

Drag Reduction using Base Flaps Combined with Vortex Generators and Fluidic Oscillators on a Bluff Body

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ABSTRACT

The potential of drag reduction on a generic model of a heavy vehicle using base flaps operated in combination with flow control devices is investigated experimentally. Base flaps are well known as drag reduction devices for bluff bodies and heavy road vehicles. However, for optimal performance their deflection angle should typically not exceed 12° . In this paper the primary goal is to increase the usable range of the deflection angles by applying flow control. The secondary goal is to find the most suitable method for flow control. A comparison is made between triangular vortex generators and fluidic oscillators as passive and active flow control methods, respectively. Vortex generators have the advantage of being very simple devices but produce drag. Fluidic oscillators are also quite simple devices but require additional air supply. Their advantages are that they can be activated when needed and that they do not generate additional drag. The wind tunnel model used corresponds to the geometrical dimensions of a 10% scaled model yielding a Reynolds number of $7 \cdot 10^5$. Various flap angles with a length of 100mm were attached to the base. Other geometrical parameters such as the height of the vortex generators were also varied as well as their axial position. The results show that base flaps deflected by 20° combined with vortex generators reduce drag by 26% compared to the baseline. At deflection angles of 22.5° the passive and active concepts show similar drag reduction. Furthermore, possibilities for performance improvement of the active concept are identified.

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INTRODUCTION

At cruising highway velocities, most of the fuel consumed by a long hauling heavy truck is spent to overcome the aerodynamic drag, since at velocities above approximately 100kph the aerodynamic drag becomes the dominant part of the total resistance of the vehicle. Therefore, the drag of truck-shaped bodies has been the focus of numerous experimental and numerical investigations during the last decades [1, 2, 3, 4, 5, 6]. Many approaches consider the modification of the flow behind the rear end which comprises the dominant part of the pressure-induced drag. In the USA drag reducing rear end add-on devices have successfully been transferred from the state of a research object to a commercially available product. However, in Europe such a development has been hindered through legislation which limits the length of the entire vehicle. In the USA aerodynamic devices of about 1.5 m additional length are allowed.

Recently the European regulations are being revised and drag reducing devices with a length of 500mm attached to the rear end of the vehicle are allowed [7] motivating research regarding short add-on devices.

One of the most promising and simplest devices are the so called base flaps which consist of deflected surfaces at the trailing edge (TE) of the trailer forming a cavity (Figure 1 and Figure 11 in the Appendix) as studied for example by Browand et al. [1], Göhring and Krämer [8], Wood [9], Englar [10], Nayeri et al [11] and Seifert et al [12]. It was found that long plates perform better than short ones as they can

recover more pressure. The optimal deflection angle has been found to be in the range of 12° to 15° . Due to flow separation at higher angles the obtained pressure recovery at the base decreases which yields to a lower flap effectiveness.

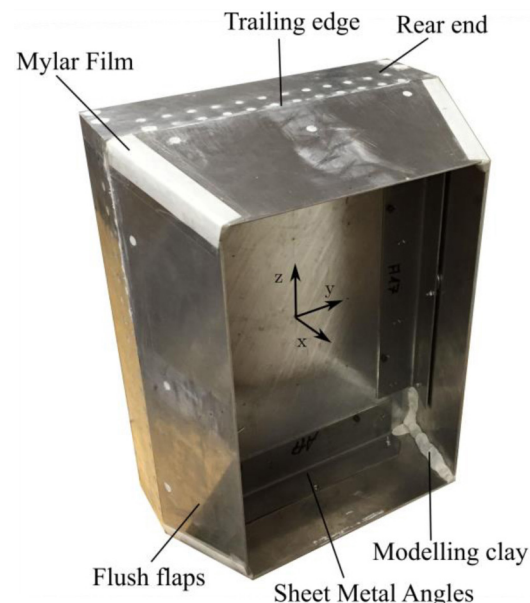


Figure 1. Illustration of base flaps leveled with the GETS model.

