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THE EFFECT OF OSCILLATORY BOAT-TAIL FLAPS ON THE NEAR WAKE OF A PROTOTYPICAL HEAVY VEHICLE

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ABSTRACT
Due to the increased interest in the aerodynamics of truck / trailer combinations as a means to reduce their fuel consumption, experiments have been conducted on a model of a trailer to study possible changes in its near wake arising form attached aft-flaps. The model was fitted with vertical flaps on both sides of the back plate, which were set to oscillate at given frequencies and amplitudes. Experiments were carried out using the PIV system in a Water Channel at Monash University. The oscillation of the flaps perturbed the flow in such a way that the shear layer was significantly changed and the roll up of vortices was moved further upstream, causing a rise in the rate of entrainment and a shorter reattachment length. It also had the effect of a reduced wake size and higher velocities within the wake. These are all effects that are consistent with an increase in the base pressure at the back plate of the trailer and therefore also a reduced drag coefficient, since they are strongly connected.

NOMENCLATURE

W	width of test section,	mm
H	height of test section,	mm
L	length of test section,	mm
w	width of model,	mm
h	height of model,	mm
l	length of model,	mm
U_{inf}	freestream velocity,	m/s
f	oscillation frequency,	Hz
A	amplitude of oscillation,	degrees
Re	Reynolds number based on w, $Re = \rho\, U_{inf} w / \mu$	
ρ	density of water,	kg/m^3
μ	dynamic viscosity of water,	Pa s
St	Strouhal number based on f and w, $St = f\, w / U_{inf}$	
B	size of the wake,	mm^2

INTRODUCTION
With the concerns over energy efficiency and reducing carbon emissions has come a renewed focus on improved fuel efficiency in heavy vehicle transport. Many countries, such as Australia, transport a large proportion of their goods using articulated tractor (prime mover) / trailer(s) combinations.

The Australian Bureau of Statistics estimated that in 2007 transportation provided by the combined rigid and articulated truck sectors accounted for 6000 megaliters of fuel, approximately 20% of Australian total Fuel consumption. These equate to 20.3% of Australia's road transport emissions, which make up 12% of Australia's total greenhouse emissions.

If a relatively modest fuel savings goal of 15% of 2008 fuel usage could be saved by aerodynamic improvements by 2020, it would save 950 megaliters of fuel and reduce CO_2 equivalent emissions of 2000 Gg. This represents more than 3% of sector emissions and 0.36% of Australia's total emissions.

Given these vehicles travel at speeds at which aerodynamic drag becomes a dominant factor and the fact that their geometry is constrained by the bluff shape of their trailers there is considerable scope to reduce their drag force and consequently fuel consumption and emissions. This paper is part of a wider study looking at passive and active control mechanisms to reduce drag in heavy vehicles. The focus of the research described here is the rear (suction) surface and the use of active control to modify the wake.

PREVIOUS WORK

The aerodynamic features of a trailer are strongly characterized by the large region of separated and recirculating flow behind the trailer. The separation is due to the abrupt change in geometry at the back of the trailer that creates the wake region and thus the low base pressure, which is the main cause of the pressure drag of a bluff body.

The vortex shedding that arises from the flow separation along the edges of a bluff body is responsible for the vortices of several scales created in that area. These vortices result in the locally large amplitude velocity fluctuations in the wake. For two-dimensional bodies this is dominated by the Kármán vortex street, which has been shown by Provansal et al. [1] to arise from a Hopf bifurcation and which results in the periodic shedding of vortices of alternate sign. Such flows have been extensively researched in the past, with much of the focus being on the wakes of circular cylinders. A relatively recent, comprehensive review of bluff body wakes, with a particular focus on the circular cylinder, has been written by Williamson [2].

In the case of three-dimensional bodies the flow becomes more complex, since the vortex shedding has components in all three directions. A further complicating effect in the case of a trailer is the effect of the ground, which becomes important because the boundary layer created along the ground influences both the pressure distribution inside the wake as well as its structure.

