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Non-symmetric bi-stable flow around the Ahmed body

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ABSTRACT

The flow around the Ahmed body at varying Reynolds numbers under yawing conditions is investigated experimentally. The body geometry belongs to a regime subject to spanwise flow instability identified in symmetric flow by Cadot and co-workers (Grandemange et al., 2013b). Our experiments cover the two slant angles 25° and 35° and Reynolds numbers up to 2.784×10^6. Special emphasis lies on the aerodynamics under side wind influence. For the 35° slant angle, forces and moments change significantly with the yawing angle in the range $10° \leq |\beta| \leq 15°$. The lift and the pitching moment exhibit strong fluctuations due to bi-stable flow around a critical angle β of $\pm 12.5°$, where the pitching moment changes sign. Time series of the forces and moments are studied and explained by PIV measurements in the flow field near the rear of the body.

1. Introduction

The Ahmed body is a bluff model body with basic aerodynamic properties of a vehicle, which was developed for investigating the influence of the slant angle at the back on the flow field and on the resulting aerodynamic forces, with suppressed interactions between the front and the rear parts (Ahmed et al., 1984). The Ahmed body has been the subject of many experimental investigations and simulations, in most cases in symmetric flow. The study of Le Good and Garry (2004) shows that the use of generic models is a good way for determining fundamental aerodynamic characteristics of cars, including side wind effects, although most models do not represent all aspects of the flow around car bodies equally well. Baxendale et al. (1994) measured drag and lift forces of 8 slant configurations under symmetric conditions in a wind tunnel. Due to the use of a moving belt and a low Reynolds number, the force coefficients differ from Ahmed et al.'s results. Further measurements of the pressure distribution, flow velocity, and turbulence properties of the Ahmed body in symmetric flow were carried out by Lienhart et al. (2000) and Lienhart and Becker (2003). The air velocity in those experiments was 40 m/s. The data were made available for the 9th ERCOFTAC/IAHR Workshop on Refined Turbulence Modelling, Darmstadt, 2001 – Case 9.4, and the 10th Joint ERCOFTAC (SIG-15)/IAHR/QNET-CFD Workshop on Refined Turbulence Modelling, Poitiers, 2002 – Case 9.4 of the European Research Community on Flow, Turbulence, and Combustion (ERCOFTAC 2001, 2002). This database is valuable for many quantitative comparisons. Conan et al. (2011) measured forces on the Ahmed body in open and closed wind tunnel test-sections and investigated the wake flow with the critical slant angle with PIV. In general, the drag was found to be larger than in Ahmed et al.'s data, for the 25° slant by 20%. A recent study of Thacker et al. (2012) addressed the suppession of the 3D separation on the rear slant of the Ahmed body with 25° slant angle by rounding of the roof/slant junction. A positive influence of this measure was found. However, during the force measurements in the sharp edge configuration, the drag was overestimated by roughly 30% (compared to Ahmed et al., 1984). The high sensitivity of the separation to the sharpness of the roof/slant junctions was identified as one reason.

Modern numerical techniques may provide deep insight into details of flows. Minguez et al. (2008) applied large eddy simulation (LES) with a spectral vanishing viscosity (SVV) technique to the Ahmed body with a 25° slanted back in symmetric flow at the Reynolds number of 7.68×10^5 based on the height of the model. Results were in good agreement with experimental data of Lienhart et al. (2000). A group around Serre studied three numerical techniques for simulating the flow around the same body at the same Reynolds number (Serre et al., 2013). The authors conclude that the simulations may provide good overall agreement with experiments. Vortical structures are well predicted, but the partial detachment of the mean flow over the slant was captured only by one method. In essence, LES for high Reynolds number flows remains challenging.

The wake determining aerodynamic forces on bodies may be asymmetric at sufficiently high Reynolds number, even for symmetric bodies. For axisymmetric bluff bodies, the axisymmetry breaks above a critical Reynolds number, which is 210 for the sphere (Grandemange et al., 2013b). The Ahmed body exhibits a similar

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symmetry breaking between two steady wake states at $Re = 340$ (formed with the height H of the body base) in the laminar regime (Grandemange et al., 2012). Increasing Reynolds number makes the wake unsteady. At $Re \sim 10^5$, at long time scales, the flow is bistable, with the recirculation region switching in a random manner between two preferred reflectional symmetry breaking positions (Grandemange et al., 2013a). As a consequence, the aerodynamic forces acting on the body are unsteady. This phenomenon is reported to be independent of the Reynolds number up to $Re \sim 3 \times 10^6$. The work referenced shows that the formation of the wake instability depends on the aspect ratio H/W and the ground clearance C/W of the body, where W is the width of the body. Small values of $C/W < 0.05$ prevent the underbody flow by viscous resistance, large values $C/W > 0.09$ allow for that flow without separation and with similar shear layers from the top and bottom of the base. The instability in the spanwise direction, which may lead to the bi-stable wake, forms for $C/W > 0.1$ and for aspect ratios between 0.6 and 1.3. One state may be preferred in cases of a residual yaw angle or wall effect.