In this investigation we aim to improve the drag reducing potential of flaps at higher deflection angles as these results in shorter additional lengths. In our approach we compare additional passive and active methods to avoid the flow separation on the base flaps at angles greater than 15° . As passive method we apply vortex generators (VG) and as active we used fluidic oscillators. Both methods are briefly described in the following.

The effectiveness of vortex generators to delay the point of boundary layer separation caused by an adverse pressure gradient has been shown in several studies and is well described (e.g., Lin et al. [13, 14, 15], Betterton et al. [16], Godard et al. [17], and Velte et al. [18]). Lin et al. extensively compared the effect of different VG types. They observed that the most effective underlying mechanism of VGs is the generation of coherent and longitudinal vortex structures evolving in streamwise direction. Additionally, Lin [19] investigated the so called micro vortex generators. These VGs are basically small triangular or trapezoidal plates/vanes applied perpendicular to the surface under a lateral angle relative to the main flow direction and could be either positioned parallel or in V-shape. These VGs produce pairs of co- or counter-rotating vortices persisting further downstream. VGs with a height of 20% of the boundary layer thickness ($h_{VG} = 0.2\delta$) and generation of counter-rotating vortices revealed to have the best effects. These results were confirmed by Betterton et al. [16] and Godard et al. [17].

Besides adding passive methods several attempts have also been made to improve the drag reducing effect of base flaps by adding active flow control (AFC). Nayeri et al. [11] combined base flaps with constant blowing, constant suction, and pulsed blowing actuation through small slots at the TE. Seifert et al. [12] examined active flow control with pulsed blowing and suction on a full size truck. Metka et al. [20], Woszidlo et al. [21] and Schmidt et al. [22] examined the feasibility of employing fluidic oscillators on a bluff body equipped with base flaps. The main advantages of fluidic oscillators are the generation of a high frequency and self-sustaining oscillating jet which affects a wide spatial area without the use of any moving parts and the possibility to turn them off when not needed.

SETUP AND INSTRUMENTATION

The generic truck model examined in this study is a 1/10 scaled General European Transport System (GETS) model introduced by Van Raemdonck and Van Tooren [6]. This model represents a European long-haul heavy duty vehicle without any of the geometric details (e.g., tires, side mirrors, gap between truck, and trailer, etc.). The external dimensions of the vehicle model are illustrated in Figure 11 in the Appendix. The front edges of the model are rounded with a 54mm radius. Tripping is applied to the front radii to reduce Reynolds number effects. Zigzag tape is used which represents a commonly used solution to suppress laminar separation (e.g., illustrated by Van Raemdonck [6] et al. and Van Rooij et al. [23]).

Interchangeable base flaps are attached to the rear end of the model. The used flap angles and flap lengths are chosen according to previous studies by Woszidlo et al. [21] and Cooper [24] (shown in Table 1).

Table 1. Overview on the investigated parameters.

Parameter	Symbol	Unit	Range
Reynolds number	Re	-	$7 \cdot 10^5$
Flap angle	α	$^\circ$	10, 15, 20, 25
Flap length	l_{flap}	mm	100
VG height	h_{VG}/δ	mm	0.2, 0.37, 0.5
Covered model sides	n	-	1, 3
Distance to BE	$\Delta x_{VG}/h_{VG}$	-	5, 10, 15, 20
VG spacing	λ/h_{VG}	-	5, 6, 7
Ground clearance	d	mm	35

The concept and the geometrical parameters of the investigated triangular vortex generators are visualized in Figure 2. The relevant geometric parameters of the VGs are the vane height h_{VG} , the length of the vanes l_{VG} , the distance between a pair of alternating vanes d_{VG} , and the vanes angle of attack β . In this study a pair of alternating vortex generating vanes will from now on be called VG. The distance between the symmetric lines of neighboring VGs is parameterized by λ . The VGs are positioned along the perimeter on the side and top faces of the GETS model with a streamwise distance Δx_{VG} between the trailing edges of the VGs and the model. The chosen geometric parameterization follows Godard and Stanislas [17]. It was shown that the geometric parameters highly depend on the considered model geometry. Thus, a parametric study was first conducted to determine the optimal configuration for the GETS model. The results of this study are illustrated in the next section. The investigated parameters are listed in Table 1.

