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Effects of Aspect Ratio on the Wake Dynamics of the Ahmed Body

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Abstract

Time-Resolved Particle Image Velocimetry (TR-PIV) data was acquired in the wake of Ahmed bodies allowing the effects of varying the aspect ratio on the wake dynamics to be revealed. The spatial structures and energy contained in the dominant wake modes within the frequency spectra were investigated. It was found that a dominant frequency existed in the near wake of all aspect ratio bodies and that this frequency appeared not to be influenced by aspect ratio. This frequency was related to an alternate vertical flapping motion of the C-pillar vortices. The influence of aspect ratio on the corner vortex strength was identified. The formation of a vortex below the C-pillar vortex that appeared dependent on the interaction between the upwash and downwash was also noted.

Introduction

Substantial work on understanding and reducing the aerodynamic drag of ground vehicles has been conducted in recent times. Because the dimensions and geometry of production vehicles are so different, comparison between specific car models is difficult. Therefore, Ahmed et al [1] defined a generalised car body that produces similar flow features to those of the major structures in the wake behind cars. One of the key features of the Ahmed body wake is the generation of C-pillar vortices (labelled "A" in figure 1) shed from the rear slant edges.

The importance of these vortices in relation to drag was first noticed by Ahmed et al. [1] who observed that high drag flow is characterized by strong C-pillar vortices. The wake dynamics of the Ahmed model have been previously studied; Vino et al. [9] showed that the rear slant and vertical base exhibit sensitivity of shedding phenomena. They suggested that an upper recirculation bubble behind the vertical base mixes with flow over the slant and that flow separation off the slant shed in phase with the recirculation bubble. It has been demonstrated that these vortices play a significant role on the drag force acting on the body and that they strengthen alternately in an anti-symmetric mode [8]. McCutcheon et al. [7] suggested that the C-pillar vortices were highly turbulent and that they experienced a rapid decay of vorticity magnitude as they advect downstream.

Lienhart et al [6] acquired high spectral resolution Laser Doppler Anemometry measurements at various downstream locations from the Ahmed body. At 0.18 body lengths downstream and below 0.27 body heights they found a distinct spectral peak corresponding to a Strouhal number of approximately 0.44 based on body height. They concluded that this feature was due to the periodic shedding of vortices emanating from upstream, however, an attempt to identify the structures associated with this frequency was not made.

The second major flow structure observable in the present study is the formation of corner vortices (labelled "B" in figure 1). These vortices emanate from the front of the body and appear to form due to separation off the front of the body. These structures are comparable to "horseshoe" vortices that form upstream of bluff bodies due to the separation of the turbulent boundary layer that rolls up into a vortex system which is then swept downstream either side of the body [2][3].

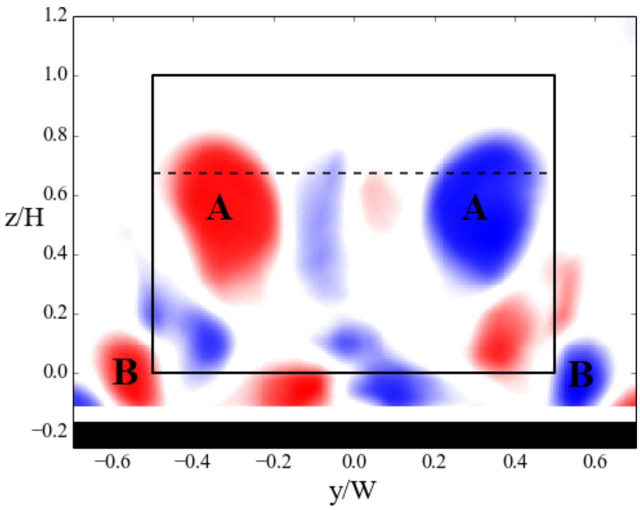

Figure 1. Temporal average of Γ_2 based on the POD reconstruction of the first three modes for the 100% aspect ratio body in the YZ plane at x/L=0.2. Positive rotation (red) and negative rotation (blue). Structure labelled "A" is C-pillar vortex. Structure labelled "B" is corner vortex.

