Journal of Wind Engineering & Industrial Aerodynamics 173 (2018) 262–278

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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

On the two flow states in the wake of a hatchback Ahmed body

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ARTICLE INFO

Keywords:
Ahmed body
Wakes
Bi-stability

ABSTRACT

Recent experimental investigations in the wake of an idealised car model – the *Ahmed body* showed the existence of two stable wake states: flow state I, where the flow is fully separated over the back slant of the Ahmed body, and flow state II, where the flow initially separates and then reattaches further along the back slant. The existence of the two flow states is confirmed numerically by using the partially-averaged Navier–Stokes (PANS) turbulence model for various configurations of the Ahmed body. The two flow states can also be distinguished by the instantaneous values of the force coefficients. In flow state I, values of both the lift and drag coefficient are lower compared to flow state II. The influence of the aspect ratio, defined as the ratio of the width of the model to that of a standard Ahmed body, on the two flow states is investigated for the 25° back slant Ahmed body. For low aspect ratios, flow state II is observed, while for larger aspect ratios, flow state I is observed. Next, the influence of the yaw angle (β) on the occurrence of the two flow states is investigated for the 35° back slant Ahmed body. For $|\beta| \lesssim 12.5^\circ$, flow state I is observed; and as the yaw angle is increased to $|\beta| = 15^\circ$, flow state II is observed, with stronger longitudinal vortices aiding the flow reattachment over the back slant.

1. Introduction

The Ahmed body, first proposed by Ahmed et al. (1984) (see Fig. 1(a)), is a generic car model used in the automotive industry among others (also see Morel (1978), Good and Garry (2004), Guilmineau and Chometon (2009), Heft et al. (2012) and Huminic and Huminic (2012)), to investigate the wake dynamics and forces experienced in a wide range of configurations. The Ahmed body has a rounded front end, a flat roof and bottom section, an angled back slant (or a rear window) and a vertical base at the rear. The angle of the back slant (ϕ) is critical to the flow structures that are formed in the near wake and subsequently influences the aerodynamic forces acting on the body. The flow behind the Ahmed body aligned to the incoming flow consists of a pair of longitudinal vortices (also known as the C-pillar vortices), a region of separated or attached flow over the back slant, and a pair of recirculating regions behind the vertical base (also see Fig. 6 of Ahmed et al. (1984)). They observed that the drag coefficient of the Ahmed body increased as the back slant angle was increased from 25° to 30°. For the 30° back slant case, two flow states were observed; a high drag state, and a low drag state by the use of a splitter plate behind the body. They hypothesised that the merging of the recirculation zones on the back slant and the vertical back base, together with weak longitudinal C-pillar vortices causes the flow separation, leading to a low drag state. For larger values of back slant angles, the low drag state was observed with the separation point fixed at the roof edge. A conceptual model of the flow structures in the high drag state of the 25° back slant Ahmed body was proposed by Zhang et al. (2015) based on the measured frequencies at various locations around the Ahmed body. McQueen et al. (2014) performed PIV (Particle image velocimetry) measurements to identify the Strouhal numbers associated with the vortices behind Ahmed bodies of different widths. The dominant frequency of the C-pillar vortices based on the vertical velocity measurements remained invariant on increasing the width of the Ahmed body. They further observed that the corner vortices were formed at the bottom of the Ahmed body, and these vortices increased in strength and persisted further downstream as the width of the body was increased. These corner vortices were observed predominantly in the absence of cylindrical supports or when the Ahmed body was mounted from the roof of the wind tunnel (Strachan et al. (2007), McQueen et al. (2014), Venning et al. (2015)), and/or in the numerical simulations where the cylindrical supports are not modelled (Krajnović and Davidson, 2004). More recently, Venning et al. (2017) presented evidence showing that the region behind the vertical base consists of two horse-shoe vortices in the high drag state of a standard width Ahmed body, with the upper vortex feeding into the C-pillar vortices and

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https://doi.org/10.1016/j.jweia.2017.10.021
Received 15 June 2017; Received in revised form 17 October 2017; Accepted 22 October 2017
Available online 27 December 2017

