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Effects of rear slant angles on the flow characteristics of Ahmed body

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ABSTRACT

Ahmed body is a simplified vehicle model which retains important features of real ground vehicles. Present study aims to investigate effects of rear slant angles ($\alpha = 25°$, 30° and 35°) on time-averaged and instantaneous flow characteristics downstream of the Ahmed body because angle of the rear slanted surface considerably affects the flow characteristics. The particle image velocimetry (PIV) technique is employed to measure the flow field in the symmetry plane $z = 0$ downstream of the Ahmed body. Demonstration and detailed discussions of the flow features are provided using time-averaged velocity vectors, streamlines, vorticity and TKE contours. Three critical flow points are revealed in the wake downstream of the Ahmed body. Namely, they are focus point 1 (F_1), focus point 2 (F_2) and saddle point (S). Variations in slant angle α cause shift in the locations of these critical flow points. Effects of change of slant angle α on each critical flow point vary according to their locations in the wake. Instantaneous vorticity contours and spectral analysis of the velocity field are also provided. As a result of the spectral analysis, a single dominant frequency location is only detected for $\alpha = 25°$, on the other hand two dominant frequency locations are detected for $\alpha = 30°$ and 35° in the wake. Mean stream-wise and vertical velocity components are compared with available data in the literature. Although there are some discrepancies between the present and previous results at certain locations in the flow field, general agreement between these results is reasonably good when taking the difference between Reynolds numbers of the two studies into account.

1. Introduction

Advanced developments in automobile industry have increased demand for detailed 3-D flow analysis over ground vehicles to reduce aerodynamic drag and improve fuel savings. Car companies try to develop new designs to reduce aerodynamic drag without constraints in comfort, stability, storage or passenger safety. Aerodynamic drag of the road vehicles is strongly related to the wake flow downstream of the vehicle. Size of the separation zone and drag force F_D depends mainly on the location of the flow separation over the model. Consequently, detailed knowledge about wake flow characteristics and its relation with body geometry is necessary for successful design of future cars. Ahmed reference model [1] is a generic simplified car geometry which can be used to investigate main flow features in the wake of the ground vehicles. Angle of the rear slanted surface strongly influences the flow downstream of the Ahmed body, which indicates that development of three-dimensional vortex separation from the rear slant surface produces a major component of the aerodynamic drag acting on the vehicle.

Ahmed et al. [1] were the first to study 3-D external flow analysis on the Ahmed body. Main objective of their study is to analyse change in drag coefficient C_D and flow characteristics with various rear slant angles. They have concluded that up to 85% of the total drag acting on the body is governed by pressure drag and the other rest of the drag is friction drag. The pressure drag generated at the rear end, which is responsible for 91% of the pressure drag, depends on the rear slant angle α. Moreover, 12.5° and 30° are two critical angles, at which flow structure changes significantly [2]. For angles below 12.5°, the flow over the rear slanted surface remains fully attached before leaving the body. At such low angles, the flow is characterized by two counter-rotating longitudinal vortices produced by the flow from the rear slanted surface and the side walls. The minimum drag around the Ahmed body occurs at an angle of 12.5°. The flow at this angle is two-dimensional except around two C-pillars vortices of the surface [1]. For angles between 12.5° and 30°, flow over the rear slanted surface becomes highly three-dimensional. Pressure drag goes up with increasing rear slant angle α and reaches its maximum value at the slant angle of $\alpha = 30°$. This angle of the rear slanted surface is a critical slant angle α. Above this angle, the behaviour of the flow changes suddenly and there is an

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important decrease in the drag coefficient C_D. For the slant angle near $\alpha = 30°$, flow separates from the sloping surface and reattaches at the bottom end of the sloping surface. This separation generates two strong contra-rotating vortices. These strong vortices are responsible for a higher drag. Counter-rotating vortices are found to be less strong for angles above the critical angle.

Thacker et al. [3] have stated that current knowledge of ground vehicle aerodynamics is no longer sufficient since it is limited with the time-averaged flow information. Although unsteady flow characteristics around the ground vehicles are of significant interest especially for flow control applications, apart from a few experimental [3–9] and numerical [10–12] studies, the physical mechanisms related to the unsteady process involved in the flow dynamics are rarely characterized. Additionally, more than half of the all studies (including flow control studies) conducted to investigate flow characteristics around the Ahmed body in the literature are numerical. Unfortunately those numerical studies need to be verified by experimental studies. Furthermore, most of the experimental studies conducted to investigate fundamental flow characteristics around the Ahmed body in the past have largely concentrated on employing either single point measurement techniques or flow visualization techniques. Therefore, they have some deficiencies to completely explain unsteady nature of the flow around the Ahmed body. Table 1 summarizes experimental studies conducted to understand fundamental flow characteristics around the Ahmed body. Their brief explanations are given as follows.