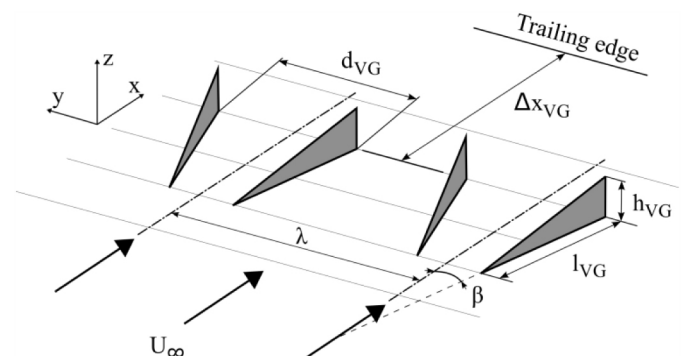


Figure 2. Geometrical VG parameters in conformity to Godard and Stanislas [17].

The AFC is provided by the fluidic oscillators which are implemented along the base perimeter just at the leading edge of the offset base flaps (Figure 11 in the Appendix). The orientation of the oscillators is in streamwise direction parallel to the model's side faces. The vertical TEs of the model contain each 17 oscillators and the upper and bottom horizontal edges contain each 11 oscillators. The air supply is provided by four pressure chambers positioned behind the base plate. A detailed description of the actuator system and the used oscillators is provided in Schmidt et al. [22]. Of importance is the inward offset of the jet nozzles by 4.6mm due to manufacturing requirements. This step presents a small discontinuity (1.3% of the model's height) which may be optimized in future investigations. For the sake of

comparability the combination of base flaps and vortex generators is considered for two cases: with the offset and without the offset (i.e. flush with the surface of the model faces).

The wind tunnel experiments were conducted in the closed-loop wind tunnel of the Hermann-Föttinger-Institut at the Technische Universität Berlin. In the present case the test section had a length of 7.5m with a general section of 2m×1.4m. A splitter plate is mounted within the test section to reduce the effects of the boundary layer as no moving belt is used. The vehicle model is mounted in the first test section close to the floor with a ground clearance of 35mm. The model's blockage of about 3.6% (taking the splitter plate in consideration) was not taken into account in the data reduction and meets the SAE J 1252 requirements [25] of 5% blockage. The freestream turbulence intensity within the test section is less than 0.5%. The freestream velocity in this study is set to $U_\infty = 35\text{m/s}$ which corresponds to a Reynolds number of about $Re = 7.0 \cdot 10^5$ based on the square root of the model's frontal area which according to Wosizdlo et al. [21] provides Reynolds number independency. The velocity is monitored by a Pitot-tube mounted above the model.

A six-component balance positioned underneath the test section is used to measure the aerodynamic forces with a sampling rate of 5Hz. The balance is able to rotate around the vertical z-axis. The maximum range is 2.2kN with an error of 0.1% full scale. The vertical rods (Figure 11 in the Appendix) are connected to the external balance, the main air supply hose, and the cables of the pressure sensors are covered by an airfoil mounted to the splitter plate's floor to prevent the distortion of the force measurements. Furthermore, the hose forces from the air supply system were minimized to avoid an influence on the force measurements. The model's alignment is set by the zero side force and yaw moment criterion described by Wosizdlo et al. [21].

