

Unsteady Aerodynamic Properties of a Vehicle Model and their Effect on Driver and Vehicle under Side Wind Conditions

2011-01-0154

Published
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FKFS

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doi:10.4271/2011-01-0154

ABSTRACT

In this paper the effect of aerodynamic modifications that influence the unsteady aerodynamic properties of a vehicle on the response of the closed loop system driver-vehicle under side wind conditions is investigated.

In today's aerodynamic optimization the side wind sensitivity of a vehicle is determined from steady state values measured in the wind tunnel. There, the vehicle is rotated with respect to the wind tunnel flow to create an angle of attack. In this approach however, the gustiness that is inherent in natural wind is not reproduced. Further, unsteady forces and moments acting on the vehicle are not measured due to the limited dynamic response of the commonly used wind tunnel balances.

Therefore, a new method is introduced, overcoming the shortcomings of the current steady state approach. The method consists of the reproduction of the properties of natural stochastic crosswind that are essential for the determination of the side wind sensitivity of a vehicle. Further, a fast-response wind tunnel balance is used to measure unsteady forces on the model resulting from the crosswind excitation. The results for a notchback model are presented in terms of aerodynamic transfer functions for side force and yawing moment and the effect of aerodynamic modifications is discussed.

With the method described, the optimization of the aerodynamic properties of a vehicle is no longer restricted to steady state values, but extended to the frequency range that is relevant from a driving dynamics point of view. To estimate the influence of an aerodynamic modification

affecting the unsteady response of a vehicle, aerodynamic transfer functions are included in a vehicle dynamics model. Further, the effect on the driver's subjective assessment is evaluated by simulation of the closed-loop system composed of driver and vehicle.

INTRODUCTION

When a vehicle travelling at high speed is exposed to a crosswind gust, side force and yaw moment cause a path deviation that needs to be corrected by the driver. Since wind gusts occur randomly in strength and direction, it is not possible for the driver to anticipate the vehicle response in this situation. His steering actions might therefore be inadequate to compensate for the crosswind disturbance, which might lead to critical driving situations. Moreover, a significant vehicle response to crosswind degrades the driver's subjective evaluation, because directional stability is expected even under strong wind conditions.

In [Figure 1](#) the time history of a flow situation under strong wind conditions is shown. The data is taken from earlier investigations [23] where measurements were done under different wind conditions on public roads to quantify the flow situation a vehicle is typically exposed to. Due to the presence of natural wind it can be seen that the approaching flow velocity differs significantly from the driving velocity of the vehicle. Further, the angle of attack shows slowly varying but also abrupt changes between $\pm 10^\circ$. In the course of the development process of a vehicle the question of the vehicle's response to these wind conditions is to be answered.

Answers can be derived from various development tools: passing a crosswind facility is a commonly used approach, but needs to be critically questioned as sometimes objective