The effect on the movement of the C-pillar and corner vortices and corresponding change in drag with varying width bodies is therefore of interest. Determining the effect of vehicle width on wake dynamics will provide a greater understanding of the drag formation and high speed handling characteristics of road vehicles of different geometries.

Experimental Method

Four 25% scale Ahmed bodies with widths varying in 20% increments from 60%-120% of the standard dimensions were manufactured as single piece bodies from Acetal. The standard width body had dimensions (L = 261mm, W = 97mm, H = 72mm). The bodies were mounted to a ground plane with an elliptical leading edge; the boundary layer was measured to be 40% of the gap height between the body and ground plane. The bodies were attached to the ground plane with two symmetric airfoil stilts located in the plane of symmetry.

The free surface water channel has a working section of 600 × 800 × 4000mm and flow velocity was 0.37 m/s, giving a Reynolds number based on height of 2.7×10^4. The flow passes through a three-sided contraction with an area ratio 5:1 to accelerate the flow through the working section and reduce turbulence levels. An upstream honeycomb section and fine turbulence screen reduce the turbulence to ~1%.

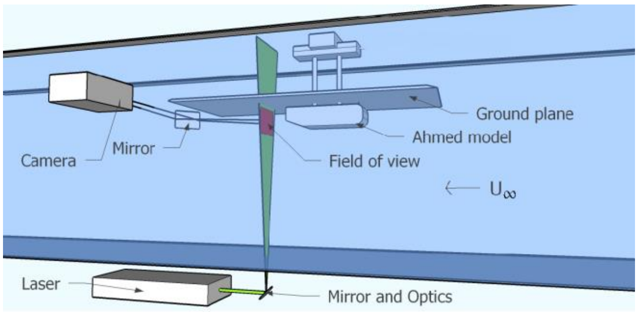

Figure 2. Experimental Setup for YZ (cross-stream) acquisition plane.

TR-PIV data was acquired in the YZ plane at downstream locations at x/L = 0.05, 0.1, 0.2, and 0.4 and in the XZ plane at spanwise positions y/W =0, 0.257 and 0.463. A PCO Dimax high-speed camera with resolution 2016 × 1504 pixels and 2016 × 1296 pixels for the YZ and XZ planes respectively was used in conjunction with a 5W continuous laser (MLL-N-532mm) to capture the velocity information. The field-of-view was 154mm × 115mm and 225mm × 145mm for the YZ and XZ planes respectively. In-house cross-correlation software [4] was used to correlate interrogation windows with size 32 × 32 pixels with a 75% overlap. This resulted in a vector field of 249 × 185 and 249 × 159 vectors for the YZ and XZ planes respectively. A total of 9750 images were capture at 200fps, corresponding to 49 seconds.

In order to understand the wake dynamics, the Fast Fourier Transform (FFT) was applied to every point in the spatial domain (hereafter referred to as a spatial FFT). This calculated the power and phase of each frequency component that contributed to the time series of the velocity. This allowed the visualisation of the power and phase of these frequencies as they varied across the spatial domain. Due to the sampling frequency of 200 Hz and the time series length of 49 seconds, the frequency resolution was 0.049Hz and the frequencies ranged from 0 to 100 Hz. These are non-dimensionalised to the free-stream velocity and the body height.

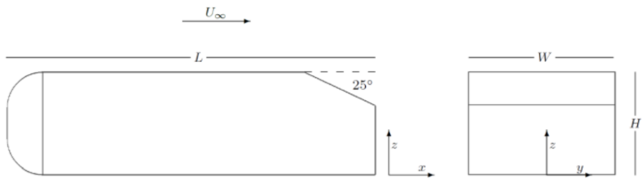

Figure 3.Ahmed Body geometry and axes reference.

