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BI-MODALITY IN THE WAKES OF SIMPLIFIED ROAD VEHICLES: SIMULATION AND FEEDBACK CONTROL

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ABSTRACT

Large Eddy Simulations are performed to investigate the bi-modal behavior of the flow past three-dimensional square-back bluff bodies. We consider two simplified road vehicle geometries: (i) the squareback Ahmed body and (ii) a simplified square-back truck geometry, with height greater than its width. The Reynolds numbers based on body height is chosen in the range 20,000-33,000, such that turbulent separation occurs for both. It is characteristic of such wakes to exhibit slow random switching between asymmetric states. The accessibility of full flow-field data allows us to extract wake flow features that offer new insights. Finally we apply a single-input single-output linear feedback control strategy to the flow. This consists of sensing the base pressure force fluctuations, and actuating a zero-net-mass-flux slot jet just ahead of separation to attenuate base pressure force fluctuations. Its effects on the symmetry of the wake and the mean pressure drag are investigated.

1. INTRODUCTION

The flow around road vehicles has been extensively studied with the main objective of reducing the aerodynamic drag, which, at high speeds, highly impacts the vehicle energy consumption. In term of fluid dynamics, because most vehicles are blunt bluff bodies, the flow separates over the blunt back end of the vehicle. As a result, the flow around the back exhibits separated shear layers forming the envelope of a large low pressure recirculation wake responsible for most of the aerodynamic drag [1]. Identifying and understanding the large coherent wake structures and topology of the wake are fundamental to identifying the main sources of drag and informing drag-reduction strategies.

Recent work has identified symmetry breaking behavior in the wakes of 3-D blunt bluff bodies [2-7]. The symmetry breaking first occurs at low, laminar Reynolds numbers - this can be predicted by weakly nonlinear analysis of the Navier–Stokes equations [8] and has been observed experimentally [2] and in simulations [7]. A very recent finding is that the asymmetry then persists to high, turbulent Reynolds numbers. It appears that the turbulent flow fluctuations cause the wake to switch between asymmetric states with slow, random timescales resulting in multi-stability [5,6] or bi-stability [3,4], also known as bi-modality. Much of the work has been on Ahmed bodies: it has also been predicted that bi-modality should occur for the Ahmed body with inverted width-to-height aspect ratio, but in that case bi-modality should appear vertically.

The present work performs Large Eddy Simulations of the flow past two simplified square-back road vehicle geometries for which experimental data are available. The goal is to investigate whether the bi-modal behaviour of turbulent wake flows can be captured in numerically. Simulations offer the benefit of access to full three-dimensional flow-field data, hence facilitating more detailed analysis of the associated wake structures. A second objective of the work is then to investigate the use of linear feedback control in order to reduce the aerodynamic drag of these 3-D squareback geometries.

Feedback control involves modifying the flow using an actuator, in response to measurements from a sensor [9,10]. This is in contrast to open loop control, where the actuator does not depend on measurements from a sensor [10]. Feedback control offers the benefits of allowing the dynamics of a system to be modified, even allowing for the stabilisation of unstable flows [11,12]. It offers a theoretical framework for dealing with the effects of uncertainty and improving the energy efficiency of the control system and also offers the potential for automatic re-tuning as flow conditions change. Feedback control has been successfully applied to blunt bluff body flows in a limited number of studies [9,13,14,15,16]. The linear feedback control strategy considered in the present work has shown impressive drag reductions for infinitely wide blunt bluff body flows [13,14]: here we investigate whether its success carries over to 3-D finite width geometries.

2. GEOMETRIES

Two geometries were considered in this work with different width to height aspect ratios. The first one is a commonly used simplified vehicle geometry, the Ahmed body [17], here chosen in its square-back configuration. The second test-case is a simplified truck geometry, for which experiments were performed, allowing validation [18].

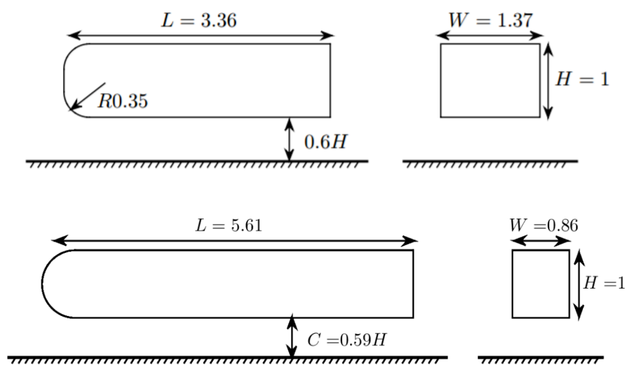

Figure 1. Schematic of the square-back Ahmed body geometry (top) and the simplified truck geometry (bottom). Dimensions are non-dimensionalised by H (body height).

