

Scaling Considerations for Fluidic Oscillator Flow Control on the Square-back Ahmed Vehicle Model

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ABSTRACT

Improvements in highway fuel economy require clever design and novel methods to reduce the drag coefficient. The integration of active flow control devices into vehicle design shows promise for greater reductions in drag coefficient. This paper examines the use of fluidic oscillators for separation control at the rear of an Ahmed vehicle model. A fluidic oscillator is a simple device that generates a sweeping jet output, similar to some windshield wiper spray nozzles, and is increasingly recognized as an efficient means to control separation. In this study, fluidic oscillators were used to blow unsteady air jets and control flow separation on rear boat-tail flaps, achieving drag reductions greater than 70 counts. The method appears to scale favorably to a larger model, and realistic effects such as a rolling road appear to have a small impact on the oscillator's control authority. This paper will summarize the effects of geometric scaling and Reynolds scaling when applying fluidic oscillators to the Ahmed model. This work addresses some of the key scaling questions that must be answered while developing flow control schemes for full-scale automotive applications, and it is important to address these questions on a simplified Ahmed model before additional complexity is introduced through use of representative auto model geometries.

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INTRODUCTION

Aerodynamic drag can account for more than 60% of total rolling resistance at highway speeds and is an increasingly important consideration for improving the fuel economy of cars, trucks and SUV's [1]. Much work is done during the design and development phase to reduce the drag coefficient within the constraints imposed by functional and styling considerations. In many instances, new vehicles are approaching optimum drag coefficients relative to these constraints. Active flow control techniques allow further reductions in drag while largely adhering to these constraints. This study used a device called a fluidic oscillator [2] to control separation at the rear of a modified Ahmed model. Controlling wake size with flaps and fluidic oscillators has been shown to be an effective strategy for increasing base pressure and lowering drag on simplified vehicle models [4, 5, 6].

The fluidic oscillator generates a sweeping jet output from a steady flow input due to the following mechanisms. As steady fluid flow enters the oscillator cavity, it attaches to one of the interior walls, as depicted in Figure 1. A portion of this flow is diverted through the feedback channel, which then forces the incoming jet to the opposite wall. This process then can repeat at rates greater than 10 kHz, depending on the flow rate and device geometry [2]. The sweeping jet has been shown to be more efficient than steady slot blowing for

controlling separation due to the generation of streamwise vortices that enhance mixing [7]. The vortices increase mixing between the near wall flow and outer flow to enhance the boundary layer's resistance to separation from the flap. This contrasts with steady slot blowing techniques that aim to overcome the boundary layer momentum deficit through brute force addition of momentum. Steady slot blowing methods have been studied extensively by Englar for drag reduction on tractor-trailers with favorable results [8]. Fluidic oscillators were investigated in this study due to their high efficiency and control authority.

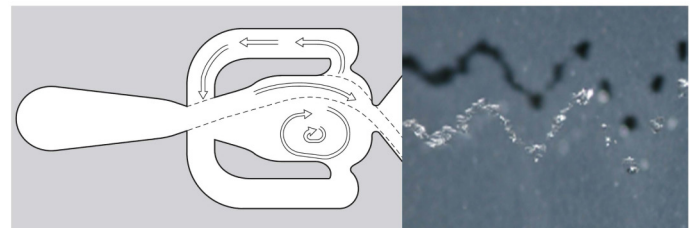


Figure 1. Fluidic oscillator and sweeping output visualization [2,3].

The square-back Ahmed model [9] was selected for this study in order to focus on and understand the essential flow features before progressing to models that are more complex. The wake on the blunt Ahmed model shows similar characteristics to that of a blunt body. Documents

SUV's that generally contain an abrupt rear geometry. The goal of drag reduction via separation control is to decrease wake size by rapidly tapering the rear of the model with flaps. Rapid tapering may be subtly implemented into vehicle design, for example, through introduction of more aggressive angles on the rear portion of an upper spoiler. While the spoiler deflection angle is limited by flow separation, the addition of fluidic oscillators can increase the usable range of flap deflection angles. For this study, oscillator jets were oriented tangentially to the flow direction, as shown in Figure 2, and placed on all sides of the rear face.

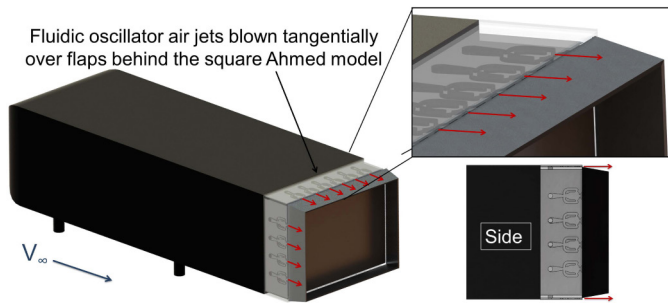


Figure 2. Square-back Ahmed model with actuators blowing over boat tail flaps.