Results

The spatial FFT was used to investigate the wake of the standard aspect ratio Ahmed body. A peak frequency corresponding to a Strouhal number of 0.23 was the dominant frequency in the wake and was identifiable in both the YZ and XZ planes at downstream locations between x/L=0.1 and x/L=0.3. This Strouhal number is approximately half the number identified by Lienhart et al. [6], however, as no reference to particular structures was made a direct comparison is difficult. From figure 4 it can be seen that two distinct regions located under the C-pillar vortices are associated with St=0.23. The frequency was predominately present in the vertical velocity component of the flow although was also seen in the spanwise component.

Examining the instantaneous frames of PIV data the dominant movement of the C-pillar vortices was revealed. As the vortices move downstream beyond x/L=0.1 they increase in size and lengthen as they extend and contract vertically. Comparing the vertical velocity time series at the base of each of the C-pillar vortices as shown in figure 5 it is evident that they extend alternately and that they are 180° out of phase.

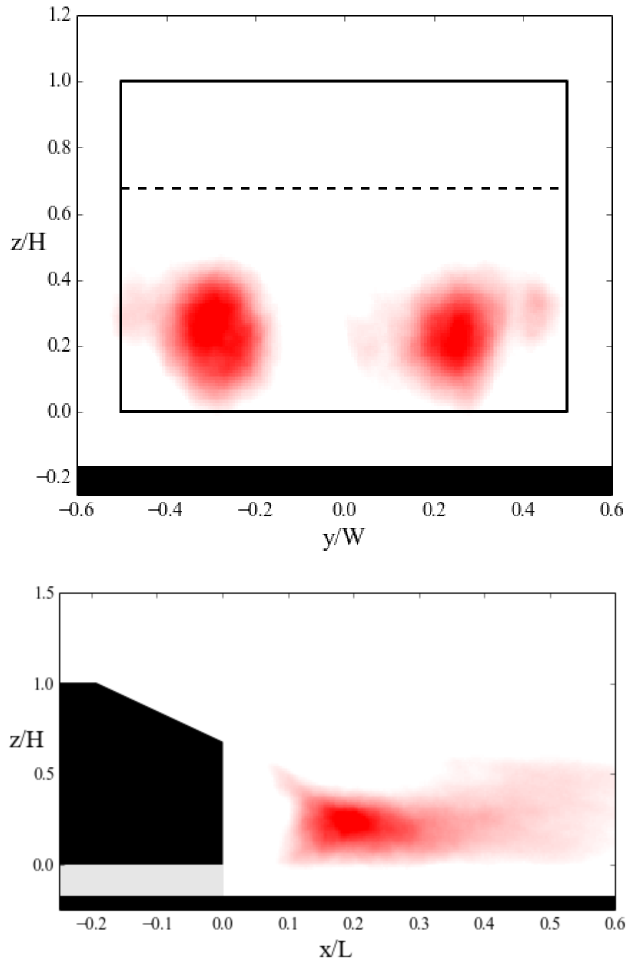

Figure 4. Spatial power spectral density distribution for St=0.23. Red colour contours represent power. Top is the YZ (cross-stream) plane at x/L=0.2, bottom is the XZ (streamwise) plane at y/W=0.257.

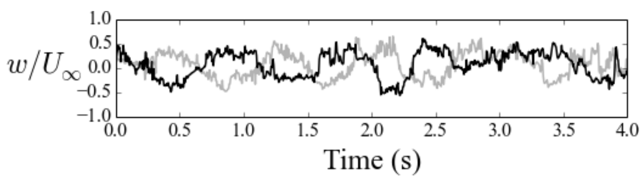

Figure 5. Time series of vertical velocity showing out of phase characteristics of the two C-pillar vortices. Grey is at y/W= -0.3 and z/H=0.3. Black is at y/W= 0.3 and z/H=0.3.

A POD (Proper Orthogonal Decomposition) filtering technique was used to reveal the dynamics of the large scale structures in the wake. A reconstruction was performed using the three most energetic spatial modes as a method of filtering out small scale structures and error terms. Figure 6 shows the iso-surface of the Γ_2 [5] criterion highlighting the C-pillar and corner vortex structures and gives an indication of both the vertical and spanwise movement. It is evident that the top of the C-pillar vortices remain stationary and that the vertical extension of the base of the vortices is associated with an upwards and outwards movement of the corner vortices. In addition, while the C-pillar vortices extend downwards alternately, the spanwise motion occurs concurrently as can be seen in figure 6. This concurrent spanwise motion is associated with the same Strouhal number as for the vertical fluctuations and increases in intensity further downstream. By x/L=0.4 the C-pillar vortices extend down to the ground plane, however St=0.23 remains present in the strengthening and weakening of the vortex.

