J. Wind Eng. Ind. Aerodyn. 145 (2015) 292–303

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Drag reduction on a flat-back ground vehicle with active flow control

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ARTICLE INFO

Keywords:
Aerodynamics
LES
Experiments
Road vehicles
Active flow control
Drag reduction

ABSTRACT

Active flow control is applied to the Honda Simplified Body (HSB), a flat-back ground vehicle model, for aerodynamic drag reduction. The use of small scale, steady jets (microjets) in normal and tangential injection orientations is investigated through experimental parametric studies and companion numerical simulations. Parameters such as injection location relative to separation point, jet diameter, and blowing ratio are explored. The flow response is characterized experimentally by aerodynamic force measurements and velocity field measurements. The computational effort utilizes Large Eddy Simulation (LES) to uncover how flow control with a steady microjet array modifies the wake and the corresponding drag. The impact of the microjets on the baseline flow field is discussed. The computational study introduces the actuator array on the top surface of the model body to support the experimental study that examines the effectiveness of flow control with microjets installed on multiple side surfaces. From both experimental and numerical analyses, it is observed that the wake can be modified with microjets such that the drag experienced by the HSB is reduced by nearly 3% with net reduction in power consumption.

1. Introduction

Automotive fuel efficiency standards have become ever more stringent due to the demands from governments and consumers, leading to vast amounts of aerodynamic studies on vehicles. Simplistic models are often used in place of more realistic geometries to study key flow characteristics while minimizing the effects of complex vehicle shapes. One such model which is vastly studied is the Ahmed (1983) model, which was initially designed to study the effect of the rear slant angle (corresponding to the angle of the rear window) on the flow topology and corresponding force measurements. Other works since its introduction offer insight into the baseline flow fields for several rear slant angles, characterizing the unsteadiness and dynamics of the Ahmed model (Gilhome et al., 2001; Vino et al., 2005; Sims-Williams and Duncan, 2003). A particular vehicle model of interest in recent years is that of a flat back geometry. This is due to the wake characteristics being very similar to many commercial vehicles such as vans, buses, and tractor trailers. In more recent works, the flow physics associated with the flat back models have been analyzed both computationally and experimentally (Krajnovic and Davidson, 2003; Lahaye et al., 2014).

Because of the vast amount of experimental studies conducted on the Ahmed model, it is often used as a canonical body to test flow control methods as well as verify emerging computational techniques. Being able to effectively reduce drag on such vehicles would increase their respective fuel efficiency, reducing the amount of emissions associated with such fleets. Control techniques applied to the forebody, such as the passive approach employing a porous surface medium by Bruneau et al. can lead to large reductions in drag (reported on the order of 40%), but would require reducing the amount of cargo/cabin space in the vehicle by 10% (Bruneau et al., 2012). With over 60% of the pressure drag on the model due to the after body separation (Ahmed et al., 1984), control is often implemented on the aft body in order to directly modify the wake to yield an aerodynamic benefit. Passive control approaches such as splitter plates, flaps, and geometric vortex generators which have been implemented on the rear of the vehicle have also showed promise (Gilliéron and Kourta, 2010; Beaudoin and Aider, 2008; Pujals et al., 2010; Krajnovic, 2014). These often have faced difficulty in full scale implementation due to length restrictions on commercial vehicles and for maintaining exterior aesthetics.

In order to limit geometric design constraints, many have focused on the development and application of active flow control techniques for drag reduction of ground vehicles (Rouméas et al., 2009; Pfeiffer and King, 2012). Control techniques from synthetic

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http://dx.doi.org/10.1016/j.jweia.2015.03.006
0167-6105/

jets (Park et al., 2013), or steady blowing (Joseph et al., 2012) have been able to reduce aerodynamic drag over a range of flow conditions; however, these often require relatively large energy inputs which negate their beneficial effect. This is shown in the studies of Littlewood et al. where steady blowing jets are used on a rear edge of a flat back vehicle model. Even though the control obtains a 12% drag reduction, the study determines the specific case to be inefficient and comments that often the most efficient control is sought – not the one that yields the largest drag reduction (Littlewood and Passmore, 2012). Thus, it is desirable to develop active flow control techniques that require small amounts of energy input while being minimally intrusive to the internals of the vehicle and the surrounding flow. One such control approach that shows promise is microjet based flow control. Microjets consist of an array of jet orifices with diameters well below the length scales of the wake or model. They are used as flow control devices which generate strong counter-rotating streamwise vortices with small energy input (Fric and Roshko, 1994; Kumar, 2008). The structures generated aid in entraining high momentum fluid closer to the model surface making the flow less receptive to separation. Microjet based actuators have been shown to impose no parasitic drag, are tunable for a range of conditions, and can be embedded in almost any surface (Kreth and Alvi, 2014; Fernandez et al., 2013). Microjet control has also been effective at eliminating separation on the rear slanted window of a 25° Ahmed model, contributing to a reduction in drag by up to 14% (Aubrun et al., 2011; McNally et al., 2012).