A similar configuration to the current study was presented by Wosidlo *et al.* [6] and Schmidt *et al.* [10] on the simplified European tractor-trailer model; however, there are unanswered questions related to scaling the technology for real vehicles. Relevant scaling effects are related to the impact of a rolling road, speed-dependent behavior (Reynolds effects), actuator sizing, and ride height. Primary geometric parameters governing oscillator effectiveness on the tangential configuration are the spacing between oscillators and the size of the oscillators. Wosidlo *et al.* suggest that increasing the spacing between oscillators does not significantly affect the ability to control separation, which is a favorable finding in terms of energy consumption [6]. They also showed that C_{μ} does not effectively capture actuator spacing effects.

The key objectives of this study were to minimize the energy requirements of flow control and to understand some of the critical parameters governing scaling. The energy usage of flow control can be minimized by maximizing the spacing between actuators and minimizing actuator size, while still maintaining control authority. Thus, the effects of actuator spacing and size were carefully considered in this work through study of multiple actuator arrays, in an effort to reduce the mass flow requirements for flow control. Another objective was to understand how the relationship between energy requirement and resulting drag savings scaled with model size. To study vehicle scaling, two Ahmed models of different scales were constructed with similar actuator configurations. To the best of the authors' knowledge, a study of the effects of geometric scaling with fluidic oscillators is a new contribution to the field. Sensitivity to a moving ground plane, ride height, and speed (Re) were also examined over the course of this study.

EXPERIMENTAL SETUP

Ahmed Vehicle Models

Two different sized Ahmed models were used, 83% and 166% scale of Ahmed's original dimensions [9], in order to understand the impact of geometric scaling on active flow control. Initial tests were done with an 83% scale Ahmed model in a low-speed wind tunnel at The Ohio State University. Scaling to 83% was needed to achieve an appropriate test section blockage in the OSU wind tunnel. This same model was also installed in the Honda R&D Americas Inc. tunnel, where most of the data for this paper was acquired. Geometric scaling tests were then done on a model twice the size of the smaller model at the Honda R&D Americas Inc. facility. Figure 3 and Table 1 present the geometry and dimensions of both models, which were based on the original Ahmed design. An additional aft portion containing the oscillators and related pressure lines was added to both models, to which a separate flap assembly was attached. Discrete flap assemblies were used for each deflection angle listed in Table 1.

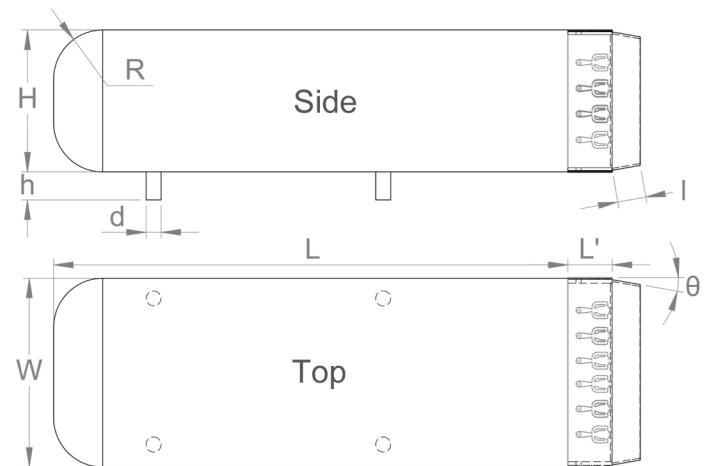


Figure 3. Ahmed model schematic with relevant dimensional notation. Actuators are placed symmetrically on all sides of the model.

Table 1. Dimensions of the two Ahmed models studied.

Symbol	Description	Small Model	Large Model
L	Base Length	869 mm	1738 mm
L'	Actuator Length	75 mm	75 or 150 mm
W	Width	318 mm	636 mm
H	Height	239 mm	478 mm
h	Ride Height	30, 55, 80 mm	94 mm
R	Front Radius	83 mm	166 mm
d	Support Diameter	25 mm	25 mm
l	Flap Length	48 mm	96 mm
θ	Flap Angle	10°, 15°, 20°	10°, 15°, 20°

Fluidic Oscillators

The feedback channel type of oscillator was used for this study, based on the design developed by Bray [11]. There are several types of designs that accomplish the sweeping jet output as outlined in [12], however this particular design was selected due to its stable operating characteristics and relatively low pressure losses. One actuator configuration was tested on the small Ahmed model, based on an initial selection of oscillator spacing and size. Three actuator configurations (depicted in Figure 4) were tested on the large Ahmed model to determine the effects of actuator size and spacing. The actuators were fabricated from laser cut acrylic pieces, including a 1.5 mm cover plate, 1.5 mm oscillator cavity, and 5 mm bottom plate with tapped holes for air fittings. Actuator arrays were positioned symmetrically on all four sides of the aft end of the square-back Ahmed model.

