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Coupling aerodynamics to vehicle dynamics in transient crosswinds including a driver model

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ABSTRACT

In this paper we assess the order of model complexity needed to capture a vehicle behaviour during a transient crosswind event, regarding the interaction of the aerodynamic loads and the vehicle dynamic response. The necessity to perform a full dynamic coupling, including feedback in real-time, instead of a static coupling to capture the vehicle performance both with respect to aerodynamics and the vehicle dynamics is evaluated. The computations are performed for a simplified bus model that is exposed to a transient crosswind. The aerodynamic loads are obtained using Detached Eddy Simulation (DES) with the overset mesh technique coupled to a single-track model for the vehicle dynamics including a driver model with three sets of controller parameters to obtain a realistic scenario. Two degrees of freedom are handled by the vehicle dynamics model; lateral translation and yaw motion. The results show that the full dynamic coupling is needed for large yaw angles of the vehicle, where the static coupling over-predicts the aerodynamic loads and in turn the vehicle motion.

1. Introduction

In the design of today's vehicles there is a strong emphasis on reducing the vehicle weight and to lower the aerodynamic drag in order to leave a smaller ecological and economical footprint. This has shown to affect the crosswind sensitivity for ground vehicles, which is of importance for handling and safety [1]. Crosswinds will impose high pressure at the windward side of the vehicle and low pressure at the leeward side, especially at the front, giving a yaw moment that will tend to turn the vehicle with the wind [2]. A more fuel efficient design moves the centre of pressure forward giving a vehicle that is more prone to deviate from its original path when exposed to crosswinds [3], hence a more unstable behaviour. The most obvious aspect is that a more unstable behaving vehicle will easier be blown off the road. However, it will also require more steer input response from the driver to be kept on the road, which is tiring and in turn unsafe.

Crosswind stability is the result of complex interactions between aerodynamics, vehicle dynamics and the driver. Hence, to assess crosswind stability the complete system has to be taken into account including the incoming flow, the aerodynamics, the vehicle dynamics and the driver, Fig. 1.

However, the aerodynamic design is usually developed in isolation from the chassis and the influence of the aerodynamics on the handling of the vehicle is most often disregarded. Today's development tools like crosswind testing facilities, with a constant relative yaw angle flow will not fully replicate real-world conditions and thus, do not capture all the relevant phenomena. A phenomenon that is not captured, is when the vehicle enters a crosswind passage giving a side force at the front of the vehicle at first, before the rear of the vehicle is affected [5]. The aerodynamic load in front of the centre of gravity of the vehicle will tend to yaw the car with the crosswind while the aerodynamic load at the rear of the vehicle, giving a negative yaw moment, will counteract the forces giving an overall lower yaw moment. Hence, an unsteady approach may give overshoots in yaw moment that will not be captured by the quasi-steady approach, which by definition makes the aerodynamic loads for the front and the rear of the vehicle to be in phase, which most wind tunnels built for development purposes are limited to.

Once a prototype is built, the vehicle can be driven on the road to check its crosswind sensitivity. However, at this late stage in the design process, it may be difficult to perform changes to the design, if needed.

During on-road conditions, the vehicle is often exposed to unsteady crosswinds due to atmospheric turbulence, landscape variations, when overtaking another vehicle or when exiting a tunnel. Several approaches have been taken to predict vehicles' performance when subjected to transient crosswinds. Wind tunnels have

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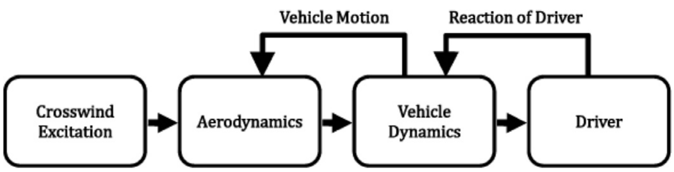

Fig. 1. View of the complete system including aerodynamics, the vehicle dynamics and the wind disturbance. Figure based on the work in [4].

been developed to measure vehicle performance when exposed to transient crosswinds using an additional inflow from the side of the tunnel, where the flow can be controlled via shutters [6,7] or by using a moving vehicle propelling across the wind tunnel [8]. However, none of these experimental setups account for the vehicle dynamic response, which may alter the flow around the vehicle. Another possibility is to perform on-road measurements to account for the vehicle dynamics and get realistic wind conditions [9]. The problem here is to get repetitive measurements as well as knowledge of the actual wind conditions. Apart from performing on-road measurements with atmospheric crosswinds, mounted fans at the side of the road can be used to produce a more repetitive and controllable crosswind [10]. However, fans will give a swirling flow, which may give different flow behaviour over the vehicle than atmospheric crosswinds and in worst case an erroneous response to design alterations. Another option is to use numerical simulations where the aerodynamic simulations through Computational Fluid Dynamics (CFD) can be coupled to a vehicle dynamics model. One possibility is to use a static coupling approach [11], where the motion of the vehicle is not considered in the aerodynamic computations. A more realistic approach is to couple the aerodynamics model to a vehicle dynamics model with feedback in real-time [12], a full dynamic coupling approach. In [12], the vehicle was modelled in a wind tunnel where the motion was imposed using the Arbitrary Lagrangian–Eulerian (ALE) approach to alter the aerodynamic domain for the yaw motion and the Navier–Stokes equations were expressed in a non-inertial reference frame to consider lateral translation. However, when simulating a vehicle in a wind tunnel configuration it is difficult to get correct relative yaw angle of the head wind onto the vehicle, which should follow its yaw motion, as when driving on the road.