Roshko [3] in his early work articulated the wake structure and its effect on the forces experienced by the body. He showed study that there is a correlation between decreased wake size, the natural vortex shedding frequency and drag force reduction. This work has provided not only a means of interpreting results but also a guide to the routes that need to be taken to reduce drag in bluff bodies.

Mechanisms to reduce drag can be passive or active. The two approaches target the critical regions of the bodies' geometries. Such regions are of two distinct types: (a) surfaces of high (upstream facing) or low (downstream facing) pressure, and (b) points where the flow is most susceptible to influence. Frequently, these latter regions are subjected to static (passive) or dynamic (active) geometry changes that are targeted at influencing the flow.

Examples of the two approaches are available in the literature and in laboratory and numerical experiments they have shown significant drag reductions, with drag coefficient reductions of 20% and above being achieved. In many cases the base body to which the drag control devices are attached or incorporated are rectangular in cross-section, reflecting the interest in drag control for ground vehicles. Another reason for the use of rectangular bodies is the recognition that the separation lines are fixed, which means that there is little opportunity to use delayed separation to affect the wake region, in contrast with more aerodynamic geometries. However, as pointed out by Greenblatt and Wygnanski [4] and Gad-el-Hak [5] there is considerable potential to affect wake flows, as defined by the large-scale Bénard-Kármán vortices (BKV), by influencing the separating shear layer (Kelvin-Helmholtz (KH)) vortices. Changes induced in the shear layer vortices can then result in upstream conditions that have a consequent effect on the BKV. This targeting of the KH vortices in preference to the BKV reflects their instability characteristics, being respectively convective versus absolute. An example of this approach was illustrated by Chyu et al. [6] who found that by forcing the KH (Bloor-Gerrard) vortices in the near wake of a circular cylinder they could have an effect on the Kármán vortex street.

In many of the instances of passive drag control the focus has been on shortening the wake length, as per the insights provided by Roshko [3]. Mair [7] showed that a disk attached to the base of an axisymmetric body could significantly reduce the drag, provided the geometry with respect to the rear of the body is optimized. These findings have resulted in other geometries that similarly reduce the drag by similar mechanisms. An example is the work of Wong and Mair [8] which demonstrated that properly oriented rear extensions to a bluff body could significantly reduce the drag. These *boat-tails* remain of considerable interest and the mechanisms by which they reduce base suction have been examined in some depth. More recently, these have been employed on truck-trailer combinations, see for example the extensive set of articles discussing this approach included in the book edited by McCallen, Browand and Ross [9]. A number of the studies discussed there (Coon and Visser [10], Heineck et al. [11])and more widely in the literature have investigated, using experiments, simulations and full-scale tests, the effect of stationary flaps to reduce the size of the wake and so reduce the drag coefficient in heavy vehicles. These studies have shown that such boat-tails can have a significant positive effect, with drag coefficient reductions as high as 20%.

The advent of new numerical and experimental techniques have been particularly useful in providing further insight into the flow mechanisms affecting the drag reduction of such approaches. Weikgenannt and Monkewitz [12], for example, have investigated in more depth the effect of attached disks to the rear of axisymmetric bodies on the wake flow structure. They found four flow regimes, depending on the separation of the disk from the rear of the body. The drag could rise or fall relative to this separation length – with this dependence being determined by the shear layers' trajectories and how they interact with the disk. This again leads us to return to the discussions of Greenblatt and Wygnanski [4] and Gad-el-Hak [5] and the importance of the shear layer in wake control.

A number of authors (Hsu et al. [13], and El-Alti et al. [14]) have examined mechanisms for doing this using active control and in several cases these have been combined with other passive measures, such as boat-tails. Primarily, these have used periodic sucking or blowing to enhance the effect of the boat-tails. In related work, the passive use of momentum alteration has been examined in the work of Bruneau et al. [15] with remarkably good drag reduction potential (up to 45% on an Ahmed body when the porous surfaces are placed at the front corner of the roof) depending on the positioning of the porous surfaces.