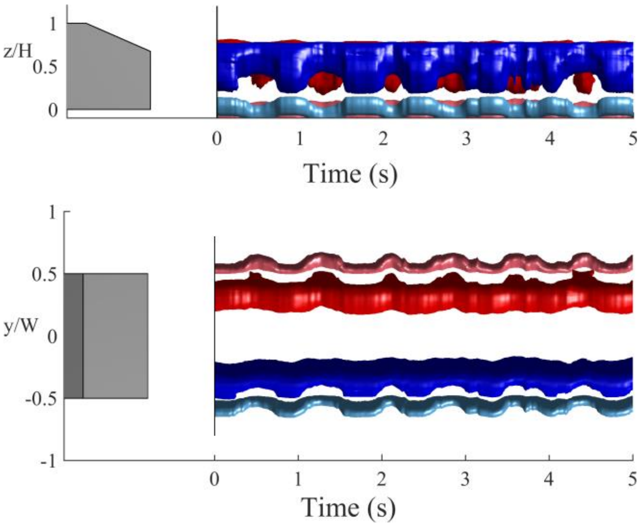

Figure 6. Wake dynamics of standard width Ahmed body. Top is side view of body depicting vertical dynamics of vortical structures. Bottom is top view of body depicting spanwise dynamics of vortical structures. Positive rotation (red) and negative rotation (blue). C-pillar (dark) and corner (light) vortical structures are shown with time increasing in the horizontal axis. The plots are iso-surfaces of Γ_2 based on the POD reconstruction using the first three modes. The PIV acquisition plane was at x/L=0.2.

The motion of the C-pillar vortices is further highlighted in figure 7 where the alternate vertical extension and concurrent spanwise motion can be observed. It is evident that this simultaneous weakening and strengthening of the C-pillar vortices results in variations in the upwash which tends to fluctuate in the spanwise direction towards the vortex that is strengthening. It is suggested that this movement of the upwash may be a contributing factor to the fluctuations of the corner vortices as they appear to be "pushed" outwards and upwards by the upwash.

Comparing the spatial average PSD for all width bodies it is evident that the aspect ratio has no significant effect on the dominant frequency as seen in figure 8. The field-of-view used to obtain the data remained the same for all aspect ratios, hence the wider bodies have a correspondingly larger wake that occupies a greater amount of the frame, resulting in a more energetic spatial average of the PSD. Since the changing aspect ratio seems to have no influence on the dominant C-pillar vortex, it is suggested that a more suitable length-scale for non-dimensionalising frequency would be the height of the body. This parameter is therefore used for the current investigation.

The dominant frequency is associated with the same motion for all aspect ratios although other flow characteristics vary. The corner vortices appear to be associated strongly with aspect ratio and become noticeably stronger as the aspect ratio increases as can be seen in figure 9. For the 60% aspect ratio body the vortices are visible although weak at x/L=0.05 and quickly dissipate downstream while for the 120% aspect ratio body they persist further downstream and remain visible at x/L=0.4 (figures not shown).

