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A detailed statistical study of unsteady wake dynamics from automotive bluff bodies

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ABSTRACT

There is a growing emphasis from automotive manufacturers on efficient performance, with a greater need to leverage unsteady aerodynamics data in the design process. Simplified bluff bodies are regularly used to generate flow features which replicate specific behaviour of flow around real vehicles. The unsteady aerodynamics of a squareback and a 40° slant back Windsor body was investigated here using Computational Fluid Dynamics (CFD) at $Re = 2.56 \times 10^6$. The results were generated using a Lattice-Boltzmann-based Very Large-Eddy Simulation (VLES) solver and experimental measurements were taken in a static-ground, in-draft wind-tunnel. This paper compares unsteady force coefficients, base surface pressures and vortex interaction in the wake. Statistical methods were defined and applied to identify the correlation present in the sampled signals, propose improvements to the calculation of confidence intervals and understand interaction between different coherent flow features. The slant modification was found to significantly shorten the integral time-scales in the near-wake. Spectral analysis of point probes revealed that the 40° slant modification favoured higher frequency content. Independent, modified confidence intervals showed a log-linear variation with sample sizes.

1. Introduction

Greater availability of resources have enabled higher-fidelity Computational Fluid Dynamics (CFD) simulations for automotive engineering. Improved modelling capability has led to reduction of turn-around time, earlier refinement of design and deep exploration of performance envelopes. Bluff bodies are extensively used to understand automotive aerodynamics by generating typical flow features which arise from various parts of a car. This can include A-pillar vortices, trailing vortices from the rear edge of the roofline and the turbulent wake, which is a significant contributor to vehicle drag and soiling (Le Good and Garry, 2004). Although time-averaged force coefficients of vehicles are widely used to assess the performance for both steady-state and dynamic drive cycles many manufacturers are focusing on a better understanding of unsteady flow behaviour. Unsteady flows are important in understanding wheel interactions (Newbon et al., 2015; Koitrand et al., 2014), cooling, soiling performance (Gaylard et al., 2017; Kabanovs et al., 2016) and also interaction between turbulent structures in the wake (Duell and George, 1999; Gaylard et al., 2007; Grandemange et al., 2014; Wood et al., 2015; Perry et al., 2015; Perry et al., 2016).

Simplified geometries are commonly used to focus on particular flow structures. Commonly used generic automotive geometries include the Ahmed body (Ahmed, 1981), the Windsor body (Windsor, 1991), the Willy model, the SAE notchback model (Wood et al., 2014; Islam and Thornber, 2015, 2016) and the DrivAer model (Heft et al., 2012; Ashton and Revell, 2015) in increasing order of complexity of surface features. The Windsor body was originally defined in a squareback and slant-back configurations (Windsor, 1991) leading to separated flow at the rear of the body making them suitable for detailed wake studies. Past investigation revealed that significant aerodynamic improvements can be achieved by modifying the base surfaces and also by tapering the roofline and side surfaces (Howell et al., 2013; Littlewood and Passmore, 2010; Robertson, 2012). Perry et al. (2016) identified a ring vortex from the time-averaged flow and also the presence of asymmetric wake structures which appeared to have intermittent, low-frequency bi-stable behaviour.

The squareback geometry also induces a wake structure similar to an Ahmed body (Ahmed, 1981) which has been used by Grandemange et al. (2013) to identify oscillating global shedding modes and intermittent, random bi- or multi-stable modes present in the wake. They found that the ground clearance was strongly related to the presence of bi-stable modes, since it induced bias towards one particular mode above a critical value of $c / H = 0.1$. They also stated that the coherent motions

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behind an Ahmed body results from the superposition of a lateral random offset, the lateral and the upper/lower shear layer interaction (Grandemange et al., 2013). Volpe et al. (2014) used conditional averaging to report that the toroidal rear wake structure often captured in time-averaged representations, have an intermittent bias resulting from this bi-stable behaviour.

Similar to an Ahmed body, the rear section of the Windsor body can be modified to alter the aerodynamic behaviour. In this investigation the rear slant was angled to 40° relative to the roofline and this was expected to cause complete separation over the surface and generation of trailing vortices from the corners of the roofline (Fig. 1). This should also generate a large lift force countering the effects of the low ground clearance on the baseline squareback geometry (Howell and Le Good, 2008).

The effect of backlight aspect ratio on the aerodynamics of the Windsor body was studied by Howell and Le Good (Howell and Le Good, 2008). The influence of tapering the rearward edges on the Windsor body was explored by Howell et al. (2013) and Perry et al.. Small chamfers on the roof trailing edge were experimentally tested by Littlewood and Passmore (2010). Perry et al. showed that surface tapers as small as 4% of the model length can significantly reduce the length of the wake and reduced separation of top and bottom shear layers can favour bi-stable behaviour; both mechanisms led to reduced drag.

The squareback baseline geometry was also used by Littlewood et al. (2011) to understand the influence of wake structure changes on the vehicle forces, with increased base surface roughness. The importance of base surfaces on bluff bodies and the unsteadiness in the near wake was emphasised by Duell and George (1999), which also inspired some of the analysis presented here. They were able to use statistical techniques to better understand the relationship between turbulent structures in the near wake and the base surface.