The success of these approaches in using separating shear layer control to effect wake control motivated the present study. Here, two-dimensional horizontal measurements have been carried out in the middle of the trailer to reduce the influence from shedding along the top and bottom edges. The concept is to use oscillating flaps attached to the edges of the back of the trailer to control the vortex shedding in a favorable way and thus reduce the base pressure drag.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were carried out in the FLAIR Water Channel, see Fig. 1, in the Department of Mechanical and Aerospace Engineering at Monash University using particle image velocimetry (PIV). The water channel has a test section that has dimensions of 600 mm (W) x 600 mm (H) x 6000 mm (L). The intensity of the freestream turbulence in the channel is less than 1% and non-uniformity of the flow in the working section is minimal.

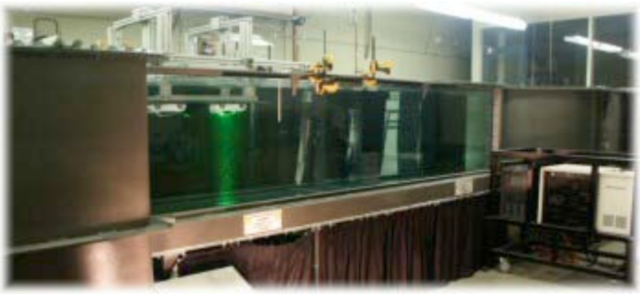

Fig. 1. The FLAIR Water Channel at Monash University.

To represent the trailer an 80 mm (w) x 80 mm (h) x 400 mm (l) rectangular cylinder made of perspex was used, see Fig. 2. It was fitted with an aerodynamically shaped head to avoid the recirculation bubble otherwise appearing along the sides of the cylinder. The cylinder was fixed 5 mm underneath a plate made of perspex, used to represent the ground. It was also fitted with vertical flaps attached to the edge of the back surface on both sides with a length of 0.31 times the width of trailer, these were also made from perspex. This flap length was chosen because previous studies [16]have shown that there is little added benefit beyond a length of 0.25 times trailer width and due to increments in the size of available material. It was not a parameter considered to have a major influence on the overall performance of the oscillating flaps, beyond choosing it to be reasonably close to the recommended value of 0.25. The use of perspex as the material of the model is based on the transparency it gives, which is a prerequisite when using PIV. The oscillation of the base flaps was controlled with a transducer which provided the capacity to set both frequency and amplitude.

Fig. 2. The model used in this study.

As shown by Okajima [17] for a square cylinder the frequency of the vortex shedding i.e. the Strouhal number becomes largely independent of the Reynolds number at high Re. This provides some confidence that the results in this report are likely to be valid at the higher values of Re seen in real life applications.

In this study measurements have been carried out at oscillation frequencies ranging from 0.5 Hz to 2.0 Hz, giving Strouhal numbers of 0.21-0.86, i.e. around the large-scale vortex shedding frequency. The flaps oscillate at these frequencies at angles of 10-30, 10-20 and 20-30 degrees, with the angle defined as being between the flap and a extended cylinder side. For comparison, measurements have also been carried out without flaps, with stationary flaps at angles of 0, 10, 20 and 30 degrees, and with a freestream velocity of 0.277 m/s and Re at 22000 at frequencies of 0.8, 1.0, 1.25, 1.6 and 2.0 Hz and oscillations at 10-30 degrees. The range of these angles of oscillation and their means were chosen based on previously published work [16]. The freestream velocity U_{inf} in the water channel was set to around 0.18 m/s, so that the Reynolds number was about 15000.