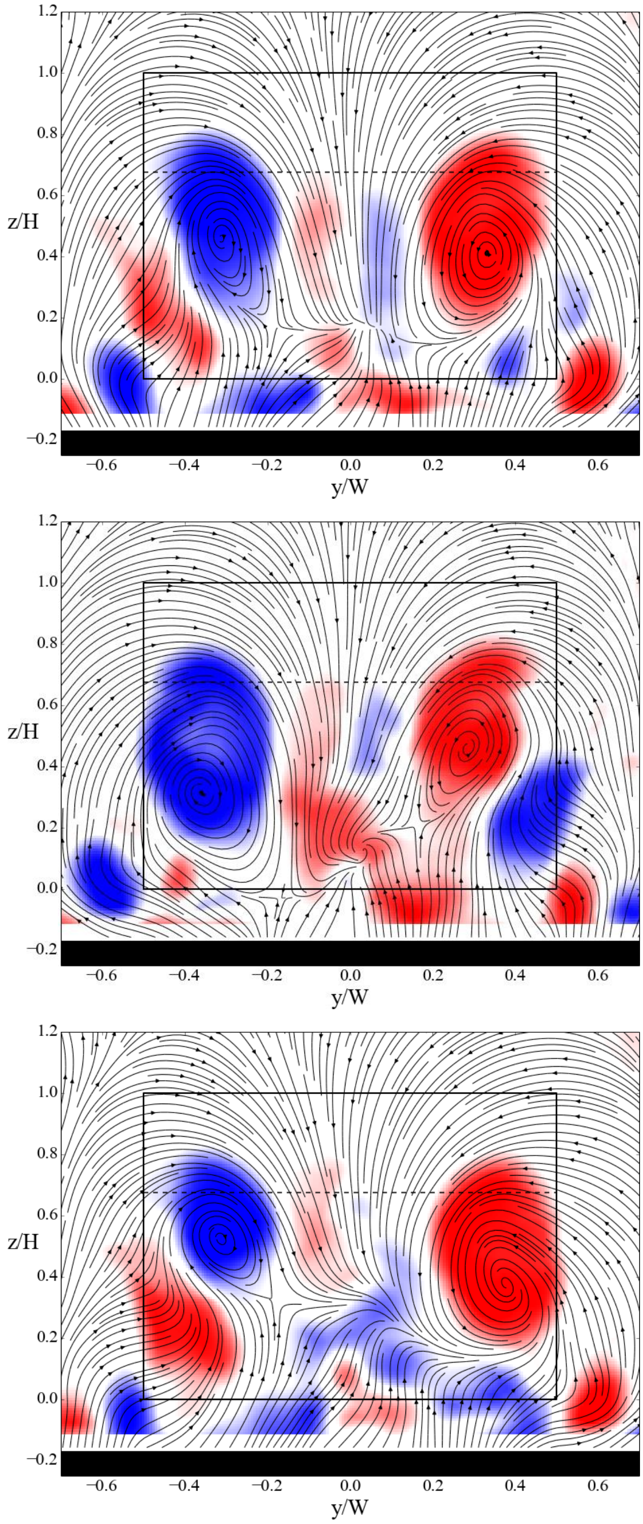

Figure 7. Instantaneous snapshots depicting the even wake state (top) and the two extremities of the wake state (middle and bottom) for the 100% aspect ratio body in the YZ plane at x/L=0.2. Filled contours are Γ_2 based on the POD reconstruction and streamlines are determined from the velocity components of the POD reconstruction. Positive rotation (red) and negative rotation (blue).

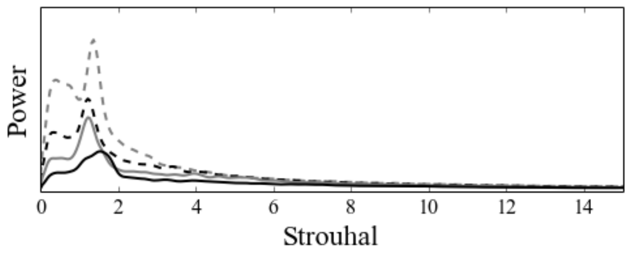

Figure 8. Average of all power in the spatial domain for various aspect ratio bodies: 60% (solid black), 80% (solid grey), 100% (dashed black) and 120% (dashed grey). Strouhal number is based on the body height.

