J. Wind Eng. Ind. Aerodyn. 117 (2013) 1–10

Contents lists available at SciVerse ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

The importance of unsteady aerodynamics to road vehicle dynamics

Joshua Fuller*, Matt Best, Nikhil Garret, Martin Passmore

Department of Aeronautical and Automotive Engineering, Loughborough University, Leicestershire LE11 3TU, UK

ARTICLE INFO

Article history:
Received 9 July 2012
Received in revised form
25 March 2013
Accepted 30 March 2013
Available online 30 April 2013

Keywords:
Unsteady aerodynamics
Vehicle dynamics
Driver model
Crosswinds
Vehicle handling

ABSTRACT

This paper investigates the influence that different unsteady aerodynamic components have on a vehicle's handling. A simulated driver and vehicle are subject to two time-dependent crosswinds, one representative of a windy day and the second an extreme crosswind gust. Initially a quasi-static response is considered and then 5 additional sources of aerodynamic unsteadiness, based on experimental results, are added to the model.

From the simulated vehicle and driver, the responses are used to produce results based on lateral deviation, driver steering inputs and also to create a 'subjective' handling rating. These results show that the largest effects are due to the relatively low frequency, time-dependent wind inputs. The additional sources of simulated unsteadiness have much smaller effect on the overall system and would be experienced as increased wind noise and reduced refinement rather than a worsening of the vehicle's handling.

1. Introduction

The aerodynamic development of production vehicles is typically done in isolation from the chassis, disregarding the effects of the unsteady aerodynamics on the handling of the vehicle. Equally, aerodynamic testing generally uses steady-state conditions, despite the on-road environment being highly unsteady and the vehicle stability is assessed based on the steady state yaw moment gradient which is compared to competitor vehicles and company defined design targets. The yaw moment arises because when in a yawed flow there are low pressure regions on the front leeside and at the rear windward edge (Howell, 1996). These create a positive yaw moment gradient that turns the cars further away from the wind source, creating an unstable situation.

The effects of the interaction between the vehicle aerodynamics and handling can only be tested with prototype vehicles and by this stage of development, the main body design is finalised and any possible geometry or shape modifications are very limited in scope. If aerodynamic induced handling problems are found, it is possible to partially mask them with changes to the suspension or by adding small flow control features such as spoilers or strakes; two examples of cars where these measures have been needed are the Mk1 Audi TT and Ford Sierra. It would be desirable to have a better understanding of the unsteady aerodynamics that cause handling issues; this could lead to preventative body shape features being included within the initial designs and allow aerodynamic and handling tests during the vehicle development process to be more targeted at the problematic conditions preventing the need for a reactive approach when problems arise.

The onset wind conditions experienced during normal driving, are highly unsteady and contain a range of different inputs and frequencies: changing vehicle speed, pitch and yaw angles, changes in weather including windspeed, direction and gusts as well as the influence of local topography, buildings, trees, etc., and other road users. The unsteady aerodynamics of bluff and quasi-streamlined road vehicles is an area of interest with a large and expanding body of research. Instantaneous flow fields around statically mounted vehicles can be significantly different from the time averaged flow field, first shown by Bearman (1984) and subsequently by Sims-Williams et al. (2001), Duell and George (1993) and Gilhome et al. (2001) among others, on fastbacks, square backs and notchbacks respectively. To investigate the effect of unsteady onset flow yaw angles a range of methods have been employed, including oscillating onset winds, crosswind gust generators and models that oscillate or move across a windtunnel (Chadwick et al., 2001; Garry and Cooper, 1986; Mansor and Passmore, 2008; Ryan and Dominy, 1998; Theissen et al., 2011; Wojciak et al., 2011). These methods have produced conflicting results, in some case showing aerodynamic coefficients measured under transient conditions to be larger than those measured on a static model and in others the same or smaller. There is also evidence of flow field hysteresis (Guilmineau and Chometon, 2008), periodic features within the flow field suppressing frequencies within the unsteady onset wind (Schröck et al., 2009), and different response times from different flow structures

* Corresponding author. Tel.: +44 1509 227 264; fax: +44 1509 227 275.
E-mail addresses: ttmap@lboro.ac.uk, joshua.fuller@hotmail.co.uk (J. Fuller).

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http://dx.doi.org/10.1016/j.jweia.2013.03.006

Nomenclature

A	frontal area (m^2)
β	yaw angle (rad)
$C_{YF\beta}$	front side force coefficient gradient
$C_{CY\beta}$	rear side force coefficient gradient
F_{Yf}	front aerodynamic side force (N)
F_{Yr}	rear aerodynamic side force (N)
ρ	air density (kg/m^3)
m	vehicle mass (kg)
I_G	vehicle inertia matrix (kg m^2)
J_{sw}	steering column moment of inertia (kg m^2)
B_{sw}	steering column damping (Nm/rad)

(Ryan and Dominy, 1998), but there is no comprehensive description of the flow field differences.