In both cases, the boundary layer just ahead of flow separation is fully-developed turbulent and there is a stationary floor below the body. For the squareback Ahmed body, the Reynolds number based on the body height is 33,000, while for the simplified truck geometry, the Reynolds number based on body height is 20,000.

3. FLOW SIMULATIONS

Flow simulations are performed using an in-house large-eddy simulation (LES) code, "Stream-LES", which solves the incompressible Navier–Stokes equations [19]. The code solves for the velocity field via a collocated finite-volume method on a cartesian grid, using a second-order accurate scheme for the fluxes. The solution is time-marched via a third-order Gear-like fractional-step method. Pressure-correction is obtained by solving the Poisson equation using a multigrid successive over-relaxation technique. The code is fully parallelised using message passing interface. The subgrid-scale stresses are simulated by the WALE (wall adapting local eddy-viscosity) model [20]. This reproduces the cubic wall-asymptotic behaviour of the eddy viscosity.

Both geometries used a structured mesh with ~57M mesh points for baseline and feedback control investigations. For the simplified truck geometry, a finer grid with ~103M mesh points was used for grid resolution checks and bi-stability investigations. In both cases, the maximum value of y+ along the separation line is close to 1: the distribution of y+ over the squareback Ahmed body is shown in Fig. 2: its maximum value of ~2 is just downstream of the front face, with values close to the separation line downstream close to or slightly exceeding 1.

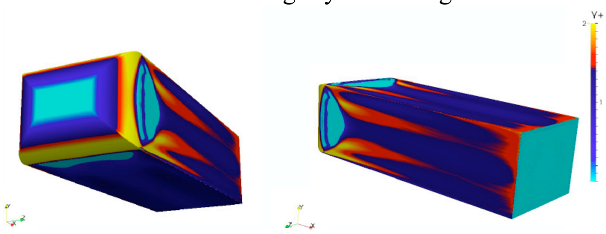

Figure 2: Variation of y+ over the surface of the squareback Ahmed body.

All simulations were conducted on 1500-3500 cores using the Imperial HPC cluster "CX2" and the UK National Supercomputing Service "ARCHER".

4. UNFORCED FLOW

The iso-pressure surface for the time-averaged flow of the squareback body is shown in Fig. 3. As can be seen, the well-known low pressure ring-structure is accurately captured.

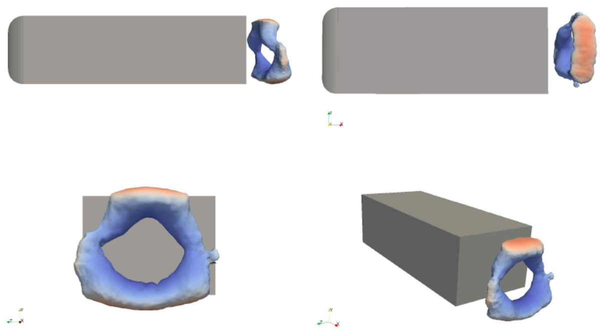

Figure 3. Iso-pressure surface for C_p = -0.2 for the squareback Ahmed body.

The time-averaged velocity field for the simplified truck model is shown in Fig. 4. The time-averaged flow is symmetric in the horizontal direction, with a slight shift in the vertical direction, possibly associated with the presence of the floor.

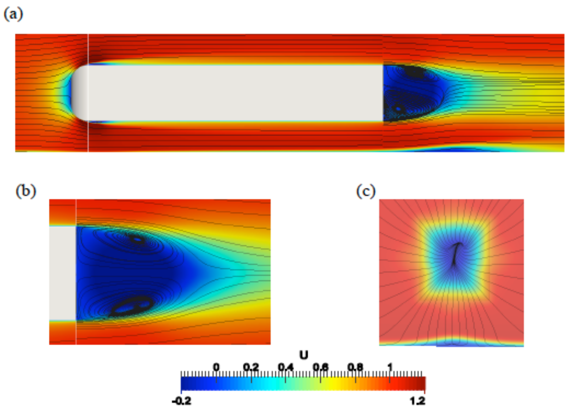

Figure 4. Velocity field around the simplified truck in the plane (a) Side view at z=0 (b) Top view at y=0 (c) Downstream plane at x=H

Although for both geometries, the time-averaged flow is symmetric, other than for the presence of the floor, the wake is found to be instantaneously asymmetric. Fig. 5 shows the vertical and horizontal base pressure gradients for the Ahmed body wake. It is clear that at around 175 time units, the wake undergoes a horizontal switch from one side to the other. The probability density functions for the base pressure gradients reveal clear bi-modality horizontally.