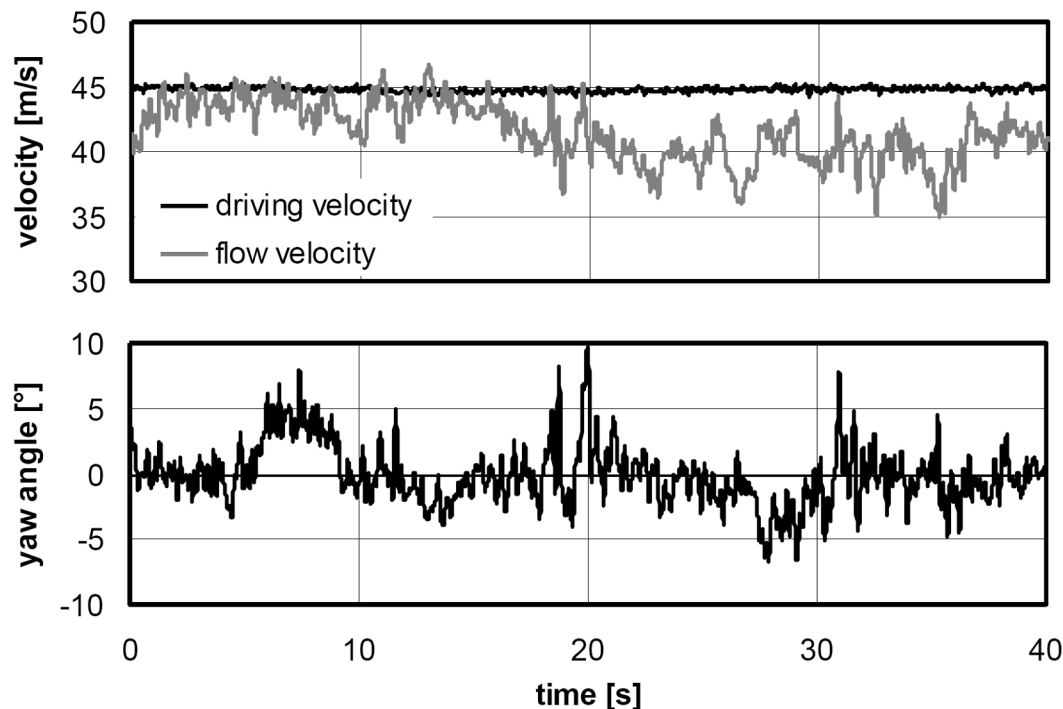


Figure 1. On-road flow situation under strong wind conditions

testing results do not correspond to the driver's subjective assessment. This is due to the well known fact of the driver's customization to the driving situation which leads to unrealistic actions with respect to the driving situation under natural stochastic crosswind [29]. Therefore, the evaluation of the driver-vehicle interaction is best performed on road under these wind conditions [12, 21, 29, 30]. However, both approaches rely on prototypes in running condition which is a mayor drawback in the early development phase. Further, the aerodynamic response of the vehicle due to a crosswind excitation is not easily derived from road measurements due to the interaction with lateral vehicle dynamics and driver response. Therefore, it is more feasible to use a model in a wind tunnel. There, the crosswind sensitivity of the vehicle is usually assessed by performing a yaw sweep. This approach however is based on average values and does not take any time dependency into account. The variations of the approach flow in time and space are neglected, which is incorrect with respect to the on-road condition as shown in Figure 1. Gusty crosswind can cause unsteady effects that cannot be captured in the steady state experiment. Different methods are reported, that aim at producing an unsteady flow in the test section of a wind tunnel (e.g. [2, 4, 5, 15, 19]). Results of the unsteady response of basic bluff bodies (e.g. [8, 9, 11, 17, 28]), thin plates (e.g. [1, 18]), trains (e.g. [6, 16, 26]) and cars (e.g. [14, 15, 22]) to the unsteady excitation are usually reported in terms of aerodynamic admittance functions. Due to the complexity of these experimental setups, a number of theoretical approaches can also be found in the literature. There, the unsteady response of the vehicle is estimated from results from thin plates, or from analytical approaches

derived for wings. The results show, that an empirical or analytical model is not sufficient to describe unsteady effects of a three-dimensional body. Thus, CFD calculations are used to simulate an unsteady excitation of the vehicle, e. g. by a single wind gust, to capture these effects (e.g. [10, 27, 31]). The results allow a deeper insight into the unsteady flow field surrounding the vehicle and provide a basis to gather a fundamental understanding of the source of unsteady forces. However, long turnaround times of unsteady simulations impede their productive use in the aerodynamic development process.

In the following a method is introduced that overcomes the shortcomings of the tools discussed above. It consists of the generation of strong crosswind gusts in the test section of the IVK model scale wind tunnel that are necessary to reproduce the transient aerodynamic response contributing to straight line stability under crosswind. It further consists of the definition of a causal relation between crosswind excitation and resulting side force and yaw moment allowing the use of methods from linear system theory to evaluate the aerodynamic response which is presented in terms of transfer functions. This allows their seamless integration into a driving dynamics model to evaluate the effect of aerodynamic modifications on the unsteady response of the complete system composed of driver and vehicle.

EXPERIMENTAL SETUP

Measurements were conducted in the IVK model scale wind tunnel of Universität Stuttgart. It is a Göttingen type wind

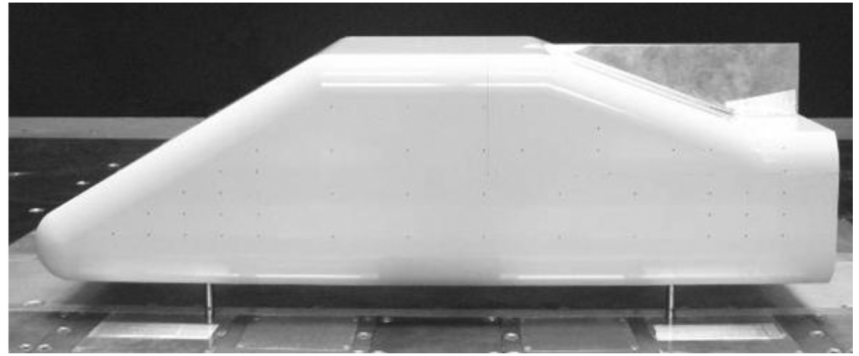
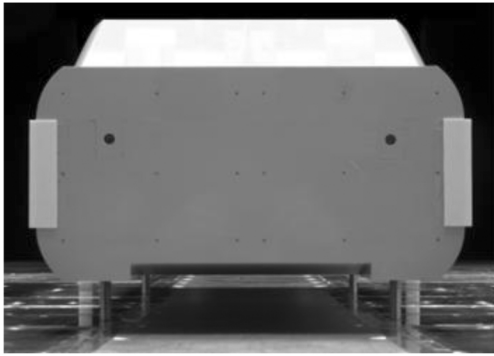