Investigations in non-symmetric flow are of interest both for science and industry for the importance of the side wind influence in car aerodynamics. In the real situation, asymmetric conditions may originate from different sources—unsteady atmospheric flows, transient crosswinds, strong lateral gusts, and from the traffic environment (passing, crossing manoeuvers). These real crosswind conditions, which may influence some conclusions drawn from experimental and numerical studies, are difficult to reproduce both in experiment and simulation. Non-symmetric flow is subject to instability which may infer important influences on the forces resulting from the flow, similar to what was reported by Grandemange et al. (2013a). An adapted, simplified Ahmed body geometry was used by Docton (1996) for experimental investigation and validation of a test rig for transient vehicle side wind simulation. Surface pressures as well as drag and lift forces were measured at full scale Reynolds numbers by Bayraktar et al. (2001). Their model was 4.7 times larger than the original Ahmed body, and the investigations included three different slant angles below the critical value of 30°, where the C-pillar vortices disappear, as well as yawing angles up to ±15°. Further investigations on side wind effects on a simplified generic passenger car shape (Willy model) were performed by e.g. Gohlke et al. (2007) and Guilmineau and Chometon (2009). As a continuation of the work of Krajnović and Davidson (2004) on the flow around the Ahmed body, the Willy model was used to investigate crosswind impact on the basis of LES (Krajnović and Sarmast, 2010). Tsubokura et al. (2010) quantified side wind effects on a vehicle model with large eddy simulation (LES) based methods, referring to findings from the Ahmed body. Experimental investigations by Ferrand (2014), exposing the Willy model to harmonic crosswind, aimed at better understanding of the flow physics and quantifying the vehicle's sensitivity to unsteady crosswind. Experiments on various car models were discussed by Drage et al. (2008). The experiments on the Ahmed body included force and pressure measurements. A comparison of experimental and numerical data is given in Meile et al. (2011). In these experiments, a significant jump of the rear axle lift and pitching moments was observed with the 35° slant at yawing angles near ±12° to 13°. The aim of the present study is to investigate experimentally the non-symmetric flow around the Ahmed body with sub- and supercritical slant angles. Special emphasis is placed on the influence of the slant angle in non-symmetric flow. Our model has a ground clearance C/W of 0.13 and the aspect ratio 0.74 and is therefore subject to the instability addressed by Grandemange and co-workers. Our paper is organised as follows: we first introduce the Ahmed body together with the experimental setup and procedure used in the study. Section 3 validates the measurements with existing data for symmetric flow. In Sections 4 and 5 we present and discuss the results from the experiments. The paper ends with the summary and conclusions in Section 6.

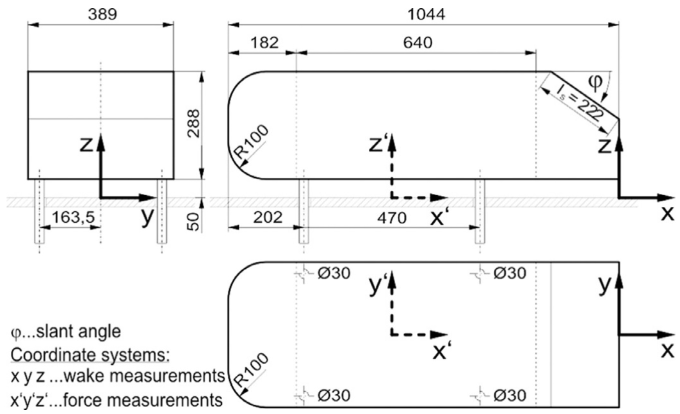

Fig. 1. Geometry of the Ahmed body used, together with the coordinate systems.

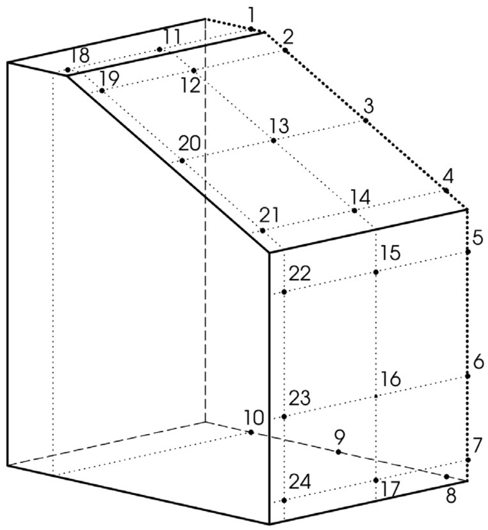

Fig. 2. Location of the pressure taps in the left rear part of the body with $\varphi = 25°$.

2. Experimental setup and procedure

2.1. The Ahmed body

The geometry of the Ahmed body investigated is depicted with its original dimensions in Fig. 1. The model was built from wooden materials, with an interchangeable rear part, so as to realise the two slant angles investigated with the same front part of the body. The model was connected to the balance below the test section floor by cylindrical aluminium stilts ($d = 30$ mm), which were fixed by screws on a special mounting support, so that the model could be turned with the balance platform. The stilts reach through a turntable disk in the test section floor without mechanical contact. The body was directionally aligned with the geometrical jet axis of the wind tunnel. The symmetry lines marked on the body were adjusted by means of measurement angles so that they coincided with appropriate lines on the bottom plate of the test section. This alignment was accurate to within ±0.1°.

The locations of the pressure taps were chosen according to the measurements of Lienhart et al. (2000) and are sketched in Fig. 2. The exact coordinates are given in Table 1. Metering points (MP) 1–10 are located in the symmetry plane ($y = 0$ mm), MP 11–17 in the plane $y = -90$ mm, and MP 18–24 in the plane $y = -180$ mm. Therefore, in Table 1 only the x and z coordinates of the MP are given. For