The base flaps (Figure 11 in the Appendix) and the base of the model are equipped with a number of pressure taps to detect the surface pressure. The pressure taps have an internal diameter of 0.7mm and are well integrated into the walls. The interference of the taps with flow can be considered as negligible. The used piezo-resistive pressure sensors (HDO series of First Sensor) measure the differential pressure in a range of $\pm 1000\text{Pa}$ with a response rate of 4096Hz and accuracy of 0.5% full scale.

RESULTS

The current section summarizes the results from the extensive experiments to understand and to improve the influence of the vortex generators and of fluidic oscillators on the aerodynamic behavior of the GETS model equipped with base flaps. First, the model without base flaps will briefly be characterized. Next, the performance of flush flaps and offset flaps without any VGs are considered and compared. Then, in a parametric study the effects of VGs on the performance of flush and offset base flaps are presented. Finally, the most promising configurations of VGs as a passive method are compared with the active flow control through oscillating jets. Although several base flaps lengths were studied only results from

100mm long base flaps are presented in this paper corresponding to normalized value of $x/\sqrt{A} = 0.33$. Schmidt et al.[22] illustrate that there is no effect beyond a certain flap length. The flap length is chosen on these results. According the categorization of the flap angles by Schmidt et al., Table 1 illustrates the range of investigated flap angles α .

Baseline, Flush and Offset Base Flaps

As a baseline (bl) configuration we considered the model without any add-on devices. An averaged drag coefficient measured over 10 increasing and decreasing Reynolds number sweeps from $5 \cdot 10^5$ to $8 \cdot 10^5$ of $\overline{C_{D,bl}} = 0.36$ was determined (Figure 3). This value is used to evaluate the changes in drag through other configurations. In his GETS study Raemdonck [5] obtained a different value of 0.31. This difference is attributed to the difference in setup as the ground clearance between model and splitter plate differs in both studies. The experiments showed that beyond $Re = 5 \cdot 10^5$ the drag can be considered as independent from the Reynolds number, thus all further measurements were carried out at $Re = 7 \cdot 10^5$. Therefore the Reynolds number criteria of SAE J 1252 [25] is fulfilled.

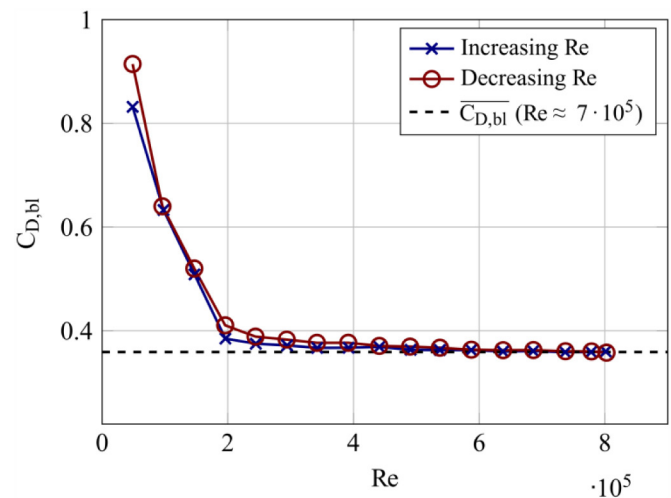


Figure 3. Baseline drag coefficient $C_{D,bl}$ as a function of the Reynolds number Re .

As in the active configuration the flaps had to be installed offset to the TE creating a step of 4.6mm height. We carried out a set of experiments to explore the influence of this step. For different flap angles Figure 4 indicates that the base flaps always improve the aerodynamic behavior by decreasing the drag and increasing the base pressure. However, the flush base flaps perform the best and achieve a minimal drag at $\alpha = 15^\circ$ where a reduction of about 33% is found. This result correlates well to findings by Cooper [24].

The shifted flaps lose performance after $\alpha = 10^\circ$ and have only very little drag reduction for angle exceeding 15° indicating a separation of the flow. A good correlation between drag reduction and base pressure is achieved when the flaps are offset. Whereas, the trend of the flush flap configuration exhibits minor deviations between base pressure and drag coefficient.