The upwash emanating from under the body is also highly dependent on aspect ratio. As the aspect ratio is decreased, the C-pillar vortices move closer together intensifying the downwash between them. This variation in upwash causes noticeable differences to the formation of large scale structures in the flow. For the 60% and 80% aspect ratio bodies where the upwash does not extend to the bottom of the C-pillar vortices the upwash moves outwards as it encounters the downwash and rolls into a vortex rotating in the same direction as the C-pillar vortex. For the 100% and 120% aspect ratio bodies where the upwash extends above the bottom of the C-pillar vortices the upwash appears to roll downwards into a counter rotating vortex.

The vortices strengthen and weaken simultaneously with the C-pillar vortices above, although, their movement is minimal and there is no clear frequency peak in the region. These structures appear to be influenced by the stronger corner vortices for the wider aspect ratio bodies and quickly dissipate as the downwash begins to dominate further downstream.

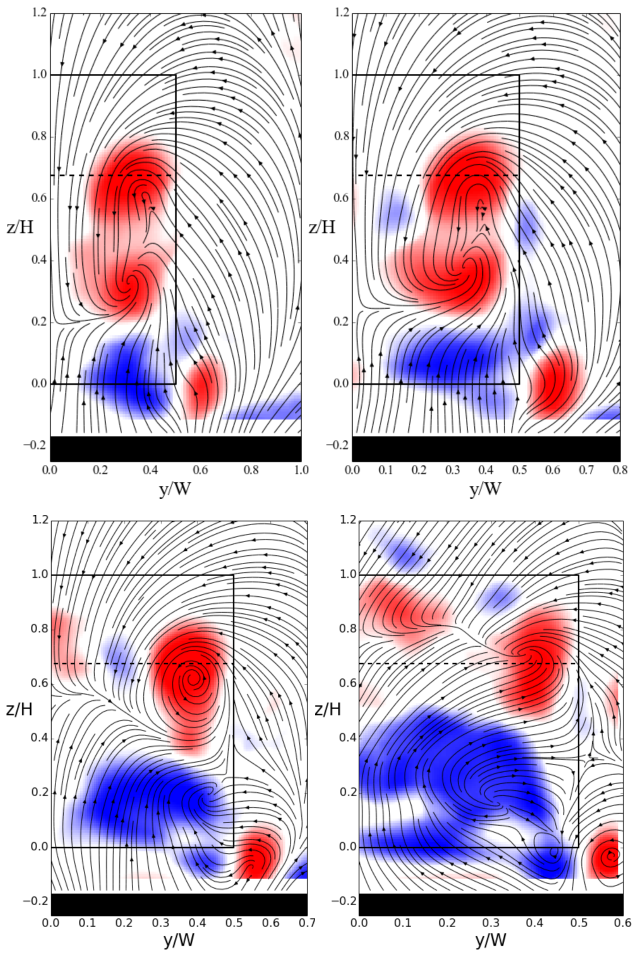

Figure 9. The right half (y/W > 0) of the instantaneous snapshots depicting the formation of a third vortex below the C-pillar vortex. The 60% aspect ratio (top left), 80% aspect ratio (top right), 100% aspect ratio (bottom left) and 120% aspect ratio (bottom right) bodies in the YZ plane at x/L=0.1 are shown. Filled contours are Γ_2 based on the POD reconstruction and streamlines are determined from the velocity components of the POD reconstruction. Positive rotation (red) and negative rotation (blue).

Conclusions

Temporally resolved PIV data was acquired in the XZ and YZ planes in the wake of Ahmed bodies of varying aspect ratios. Fast Fourier transforms in conjunction with Proper Orthogonal Decompositions were used to reveal the characteristics of the major structures within the wake dynamics. It was found that a dominant frequency (St=0.23) mainly associated with the vertical velocity fluctuations of the C-pillar vortices was present for all aspect ratio bodies and that the frequency appeared not to be influenced by aspect ratio. As a result it is suggested that a more suitable length-scale for non-dimensionalising frequency would be the height of the body. Contrarily, the corner vortices appeared to be strongly influenced by aspect ratio, they were stronger and persisted further downstream as the aspect ratio increased. The C-pillar vortices moved closer together for decreasing aspect ratio and as a result the strength of the downwash increased. This led to the formation of a vortex below the C-pillar vortex that was also dependent on aspect ratio.

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