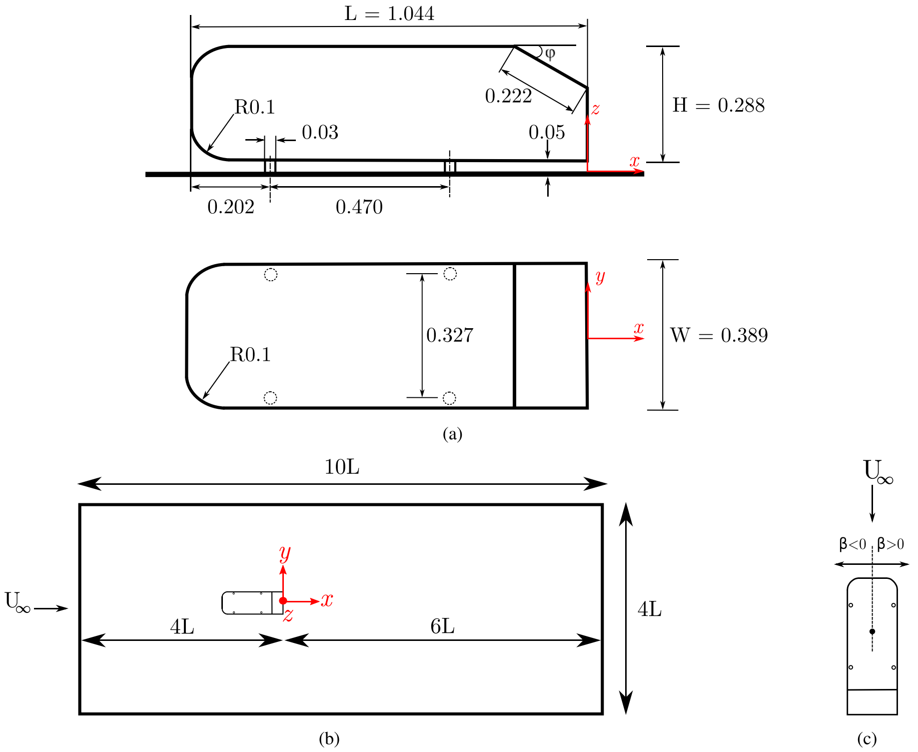

Fig. 1. (Colour online) (a) The Ahmed body in side and plan views. Two back slant angles of $\varphi = 25^\circ$ and 35° are considered in this study. All dimensions are in metres. (b) Schematic of the computational domain in plan view. The origin is located midway along the vertical base on the ground, and the coordinate axes is shown in red in (a) and (b). (c) Definition of the yaw angle when the Ahmed body is rotated about a point midway between the support structures.

strengthening it. The two flow states have been observed both numerically (Guilmineau et al., 2017), and experimentally (Lienhart et al. (2002), Meile et al. (2011), Wang et al. (2013)). Surface oil flow visualisations showing the two states for the 30° back slant Ahmed body are presented in Conan et al. (2011). At this critical angle, they state that the probability of the occurrence of the low drag state to the high drag state was 3:1. PIV measurements by Tunay et al. (2014) at $Re = 1.48 \times 10^4$ showed the detached flow state for the 30° and 35° back slant Ahmed body, while for the 25° back slant case, the flow remained nearly attached over the back slant. In a recent study by Kim et al. (2016), the two flow states were achieved by using a passive flow control device - an automatic moving deflector on the back slant. When the deflector was extended above the back slant of the 25° back slant Ahmed body, the low drag state was observed with separated flow behind the Ahmed body, and when retracted, led to the high drag state. These studies collectively show that the angle of the back slant plays a critical role in determining the flow state behind the Ahmed body.

Corallo et al. (2015) performed steady numerical simulations at $Re \simeq 10^5$ for the 25° back slant Ahmed body for $0.6 \geqslant \mathcal{AR} \geqslant 1.6$. As the aspect ratio ($\mathcal{AR}$, defined as the ratio of the width of the Ahmed body under consideration to the width of the standard Ahmed body), was increased from 0.6 to 0.85, a monotonic increase in the lift and drag coefficients was observed, and for $\mathcal{AR} \leqslant 0.9$, a sudden drop in these values was observed; with the lift coefficient being nearly zero. Beyond $\mathcal{AR} = 1.2$, both the lift and drag coefficients monotonically increased with an increase in aspect ratio. The flow underwent a change of state as the aspect ratio was increased beyond the critical value of $\mathcal{AR} \simeq 0.9$. At lower aspect ratios, the flow over the back slant reattaches on account of the C-pillar vortices being closer together, and at aspect ratios larger than the critical value, the flow does not reattach over the back slant, leading to the flow being fully separated with the C-pillar vortices further apart and diminished in strength. A similar experimental study by Venning et al. (2015) showed the critical value where the discontinuity in the force coefficients occurs to be between $1 \geqslant \mathcal{AR} \geqslant 1.1$. This minor difference between the two studies was attributed to the streamlined supports used in the experiments, while no supports were used in the numerical investigations. Similar observations were made by Okada et al. (2005) at $Re = 7.42 \times 10^4$, where they distinguished the two flow regimes based on the width of the Ahmed body. They observed the C-pillar vortices were stronger and were located closer to the ground plane for the 75% width Ahmed body as compared to the standard width case, while those of a 125% width Ahmed body were weaker and located higher above the ground plane. Numerical investigations using Large Eddy Simulations (LES) and PANS at $Re = 30,000$ for an Ahmed body of $\mathcal{AR} \simeq 0.87$ predicted the reattachment of the flow over the back slant (Mirzaei et al., 2015); although the reattachment length predicted by PANS simulation was longer than that predicted by LES. Nonetheless, the standard width Ahmed body is at a critical juncture between the two flow states, and the realisation of these two states depends not only on the back slant angle, but also on the aspect ratio of the body (Kohri et al., 2016). They showed that flow state II was observed for Ahmed bodies with large back slant angles when the aspect ratio was lower. For a back slant angle of $\phi \simeq 27.5^\circ$, Kohri et al. (2016) observed that the separated flow over the back slant did not reattach, but coalesced with the recirculation region behind the vertical base, leading to a vortex being shed aperiodically behind the vertical base of the body. However, for a critical combination of the back slant angle and aspect ratio, a larger separation region was observed behind the body. The longitudinal vortices were pushed further outwards by the separated region, leading to fully separated flow behind the Ahmed body. They hypothesised that this separated region could possibly trigger the transition to flow state I. However, similar numerical investigations undertaken by Kobayashi et al. (2016), showed that the fluctuations which originated upstream of the body, traversed along the sides of the Ahmed body and merged with the downwash could possibly trigger the transition to separated flow behind the body.

Modifications to the rear surfaces by filleting the intersection of the roof and the back slant edge have been known to reduce the drag coefficient on the 25° back slant Ahmed body by 10–16% (Thacker et al.