Although CFD is widely used in engineering, there are some areas which require further development for improved integration into, and acceleration of the design process. In particular, complex geometries, high-quality mesh generation and scalability of high-fidelity, unsteady CFD requires attention. The Lattice-Boltzmann Method (LBM) employed in this investigation is an alternative to the traditional finite-volume, Navier-Stokes approaches widely used in industrial applications (Chen et al., 2003; Kotapati et al., 2009). This is equivalent to a Very Large-Eddy Simulation (VLES) with a wall-model sensitised to pressure gradients (Chen et al., 1998) making it suitable for high-Reynolds numbers.

Although eddy-resolving methods are gaining popularity especially with hybrid approaches such as Detached-Eddy Simulation (DES) and its variants (Islam and Thornber, 2015, 2016; Spalart et al., 1997, 2006; Shur et al., 1999; Spalart, 2009), statistical tools can be devised to leverage unsteady aerodynamic data. Many steady-state aerodynamics studies compare designs based on qualitative metrics such as the mean size of a wake or a recirculation length from planar contours and quantitative measures such as mean force coefficients. This article presents additional analysis techniques for unsteady aerodynamics inspired by the work of Duell and George (1999), Sims-Williams and Duncan (2003) and Gaylard et al. (2017).

In summary, this paper demonstrates an analysis framework for external aerodynamics, applying existing and novel statistical techniques. Standard deviation of unsteady data is often reported but rarely used to identify the flow structures responsible for the unsteadiness at specific frequency ranges (Sims-Williams and Duncan, 2003). Only the most detailed studies use sophisticated techniques to aggregate errors from experimental and numerical sources. The techniques explored here consider the correlation in unsteady signals to determine realistic confidence bounds. This further quantifies the mutual dependence of flow features around the bluff body and offers a better insight into turbulent interactions.

This article has been organised into 4 sections, with the first defining the experimental setup and outlining the computational approach to replicate this. Afterwards, the statistical techniques are developed for the unsteady aerodynamic data. Thereafter, this methodology is applied to the comparative study of Windsor body variants, to assess its effectiveness.

2. Problem definition

2.1. Experimental setup

The experimental setup used for the measurements was identical to other past studies using the Windsor body in the Loughborough University tunnel (Johl et al., 2004). This is an in-draft wind-tunnel with a stationary ground plane. The inflow velocity and turbulence intensity profiles were measured experimentally ahead of the tunnel test section. The velocity profile matched a 1/7th Power Law profile well. The freestream velocity was set to a constant value of 30.5 m/s, with a uniformity level of ±0.4% (Perry et al., 2015; Johl et al., 2004).

The model ground clearance was 50 mm above the test section floor and the 99% velocity boundary layer thickness was 60 mm. The models were mounted using 4 pins having 8 mm diameter each. These pins were located 10 mm inboard from the sides of the model.

All the longitudinal and rear edges were sharp and leading edge radii were 50 mm. The wind-tunnel measurements were taken at a sampling frequency of 260 Hz and mean results were averaged over a period of 31 s. The cross section of the tunnel test section was 1920 × 1320 ($W \times H$) mm and led to a blockage ratio of 4% with the model frontal area of 0.112 m^2. A one-dimensional blockage correction derived by Carr and Stapleford (1986), was used for both the pressure measurements and force coefficients. This is defined below

$$C_{pCorr} = \frac{C_{pM}}{(1 - A_M/A_{WT})^{-2}} \tag{1}$$

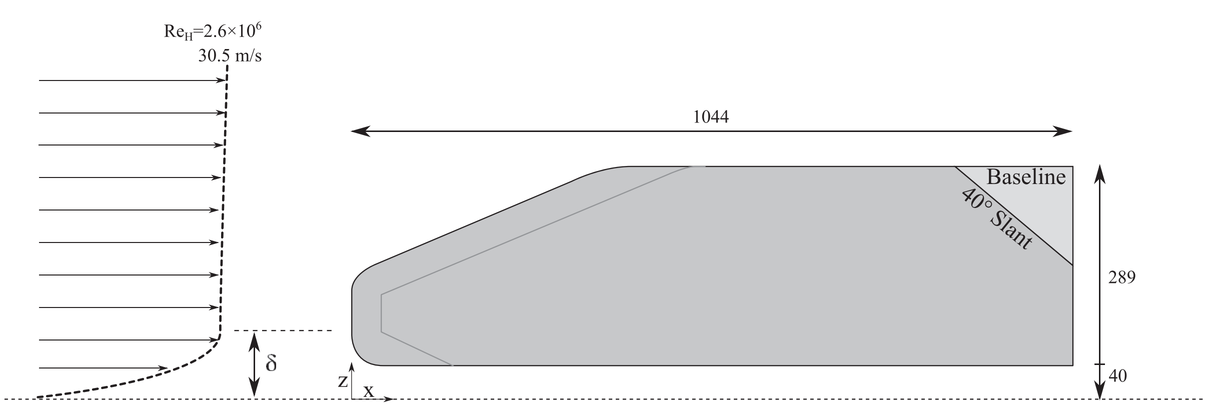

Fig. 1. Details of the Windsor body variants used in this investigation.