Ahmed et al. [1] have analysed time-averaged wake structure around the Ahmed body at the Reynolds number of $Re_H = 1.2 \times 10^6$ by varying base slant angle α between 0° and 40° in steps of 5°. Important implications of their studies are mentioned above. However, their studies have not given information about unsteady flow characteristics of the flow around the Ahmed body because they are mainly based on the time-averaged flow data. Bayraktar et al. [13] investigated external aerodynamics of the Ahmed body for slant angles of $\alpha = 0°$, 12.5°, and 25°. Their main concerns are the Reynolds number effect on drag and lift coefficients and calculating wind averaged drag coefficients. They have measured pressure and force with a 10-inch water column having electronic-scanning module and a force balance system, respectively. Lienhart et al. [14] employed the Ahmed body to develop, refine and validate the latest generation of turbulence models experimentally. Their measurements were done for two rear slant angles of $\alpha = 25°$ and 35° using a 2-component laser-Doppler anemometer (LDA) mounted on a traversing system. Although Lienhart et al. [14] have conducted most comprehensive investigations of the flow around the Ahmed body, they do not include unsteady analysis of the flow field and investigation of the flow around the critical slant angle of $\alpha = 30°$ in their study. Sims-Williams [4] analysed the flow characteristics around the Ahmed body with $\alpha = 27.5°$ and 30° slant angles by using spectral methods. His work confined the investigation of self-exited, large-scale periodic structures. He has found high levels of unsteadiness existed in the wake with a shedding frequency giving a Strouhal number St of about 0.35 (based on square-root of the frontal area). Spohn and Gillieron [15] conducted experiments on the flow characteristics of the Ahmed body with slant angle of $\alpha = 25°$ in a closed water tunnel using the electrolytic precipitation technique at the Reynolds number of $Re_H = 8.3 \times 10^3$. They visualized flow at both front and rear sides of the Ahmed body. They have found some differences between their results and previous literature in the rear part separation zone. Beaudoin et al. [16] have studied wake of the Ahmed body with $\alpha = 25°$ slant angle in a hydrodynamic flow using the cavitation technique which provides non-intrusive bulk measurements of the pressure minimum. Their findings are mainly on the pressure coefficient C_p of the wake flow. They have found that the pressure coefficient C_p of the longitudinal vortices is equal to $C_p = -1.67$, which underlines their strong contribution to the global drag. Vino et al. [5,6] have investigated steady and unsteady characteristics of the wake downstream of the Ahmed body with slant angle of $\alpha = 30°$ experimentally using multi-hole probe. They have found that near-wake structure has inconsistency with the previous literature in the interaction between a separated region over the slanted surface and the recirculatory flows downstream of the model. Additionally, they have stated that the shedding downstream of the model is analogous to vortex shedding downstream of bluff bodies, with most of the fluctuations confined to the axial direction. Strachan et al. [17,18] have presented flow around the Ahmed body with various slant angles under the effect of moving ground plane using the LDA technique. They have found that inclusion of the ground simulation produces a reduction in the size and strength of the vortices shedding downstream of the Ahmed body. They have also reported vortices shedding from the underside of the model. Conan et al. [19] have conducted experimental studies related to the flow around the Ahmed body focusing on the influence of the rear slant angle α on the drag coefficient C_D by changing the rear slant angle α from 10° to 40° using PIV and oil visualization techniques. However, they have only employed PIV and oil visualization techniques together to the slant angle of $\alpha = 30°$ and they have not given detailed information about unsteady flow characteristics except providing some information about instantaneous velocity and vorticity field of the flow. Fourrié et al. [20] have studied on the flow around the Ahmed body with slant angle of $\alpha = 25°$ through wall shear stress measurements using an electrochemical method. They gave specific attention to the convection processes

Table 1
Experimental studies conducted to understand fundamental flow characteristics around the Ahmed body.

No	Researchers	Slant angles	Type of tunnel	Measurement technique	Reynolds number, Re_H
01	Ahmed et al. [1]	0°, 5°, 10°, 12.5°, 15°, 20°, 25°, 30°, 35°, 40°	Wind	Ten hole directional probe and strain gauges balance system	1.2×10^6
02	Bayraktar et al. [13]	0°, 12.5°, 25°	Wind	Water column, force balance system	$0.6–3.6 \times 10^6$
03	Lienhart et al. [14]	25°, 35°	Wind	LDA	7.68×10^5
04	Sims-Williams [4]	27.5°, 30°	Wind	Hotwire, pressure transducers, five hole pressure probes	1.3×10^5
05	Spohn and Gillieron [15]	25°	Water	Electrolytic precipitation technique	8.3×10^3
06	Beaudoin et al. [16]	25°	Water	Cavitation technique	$3.6–7.2 \times 10^5$
07	Vino et al. [5,6]	30°	Wind	Multi-hole probe	$5.5–7.7 \times 10^5$
08	Strachan et al. [17,18]	0°, 5°, 10°, 15°, 20°, 25°, 30°, 40°	Wind	LDA	4.7×10^5
09	Conan et al. [19]	10°, 20°, 25°, 30°, 40°	Wind	PIV, oil flow visualization	$0.25–1.2 \times 10^6$
10	Fourrié et al. [20]	25°	Water	Electrochemical method	2.4×10^5
11	Wang et al. [21]	25°, 35°	Wind	PIV	5.3×10^4
12	Thacker et al. [3,9]	25°	Wind	PIV, hotwire anemometry, pressure transducers	$3.9–7.7 \times 10^5$
13	Present study	25°, 30°, 35°	Water	PIV	1.48×10^4