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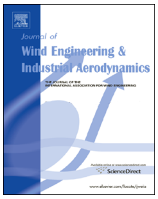

Forces and flow structures evolution on a car body in a sudden crosswind

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ABSTRACT

A vehicle driver is commonly exposed to strong side air flows, for example when passing through a wind gust. The aerodynamic efforts generated in these situations may induce undesired lateral deviations, which can lead to dramatic effects, if the driver is surprised. In order to simulate a sudden yaw angle change on a moving vehicle, a double wind tunnel facility, adapted from the one of Ryan, Dominy, 2000. Wake Surveys Behind a Passenger Car Subjected to a Transient Cross-wind Gust. SAE Technical Paper No. 2000-01-0874 is developed. Two Windsor car body models, differing from their rear geometry, are analysed. The transient evolution of the side force and yaw moment aerodynamic coefficients are interpreted in connection with the unsteady development of the flow, based on TR-PIV and stereoscopic PIV measurements. Our analysis shows that the region which is most sensitive to crosswind is located at the rear part of the leeward flank. However, changes in the rear geometry (from squareback to fastback body) only affect the established lateral coefficients values while transient duration and the force overshoots appear not to be significantly modified. Furthermore, the circulation of the most energetic leeward vortex appears to be correlated with the lateral coefficients transient evolutions.

1. Introduction

It is a relatively common experience, when travelling by car, to come across any kind of unsteady side wind, for example a natural wind gust or simply the air mass displaced by the vehicle arriving from the opposite direction. It is also known that great care has to be taken when driving during these short lapses of time, because the pressure imbalance between the windward and the leeward flank generates unsteady aerodynamic forces. These efforts are a potential source of hazard, since the vehicle can be deviated from its trajectory by the combined action of side force and yaw moment. More likely in the case of buses, trucks or lightweight trains, the vehicle can be also overturned by the effect of roll moment, as it has been detailed by Baker (1986). As a matter of fact, in the quasi-steady analysis held by Hémon and Noger (2004), it was demonstrated that when a vehicle is subjected to a steep change of wind direction, transient growth of energy occurs, this causing dynamic instability. Moreover, the driver himself can negatively affect the vehicle stability, if he is surprised and accidentally over-corrects the steering angle, (Emmelmann, 1998). The dynamic stability of a given vehicle to a wind gust can be estimated starting from non-linear vehicle models. However, in order to close these models and calculate vehicle trajectory, it is necessary to give as an input the aerodynamic forces evolutions, as recommended by Gilliéron and Kourta (2011).

For many years, it has been thought that lateral forces evolutions could be considered as quasi-static, and that it would be sufficient to measure the steady force coefficient of a static yawed model to predict vehicle behaviour in crosswind. However, Beauvais (1967) showed that the unsteady yaw moment peak can be 40% greater than the corresponding steady effort, if the yaw angle is higher than 10°. This means that it is necessary either to model unsteady effects from the steady measurements, or to reproduce directly a wind gust by means of adapted test benches. In next paragraph, a brief summary of experimental and numerical techniques, used for estimating the unsteady lateral forces evolution is presented.

1.1. Experimental and numerical simulation of lateral wind gusts on ground vehicles

The most realistic approach to experimentally simulate a wind gust on ground vehicles is to propel a vehicle model on a rail trough the flow generated by a lateral wind tunnel. When performing these tests, the main goal is usually to evaluate the ratio between the unsteady efforts peaks and the corresponding

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values resulting from the steady state case. Most of the authors, such as Beauvais (1967), Cairns (1994), Baker and Humphreys (1996), Chadwick (1999) agree that this ratio is 1.2 to 1.5, whereas Stewart (1977) and Kobayashi and Yamada (1988) measured yaw moment peaks up to more than the double of the static force. Also, Baker and Humphreys (1996) studied the influence of the yaw angle and found out that the peak overshoot tends to disappear in the range between 40° and 60°. Another result of interest is the establishment time of the force coefficient, expressed as the number of times the vehicle has travelled its own length through the side wind wall. Little agreement was found between the authors: Beauvais indicates the establishment time after 4 vehicle lengths, but in Cairns and Chadwick tests, where a 5 vehicle wide gust was employed, no force establishment was seen. In Stewart's case, this time is dependent on the vehicle geometry. Such scattered data between the different authors can derive from the main drawbacks of this kind of test bench, that is the presence of noise in the signal and the difficulty in having data with high repeatability. The noise mainly derives from both the vibrations induced by the small irregularities on the rail and the resonance frequencies of the moving facility itself, excited by the wind tunnel flow. An elevated number of test repetitions is then needed and great care has to be taken during the processing data phase.