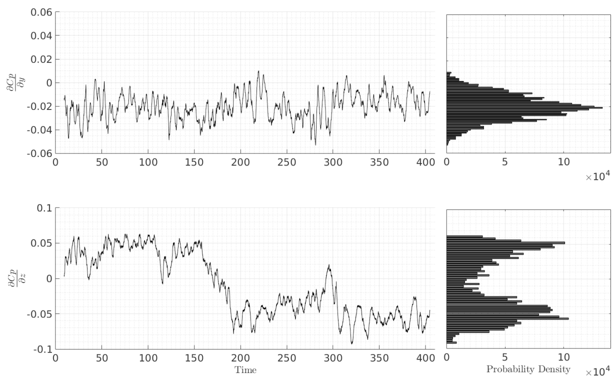

Figure 5. Time variation of the vertical (top) and horizontal (bottom) base pressure gradients for the squareback Ahmed body, with corresponding probability density functions on the right.

The same plots for the simplified truck model are shown in Fig. 6. This time, a clear switch at ~380 time units occurs in the vertical direction. The probability density functions indicate vertical bi-modality.

These findings are consistent with recent experimental investigations, suggesting that due to the different width to height aspect ratios, the wakes would be expected to exhibit different asymmetric switching [3]. The Ahmed body wake is expected to show horizontal bi-modality, while the truck model wake is expected to show top-to-bottom bi-modality, exactly as seen in the simulations.

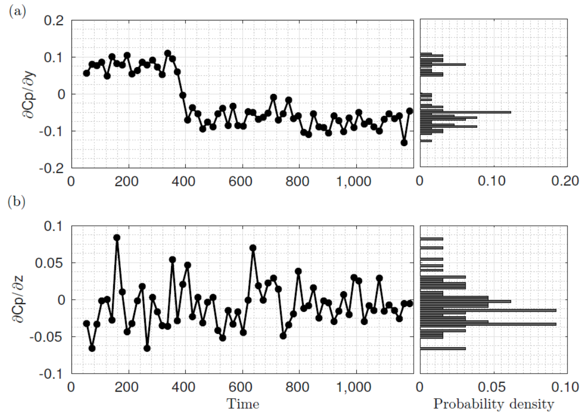

Figure 6: Time variation of the base pressure gradients for the truck geometry in the vertical (y-direction) and horizontal (z-direction) and their corresponding probability density functions.

The accessibility of full flow-field data allows us to extract wake flow features that offer new insights.

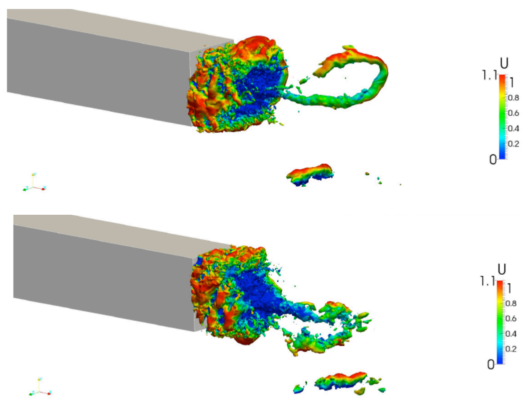

Figure 7. Instantaneous iso-contours of pressure in the wake of the lorry geometry taken at C_p = -0.15 and colored by velocity. Top: wake at the top location, Bottom: wake at the bottom location.

For the simplified truck geometry, Fig. 7 shows that wake is composed of a low-pressure ring structure that is tilted according to the current bi-modal location. Additionally, clear horseshoe structures are shed downstream from the longest part of the wake, the longitudinal pillars of which are shed directly from the core of the wake. In contrast to previous thinking [21], this suggests that the wake ring structure and the horseshoes are two different entities.

5. FEEDBACK CONTROL STRATEGY

This section will focus on the use of linear feedback control to reduce the pressure drag of the simplified truck geometry. It has previously been shown that linear feedback controllers can achieve a time-averaged drag reduction by targeting a reduction in time-fluctuations in the spatially integrated base pressure [13,14]. The bluff body geometries considered in these studies were all infinitely wide. We now investigate the extension of the feedback control strategy to 3-D bodies of finite width.

Experimental base pressure measurements on the same simplified truck geometry, albeit at higher Reynolds number, identified two dominant modes flow: a bubble-pumping mode at $St_H \sim 0.08$ (with St_H the Strouhal number based on body height H) and a vortex shedding mode at $St_H \sim 0.17$-0.20 [18]. The present simulations identify very similar unforced dynamics, as shown in Fig. 8.