In this report, we present findings from the joint experimental and computational effort to examine the effectiveness of active flow control with steady microjet actuators to reduce drag on a generic ground vehicle with a flat back. This model geometry is slightly different from the original Ahmed body. Due to the flat back, it is anticipated that wake control is necessary to reduce the drag on the body. As the goal is to develop an energy efficient flow control technique, the intention is to leverage the inherent flow instabilities and their interaction with the wake to globally alter the flow field to achieve drag reduction.

We utilize both experimental and computational analyses to characterize the baseline flow over the model body. The understanding is then utilized to develop the flow control strategy using arrays of steady microjets for active drag reduction control. Initially, the computational effort was performed to gain as much knowledge of baseline flow physics as possible while the model and actuator fabrication were undertaken. Once the major experimental components were prepared, a large number of wind tunnel experiments were performed to conduct parametric studies to seek efficient flow control setups. In what follows, we discuss the model geometry, the analysis methodology, and the flow control results obtained from experiments and computations.

2. Setup and techniques

The base model for the study, introduced in the current work, is the flat back Honda Simplified Body (HSB). The HSB is a modified version of the flat back Ahmed (1983) model. The HSB consists of a square frontal area which is rounded on both the front and rear sides with radii of 50 mm and 20 mm, respectively, as shown in Fig. 1. The model aspect ratio as scaled with the height is 1:1:2.68. Identical dimensional scales of the model are used in both the experimental and computational efforts. Due to the difference of 3 mm in the boundary layer heights between the experiments and the numerical simulation, the ground clearance of the model was set to be 48 mm above the ground in the experimental setup and 45 mm above the ground in the LES. This approach is taken to match under body clearance between the model bottom and the ground plane boundary layer. The model has four legs, each with a leg diameter of 15 mm. Details of the experimental and computational setup will be discussed in the following sections.

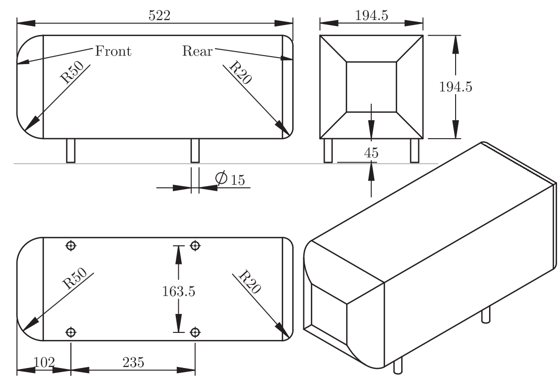

Fig. 1. The HSB with dimensions in mm.

2.1. Experimental setup

2.1.1. Facility

Experiments were carried out in the Florida Center for Advanced Aero-propulsion's (FCAAP) low speed wind tunnel facility at Florida State University. The wind tunnel is a single-pass, suck down facility with test section dimensions of 0.762 m× 0.762 m × 1.52 m (width × height × length). The flow is driven by a 200hp fan which is controlled via a variable frequency drive, allowing for the wind tunnel to achieve speeds between 1 and 80 m/s. The wind tunnel is outfitted with a series of flow conditioners and straighteners upstream of a 9:1 contraction, yielding a free stream turbulence intensity of less than 0.5% at 28 m/s. The test section walls are made of 25 mm thick acrylic, which allows for full optical access from all four sides of the test section. The unobstructed views allow for optical diagnostic techniques such as Particle Image Velocimetry (PIV) with minimal viewing obstruction. A view of the upstream portion of the wind tunnel and test section is shown in Fig. 2a. Unless otherwise noted, tests reported on the HSB were conducted at a free stream velocity of $U_\infty = 28$ m/s, corresponding to a Reynolds number of 9.7×10^5, based on the length of the model ($L = 522$ mm).

2.1.2. Aerodynamic force measurements

Force measurements were collected using a six-component torque and force balance, mounted near the center of gravity of the model. The HSB shell floats around the load balance and mounting table via connections made through the hollow legs of the model shell (Fig. 2b). The load and torque balance used was the Mini40 developed by ATI Technologies, with a full range lift and drag output of 88 N and 44 N, respectively. The resolution associated with the load balance is 0.01 N and 0.02 N for the drag and lift measurements, respectively. The uncertainty based on repeatability of tests and 3σ analysis of drag and lift coefficients is estimated to be within $\Delta C_D = 0.003$ and $\Delta C_L = 0.006$, respectively, for a 99.7% confidence interval. Force coefficients were non-dimensionalized by the full frontal area of the model including the legs ($A = 0.0392$ m^2). Aerodynamic forces were measured over a series of repeated tests at a sampling frequency of 100 Hz for a period of 10 s.

2.1.3. Particle image velocimetry (PIV)

Modifications to the flow field from microjet injection are investigated through the use of planar PIV along the centerline of the model. A LaVision PIV system was used to acquire planar PIV in the wake of the model. The LaVision system consists of two Imager sCMOS