Figure 2. Aerodynamic modifications: separation edges (left); tail fin (right)

tunnel, i. e. a wind tunnel with a closed air circuit and an open jet test section. The cross sectional area of the nozzle exit is $A = 1.65 \text{ m}^2$. A maximum free stream velocity of $v_\infty = 80 \text{ m/s}$ can be reached.

In order to conduct unsteady measurements successfully, a fast-response wind tunnel balance is necessary. Since the standard underfloor balance of the IVK model scale wind tunnel is not suited to resolve forces in the desired frequency range, the 5 belt road simulation system is removed from the wind tunnel floor and a fast response model balance from RUAG Aviation is inserted in the available space. This means, that neither the boundary layer conditioning system nor the road simulation system is used at the current state of these investigations. In order to obtain the aerodynamic forces and moments acting on the model, the measuring data from the balance needs to be corrected with the system's mechanical transfer function. This is necessary, because resonance and damping of the mechanical system alter the amplitude of forces and moments at specific frequencies. The transfer function is determined via the impulse-response method, which means that the model is excited with an impulse hammer and the resulting forces are measured. The transfer function is then calculated from the spectrum of the excitation and the spectrum of the response.

For the development of the method and the study of fundamental unsteady aerodynamic effects, a 20% SAE notchback model is used. Two aerodynamic modifications are realized: the first consists of two separation edges attached to the end of the model; the second consists of a tail fin as can be seen in [Figure 2](#).

The determination of the unsteady aerodynamic properties of a vehicle under crosswind conditions requires the simulation of crosswind gusts in the wind tunnel. This is done with an active airfoil gust generator (see also [24, 25]). The system is capable of generating single generic crosswind gusts at specific frequencies and amplitudes, but can also be used to simulate a broad band gust spectrum covering the frequency range relevant to driving dynamics. The latter is the preferred

method used in these investigations, since, in comparison to an excitation at single frequencies as in [2, 15] or the generation of single events as in [10, 19, 27, 31], the entire frequency range can be measured at the same time. The flow field generated is fully coherent across the width and height of the model and neglects locally existing small scale flow structures and a boundary layer profile. This is a distinct difference to systems known from literature that aim at reproducing part of the atmospheric boundary layer (e. g. [4, 5]). The flow situation generated with the active airfoil gust generator reproduces the properties of atmospheric crosswind gusts that are essential to simulate the flow situation necessary to reproduce the transient aerodynamic response contributing to straight line stability. The simplifications that are made allow the definition of the test setup as an input output relation with the crosswind excitation as the input and side force or yaw moment as the output of the system. This is the mathematical basis for the determination of the unsteady aerodynamic properties of the vehicle in terms of transfer functions as will be outlined in the following chapter.

To characterize the incident flow, measurements were done with a fast response Cobra Probe. The probe is positioned in the center of the empty test section at $x = y = 0 \text{ mm}$, and $z = 200 \text{ mm}$ above the test section floor. The time histories of the flow angle when single generic crosswind gusts are generated are shown in the left plot of [Figure 3](#). The sinusoidal behavior of the flow is clearly recognizable for the different frequencies simulated. Further, for all frequencies maximum amplitudes of $\pm 10^\circ$ are reached. The second plot of the Figure shows the time history when a broad band gust spectrum is generated. This particular flow situation simulates the essential properties of strong crosswind gusts as found during road measurements and is the preferred excitation in this investigation. [Figure 4](#) shows a plot of the frequency distribution of the flow angle in the empty test section when the system is in operation. It can be seen, that the unsteady yaw angle follows a normal distribution with maximum amplitudes of $\pm 10^\circ$. Further, the spectral content is shown in [Figure 5](#). It follows the von Kármán spectrum which

describes the energy distribution of a fully developed atmospheric boundary layer.