This is one of the reasons why the steady wind tunnel tests with yawed vehicle have not been completely disregarded. As a matter of fact, when the side wind is stochastically expressed by its spectrum, it is possible to obtain the corresponding spectra of the unsteady force coefficients, by means of a correction function called “aerodynamic admittance”, which also requires the steady coefficients values. This function is defined in the complex domain and has been described by Cooper (1984) and Baker (1991a). This aerodynamic admittance can be measured from static yawed model tests, at high turbulence intensity, or by means of the test bench proposed by Bearman and Mullarkey (1994), in which a static model is subjected to a sinusoidal flow created by an upstream series of oscillating profiles. The latter tests have to be repeated at different oscillation frequencies, to collect the information for the whole spectrum. Furthermore, the aerodynamic admittance can be approximated with the formulae proposed by Baker (2010) or estimated with the model of Tomasini and Cheli (2013). Once the aerodynamic admittance is known, it is possible to derive a weighting function which relates the force evolution to the side wind history with a convolution integral.

Another advantage of static tests is that it is simpler to retrieve information about the flow field, which mainly presents two different patterns, depending on the yaw angle, as described by Baker (1991b) and numerically confirmed by Khier et al. (2000). For small yaw angles, from 0 to 30°, the vehicle can be considered as a slender body, and a detailed description of the flow field can be found in the work of Mair and Stewart (1985). A schematic drawing of this kind of flow is depicted in Fig. 1, for a simplified shape of squareback vehicle. In the slender body flow, the most energetic structure, Γ_A, originates from the front of the vehicle, near the roof, and expands along the leeward flank. A second twin vortex Γ_B originates from the vehicle underbody. A last vortex, Γ_C, develops from the windward side of the roof. The intensity and the size of these structures grow up with the yaw angle, in the range of 0°–30°.

Chiu and Squire (1992) expanded this study to higher yaw angles. In particular, they showed that for very high yaw angles, starting from 60°, vortex shedding is visible in the wake, since the vehicle can be considered as a bluff body. In the intermediate range between 30 and 60°, they also showed that the vortex shedding wake and the flow pattern from Fig. 1 coexist. More precisely, there is a dynamical switch between the two flow configurations.

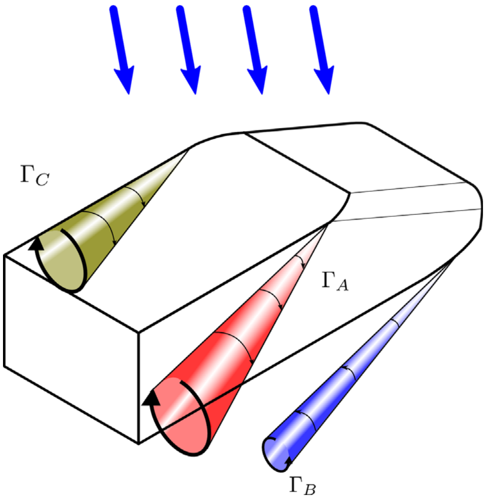

Fig. 1. Vortices representation for a vehicle subjected to steady crosswind, $0^\circ < \beta < 30^\circ$. Image inspired by Baker (1991b).

Other kinds of side wind test benches have been conceived, in order to join the advantages of both previous approaches. For example, Garry and Cooper (1986) mounted their 1—box vehicle models on an oscillating turntable, situated in a middle of a wind tunnel. A similar technique was used by Cairns (1994), except that a sudden yaw angle change was imposed, with no oscillation. No force overshoot was seen. However, in both cases, the unsteady effort appeared to be delayed, if compared to the steady effort at the equivalent yaw angle. The work of Chometon et al. (2005), based on PIV measurements, allowed to give an explanation. In fact, the formation of flow field vortices is not instantaneous, but occurs with a phase shift. In particular, Ferrand and Grochal (2012) proved that the phase shift of the side force is greater in the rear part of the body.

Another interesting kind of test bench is the moving side jet facility proposed by Dominy (1991). With this approach, the moving model principle is completely reversed: the model is now static, and two wind tunnels produce an unsteady side wind. The main wind tunnel is classically used to simulate the streamwise vehicle motion, while the auxiliary one produces the wind gust. The passage of the auxiliary air flow in the measurement region is driven via a user-controlled intercommunication system. In the main results presented in Ryan (2000), Ryan and Dominy (2000), side force and yaw moment overshoots were seen at the gust entrance, varying from 7% to 55%, depending on the studied geometry. The flow establishes after 7 vehicle lengths. The flow field was also inspected by hot-wire probing and the origin of force overshoots was attributed to the delayed formation of the separation region near the front leeward corner.

As far as the numerical simulations are concerned, the rigorous reproduction of a vehicle moving through a wind wall is not an easy task. As a matter of fact, sliding or deforming meshes are needed, which can lead to convergence difficulties and calculation time enhancement. At first, 2D analyses on simplified car bodies, overtaking each other, were made by Clarke and Filippone (2007) and Corin et al. (2008). In particular, in the latter work, it was found that steady simulations underestimate the unsteady results, as seen in experiments. Recently, a simulation of a heavy-duty truck crossing a wind gust has been made by Nakashima et al. (2012). In this simulation, the fluid equations, in which the large eddy simulation (LES) approach has been used, were coupled with a 3 degree-of-freedom model of the vehicle's dynamic motion. A simple driver model was also added. The calculated yaw moment presents overshoots up to 200% at the entrance and at