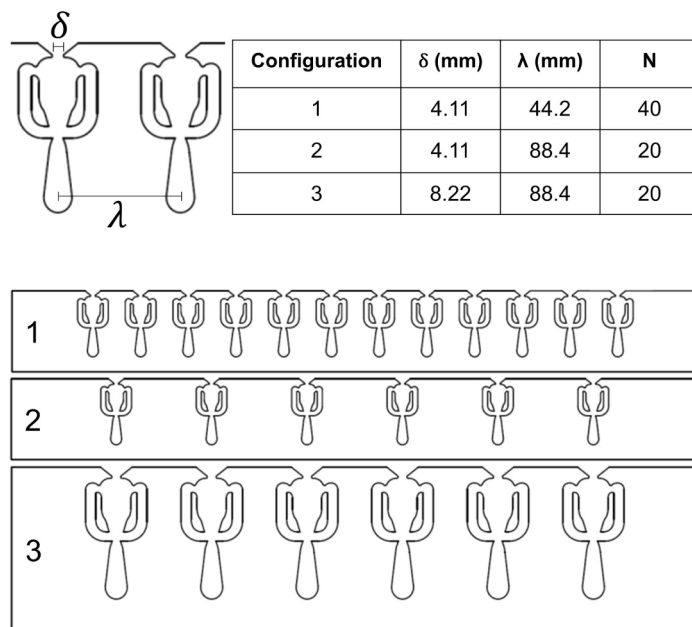


Figure 4. Actuator dimensions and relative size comparison. The arrays shown in the lower portion of the image are placed on the upper and lower sides of the model. The sides have fewer oscillators, but the same relative scaling.

The first actuator array on the large Ahmed model used twice as many oscillators of the same size as what was used on the small Ahmed model. The second configuration involved doubling the distance between actuators, while keeping the oscillator size and thickness constant (relative to the small Ahmed model study). The third configuration involved scaling all dimensions of the original actuators on the small Ahmed model by a factor of two, except the cavity depth, which was held at 1.5 mm for all oscillators. The momentum coefficient (C_μ), defined by Eq. 1, was kept constant for all of the tests.

$$C_\mu = \frac{N \rho_j A_j V_j^2}{\frac{1}{2} \rho_\infty A V_\infty^2} \quad (1)$$

C_μ is a common figure of merit for determining the effectiveness of a flow control technique, and is roughly interpreted as the ratio of actuator input momentum relative to the flow momentum displaced

by the model's frontal area. This particular definition, which refers to model frontal area as the reference area and N is the number of oscillators on the model, is common for vehicle flow control studies and allows for comparison to other results [6, 8]. The jet exit velocity may be inferred from the mass flow through the oscillators, which allows C_μ to be defined as

$$C_\mu = \frac{2 \dot{m}^2}{\rho_\infty^2 A A_j N V_\infty^2} \quad (2)$$

Oscillator frequency depends on both the scale of the device and the mass flow rate. This results in frequency differences for the three actuator configurations at a given C_μ . The effects of frequency were not directly examined, however the high oscillation frequency of these tests (close to 1 kHz) relative to natural instabilities, along with the random phase between oscillators, make flow structure amplification via specific frequencies unlikely.

Wind Tunnel and Equipment

Honda R&D Americas Inc. Wind Tunnel

Data for this paper was acquired in two different wind tunnel facilities, at either OSU or Honda R&D Americas. The Honda R&D scale wind tunnel, depicted in Figure 5, has an open test section that can accommodate vehicle models up to 50% scale [13]. The tunnel is capable of 70 m/s test section speed and turbulence levels less than 0.16%. The test section length is 2.1 m and the nozzle exit plane that defines the test section has an area of 4.15 m². A 0.42-m wide moving belt is located in the center of the test section to simulate a moving ground plane. Control of the floor boundary layer is accomplished with two-stage suction and blowing, such that the wall velocity ahead of the moving ground plane is uniform in the vertical direction to within 1.5% of free stream velocity.

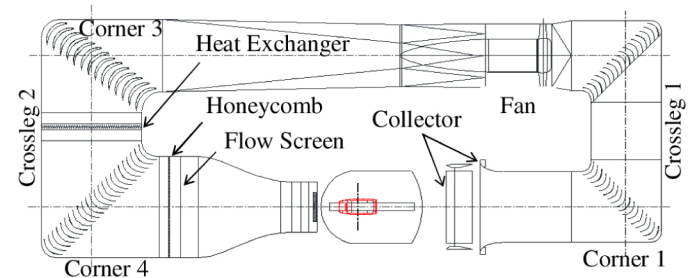


Figure 5. Honda R&D Americas Inc. wind tunnel schematic [13].

The Honda R&D Americas Inc. tunnel is equipped with a 6-axis load cell with 2σ uncertainty of ± 0.07 N. In practice, the 2σ uncertainty is within $C_D \pm 0.0007$. The four posts that connect to the model are part of the load measurement system. Further details of the tunnel and load cells can be found in [13]. In this study, drag was averaged over three separate 60-second periods. The thrust generated by the oscillators was removed from the measured C_D by taring the model with the actuators on and tunnel off. This results in a conservative estimate of the effective drag reduction because the beneficial thrust component (which would be present in vehicle operation) is removed.