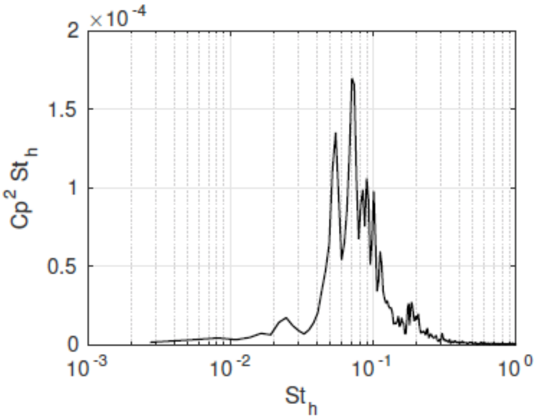

Figure 8. Unforced premultiplied base pressure spectrum identified from simulations of the simplified truck geometry.

The feedback control strategy uses body-mounted sensing and actuation for practical applicability. It senses the spatial Fourier modes of the base pressure fluctuations. It actuates using zero-mean slot jet velocity forcing through a thin slot just ahead of separation. The actuation can be all around the perimeter of the base; alternatively, just top and bottom edge forcing, either in phase or out of phase, can be applied. The arrangement is shown in Fig. 9.

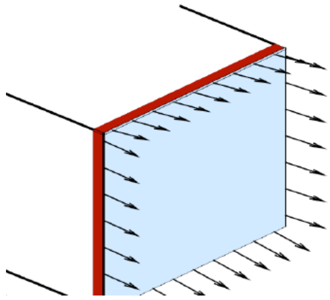

Figure 9. Sensing (blue) and actuation (arrows) arrangement for feedback control

The linear feedback control strategy can be explained using the frequency domain block diagram in Fig. 10, where 's=iω' denotes the Laplace transform variable. Denoting the chosen sensor signal as Y(t), when actuating the flow with a varying slot jet velocity, $U_j(t)$, Y(t) can be assumed to vary both due to the actuation, $U_j(t)$, and due to other disturbances in the flow (for example boundary layer and shear layer disturbances), lumped together as D(t). This captures the fact that even in the absence of actuation, the flow is fundamentally unsteady.

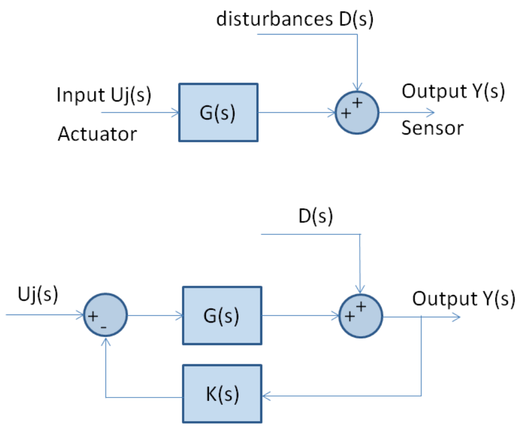

Figure 10: Model for the open-loop control system (top) and the closed-loop control system (bottom).

By adding a feedback loop, in which the actuator responds to sensing of the spatially integrated base pressure, Y(s), via a control law, K(s), shown in the bottom of Fig. 10, it can be deduced that the ratio of sensor fluctuations with and without feedback control is given by:

$$\frac{|Y(s)|_{\text{with control}}}{|Y(s)|_{\text{without control}}} = \frac{1}{|1 + G(s)K(s)|} = |S(s)|$$

The aim of the linear feedback controller, K(s), is then to ensure that the sensitivity transfer function, S(s), has magnitude less than unity over the dynamically important frequencies i.e. those shown in Fig. 8.
System identification is used to identify the plant transfer function, G(s). This is performed by applying a harmonic actuation input and measuring the corresponding gain and phase lag of the sensor response, across different forcing amplitudes and frequencies. A frequency domain fit to the response data is then obtained.

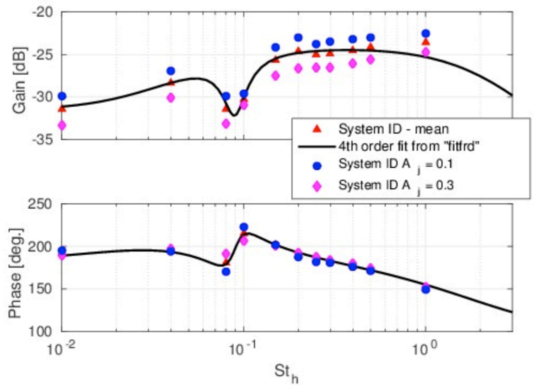

Figure 11: System identification performed using two forcing amplitudes (A_j=0.1 and A_j=0.3) over 10 different forcing frequencies (St_H = 0.01 – 1) on the truck geometry.

This system identification will be used as the basis for designing a linear controller to suppress base pressure fluctuations. The controller will be implemented in flow simulations and its effect on the mean base pressure measured. This will be repeated for sensing using different spatial Fourier modes, and actuation all around the base perimeter and only on the top/bottom edges. The effect on the wake flow dynamics and topology will be investigated, in order to deduce insights into reduced drag conditions.

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