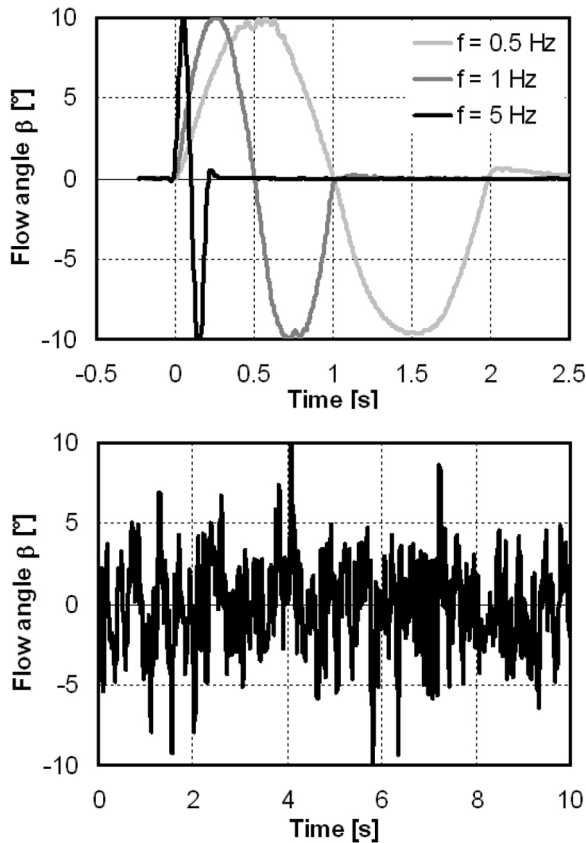


Figure 3. Time history of flow angle in the test section of the model scale wind tunnel: generic wind gusts at different frequencies (above); broad band gusts (below)

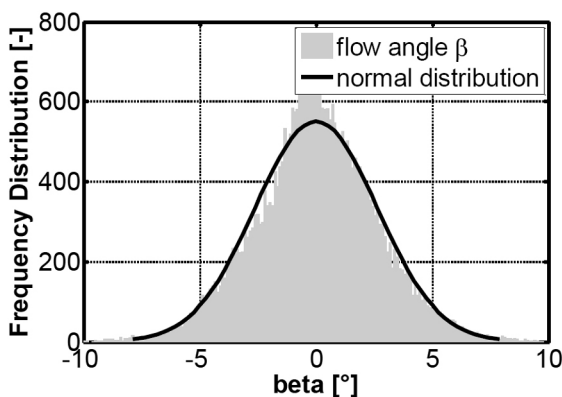


Figure 4. Frequency distribution of flow angle in the test section of the model scale wind tunnel when system is operated with broad band gust spectrum

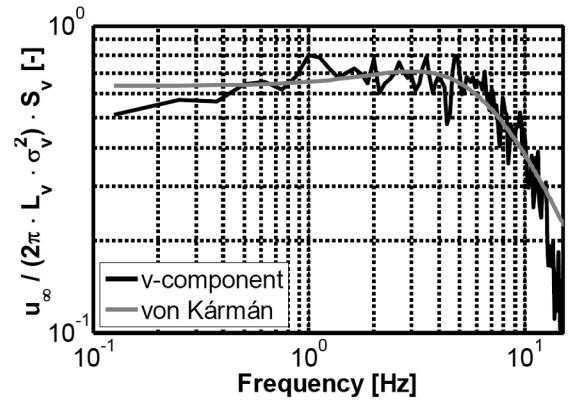


Figure 5. Spectral content of v-velocity component in the test section of the model scale wind tunnel when system is operated with broad band gust spectrum

DETERMINATION OF THE UNSTEADY AERODYNAMIC VEHICLE RESPONSE

It is common practice to use aerodynamic coefficients from steady state wind tunnel experiments to calculate forces due to an unsteady wind excitation. However, this approach implies that the unsteady flow field is fully coherent over the vehicle body and behaves in a quasi steady way. But this assumption does not hold true for the entire frequency range of interest. Therefore, the aerodynamic admittance function was introduced by Davenport [7]. It is a dimensionless function that takes the frequency dependency of the generation of unsteady forces due to an unsteady excitation into account. It is calculated by relating the spectrum of measured unsteady forces to the spectrum of forces derived from a quasi steady theory using the spectrum of the unsteady wind input and the stationary coefficient gradient. With respect to side force and yaw moment the aerodynamic admittance function of a vehicle can be defined as

$$X_{a,S,N}(f) = \sqrt{\frac{S_{c_S, c_N}(f)}{\left(\frac{dc_{S,N}}{d\beta}\right)^2 \cdot S_\beta(f)}} \quad (1)$$

Figure 6 shows the principal run of an admittance function. For frequencies approaching zero turbulent length scales are to a considerable degree larger than the vehicle itself and the angle of the approach flow varies very slowly. The quasi-steady theory should therefore hold true and the admittance function approaches unity.

$$\lim_{f \rightarrow 0} (X_{a,S,N}(f)) \rightarrow 1$$