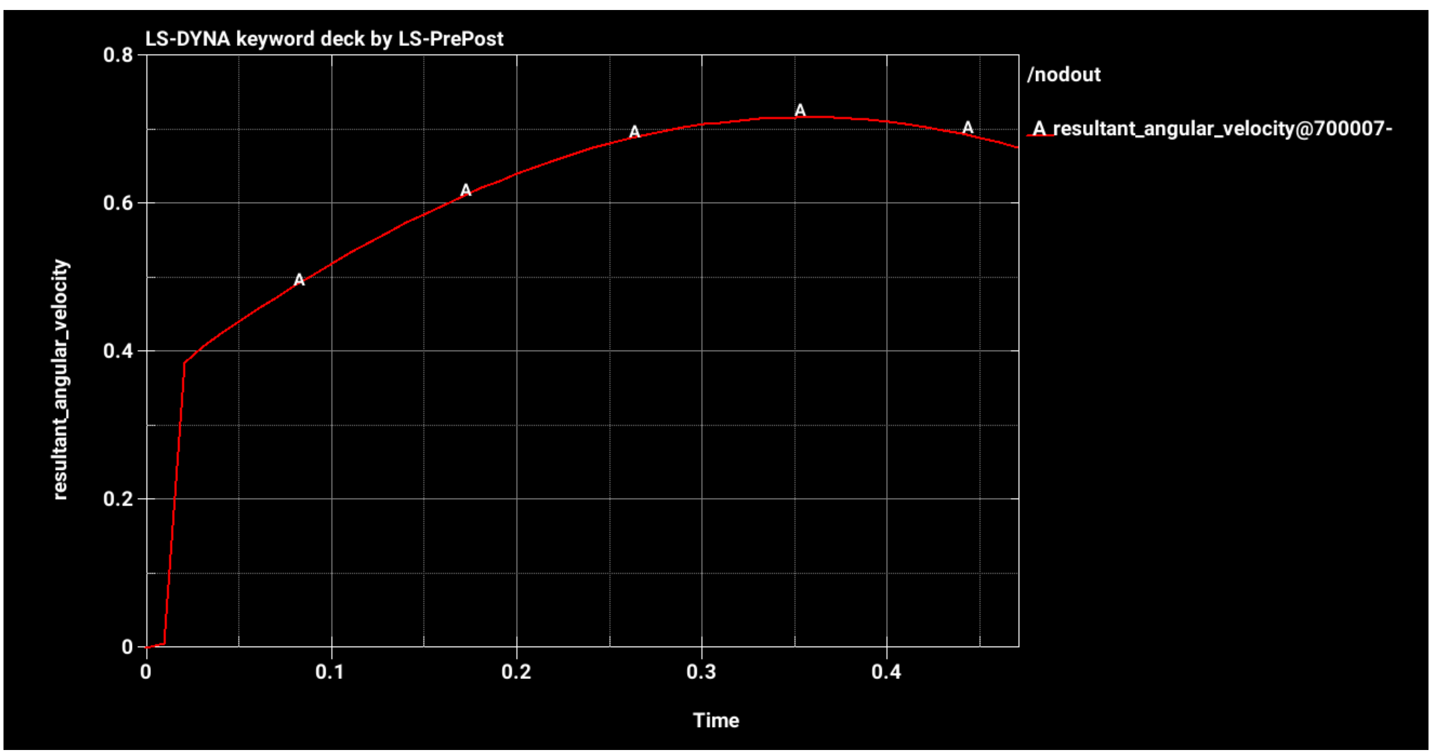

Figure 5: Velocity of the bus center of mass during rollover.

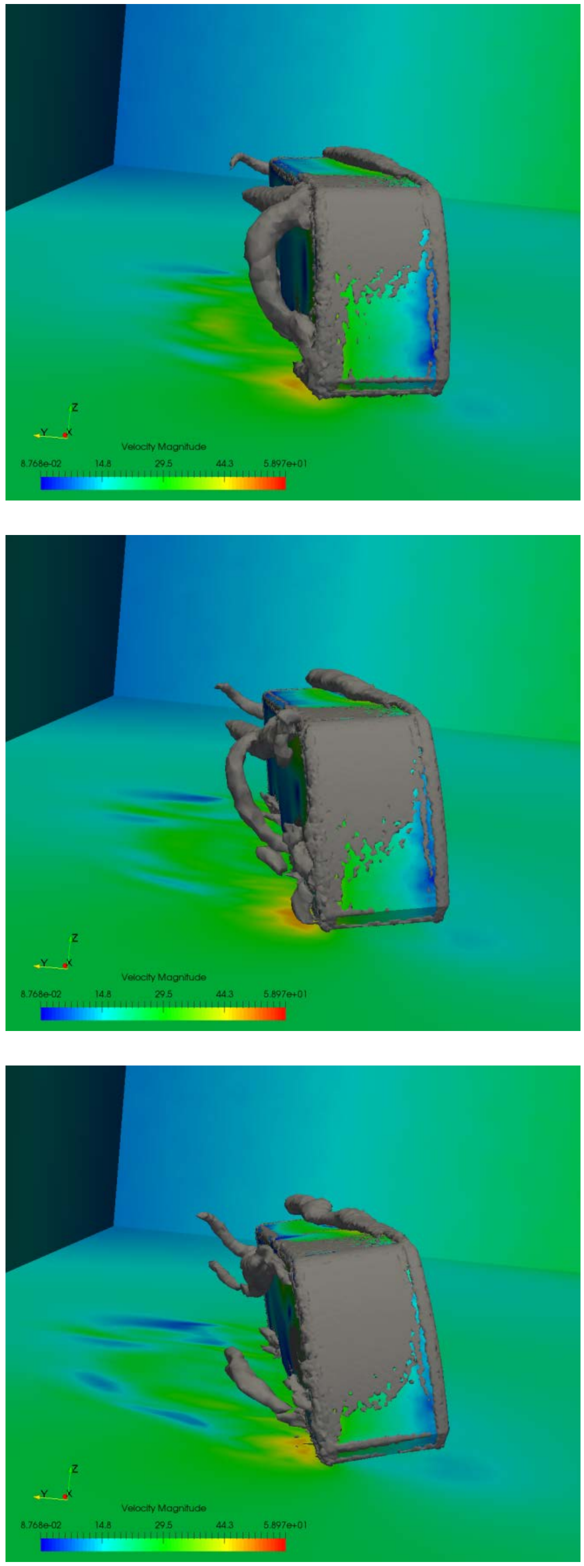

Figure 6: Bus rollover sequence.

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