The aim of this work is to assess the needs to perform a full dynamic coupling of the aerodynamics and the vehicle dynamics including a driver model when predicting vehicle performance when exposed to transient crosswinds through numerical simulations. A new approach in this context is used to consider the aspects that previous studies mentioned did not capture. This work is an important step in the process to develop a virtual development tool, where the effect of different vehicle designs on safety, comfort and energy efficiency can be evaluated in an early phase of vehicle development. That is before any prototype is built.

Additionally, some parameter changes have been made to show the robustness of the method used.

2. Methods

The vehicle dynamics model dictates how the vehicle moves in time when exposed to the aerodynamic load imposed on the vehicle. To study the effect of how the motion of the vehicle affects the aerodynamic loads and in turn the motion of the vehicle, the aerodynamic computations are coupled to the vehicle dynamic model via a full dynamic coupling (two-way) and via a static coupling (one-way). For the two-way coupling approach, the position of the vehicle is chosen to be updated at every time instant from the vehicle dynamics model. For the one-way coupling approach, the aerodynamic loads are first computed without feedback from the vehicle dynamics model and then used as input to the vehicle dynamics model to compute the motion of the vehicle. The aerodynamic and the vehicle dynamic model are described under Sections 2.1 and 2.2, respectively. To get a more realistic scenario than simply holding the steering wheel straight and letting the vehicle drift with the wind, a driver model was added, see Section 2.3.

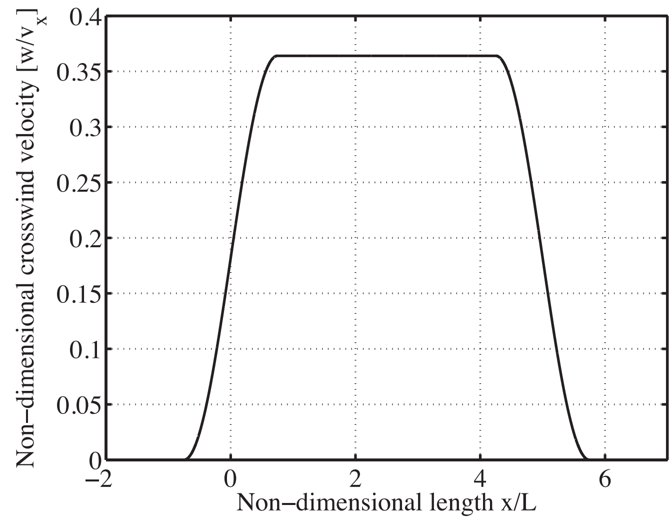

Fig. 2. Crosswind velocity profiles with a slope time corresponding to 1.5 vehicle lengths.

The computations are performed for a simplified bus geometry, which is based on a simplified tractor-trailer truck model developed at SANDIA National Laboratories [13], which is shortened to resemble a bus. The bus travelling with a speed of 90 km/h (25 m/s) running through a crosswind passage with a wind speed of 9 m/s corresponding to a maximum relative yaw angle of 20^o is simulated. The crosswind velocity was chosen from the fact that a crosswind with a relative velocity of just above 20^o gives maximum yaw moment on the vehicle and is frequently experienced in real life [14]. More recent measurements propose that the side wind is often sinusoidal with an amplitude of 3–6 m/s [15].

The assumed shape of the crosswind gust at the side inlet to the aerodynamic domain is shown in Fig. 2 as wind speed w non-dimensionalized with the vehicle speed v_x. The length of the wind gust is chosen to be five vehicle lengths, starting at the non-dimensional length zero in Fig. 2, to not develop steady flow conditions around the vehicle body, which is expected to occur after seven vehicle lengths [16]. The ramp up and down time used, corresponds to 1.5 vehicle lengths based on a cosine function in accordance to natural crosswinds [17]. The wind profile used is not changing with height, which in reality may be less strong close to the ground due to a developed boundary layer in relation to obstacles near the road.

The method applied is also suited for studying other aerodynamic and vehicle dynamics coupling phenomena than crosswind sensitivity, as for example the influence of unsteady flow structures on the pitch motion and handling, which previously has been studied though a predefined vehicle motion [18].

2.1. Aerodynamics

The Detached Eddy Simulation (DES) approach, known for its capabilities to predict aerodynamic performance for both space and ground vehicles [19] [11], is used for the aerodynamic computations. The DES approach is a hybrid method aimed at simulating high Reynolds number, massively separated flows. DES