Research into the interaction between vehicle aerodynamics and handling has only seen sporadic interest over the past 30 years (Aschwanden et al., 2008; Baker, 1993; Juhlin and Eriksson, 2004; Klein and Hogue, 1980; Macadam et al., 1990; Schröck et al., 2011; Willumeit et al., 1988) but none considers which components of the unsteady onset flow or resultant flow fields are important to the handling of the vehicle. Goetz (1995) states that inputs in the frequency range 0.5–2 Hz affect the vehicle due to interactions with the suspension resonances, Wagner and Wiedemann (2002) also showed that this frequency range produced the worst response from a driver, and that higher frequencies are a NVH (noise, vibration and harshness) problem. Amongst the published work, there is a general consensus that good subjective assessments of a vehicle's handlings in crosswinds correlate with low vehicle yaw rates and yaw rate RMS. Lateral deviation due to crosswinds is only of secondary importance in driver subjective assessments although important for lane discipline, directional control and refinement.

This paper will use experimental aerodynamic results in a simulated driver and vehicle model to assess the importance of the different sources of crosswind aerodynamic unsteadiness on vehicle handling. The vehicle model was subjected to two onset wind conditions creating unsteady side force and yaw moments, one representing naturally occurring crosswinds typically found on a motorway and the second an extreme and sudden crosswind gust with an onset flow yaw angle of 30°. To these onset conditions, different sources of unsteadiness were applied

- difference between a steady-state and transient yaw angle;
- time delay between the front and rear of the vehicle;
- yaw moment hysteresis;
- instantaneous unsteadiness in side force;
- frequency dependent yaw moment magnification.

2. Vehicle aerodynamics

The aerodynamic loads used in the simulated vehicle model were based on experimental results collected in the Loughborough University 1/4 scale windtunnel using a Davis model (Davis, 1982), which is shown in Fig. 1; all the edges having a 20 mm radius.

The windtunnel is an open circuit design with a closed working section which has a fixed floor, boundary layer thickness of 60 mm and a freestream turbulence intensity of 0.2%; further details are in Johl et al. (2004).

The model was mounted 40 mm above the ground plane of the windtunnel to the underfloor balance via a Ø20 mm shaft from the centre of the model. The balance is accurate to ± 0.12 N in drag, ± 0.52 N in side force and ± 0.045 Nm in yaw moment. This gives accuracy in the lateral coefficients of $\pm 3\%$ or side force and $\pm 2\%$ in yaw moment; as will be seen in the results, this level of error is insignificant compared to the variations that occur in these parameters due to other factors. Data was sampled for 20 s to record a repeatable mean within ± 1 count. Steady-state data was collected using the underfloor balance at static yaw angles in steps of 2° between $\beta = \pm 30°$ at a tunnel speed of 40 m/s, giving a Reynolds number, based on model length, of 1.7×10^6. This value is above the typical lower threshold of Reynolds number independence for scale model tests of 1×10^6, and for this model a simple Reynolds sweep shows that the aerodynamic coefficients become reasonably Reynolds number independent above 1.3×10^6. However it is acknowledged that when applying this data in a full scale vehicle simulation there is likely to be some Reynolds number dependency particularly in the coefficients in extreme conditions. The loads were corrected for model blockage using the MIRA blockage correction (Carr, 1982), and converted to coefficients using the standard equations and SAE coordinate system.

The steady-state front and rear side force and yaw moment coefficients produce linear results, $r^2 > 0.97$, with gradients in Table 1.

The flow fields around the model are naturally unsteady, causing instantaneous variations from the mean values of the aerodynamic loads acting on the model. The standard deviation of the side forces was found from high frequency, surface pressure measurements on the two sides of the model. The model was mounted in the windtunnel in the same way as for the steady-state force measurements, with 63 pressure tappings on each side of the model connected to two 64 channel miniature pressure scanners via lengths of flexible plastic tubing. Data was collected at 260 Hz for 32 s, giving 8192 data points at each pressure tapping. The pressure transducer is accurate to 0.9 mm H_2O, meaning that the uncertainty in the readings is of the order 1%–2%, and was post processed to remove distortions caused by the tubing; these were dominated by a resonance at 95 Hz and an increasing phase lag at higher frequencies. Area weighted side forces were calculated at each instantaneous time step and at each

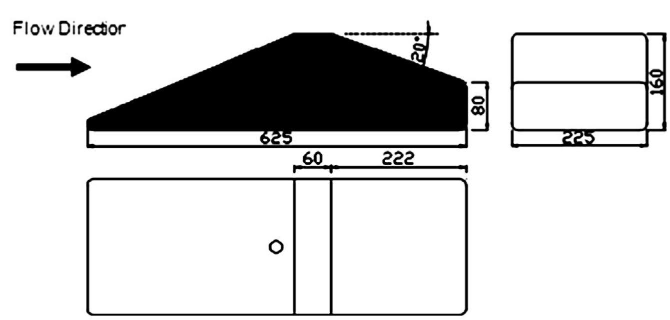

Fig. 1. Davis model.

Table 1
Steady state lateral aerodynamic coefficients.

Front side force coefficient gradient/deg ($C_{YF\beta}$)	0.0194
Rear side force coefficient gradient/deg ($C_{YR\beta}$)	0.0088
Yaw moment coefficient gradient/deg	0.0055