The measurements were all carried out using an in-house PIV system. The water was seeded with spherical polyamide particles with a mean diameter of 20 μm. The particles were illuminated by a thin laser sheet produced by two Nd:YAG lasers and captured on a Nikon high-resolution digital camera fitted with a 105 mm lens. By using an external trigger coupled to the transducer controlling the flap oscillation, it was possible to time the measurements such that a sequence of them could be made that were all taken at the same phase within the oscillation cycle. The image pairs were processed by the in-house developed code and the resulting velocity vector fields, and derived vorticity fields, are the basis for the results presented in this paper.

All results presented are averaged based on 400 instantaneous measurements unless otherwise mentioned. The velocity and spatial coordinates are non-dimensionalized by the freestream velocity, U_{inf}, and the trailer width, w, respectively

RESULTS AND DISCUSSION

The objective of this study is to examine whether the introduction of oscillating flaps attached to the rear surface of a trailer changes the size and structure of the wake and also shows further improvements in drag reduction compared to using stationary flaps.

To compare the different results arising from the different frequency and amplitude settings of the oscillating boat-tails and to also compare these with the experiments carried out without flaps and with stationary flaps, the reattachment length and the size of the wake has been plotted in Fig. 3 and Fig. 4. The reattachment length is defined as the distance between the body and the stagnation point at the end of the wake, while the size of the wake is defined as the area in which the downstream velocity is below 99% of the freestream velocity.

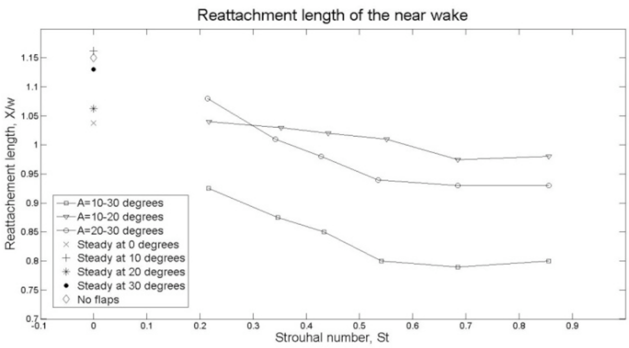

Fig. 3. Comparison of the reattachment length of the near wake at varying frequencies and amplitudes.

Fig. 3 shows there is a significant reduction (up to 31%) in the reattachment length for all settings compared to the benchmark where no flaps were used. There were also reductions in most cases compared with the 0 degree stationary settings (up to 23%). It is also evident from Fig. 3 that for the different amplitudes of oscillation there are similar trends in the effect of the frequency. As the frequency increases up to a limit (f = 1.25-1.6 Hz, St = 0.55-0.70) the reattachment length reduces, following the reaching of this limit the reattachment length remains constant or marginally increases.

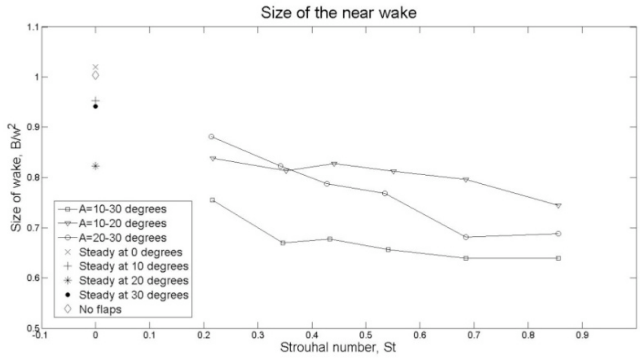

Fig. 4. Comparison of the size of the near wake at varying frequencies and amplitudes.

Fig. 4 shows similar trends to those seen in Fig. 3 with respect to the effect oscillation amplitude and frequency settings. Again, there is a tendency for the wake length to level out at the same frequencies (f = 1.25-1.6 Hz, St = 0.55-0.70) for the 10-30 and 20-30 degrees oscillations. For the 10-20 degree oscillation on the other hand the wake size seems to further decrease while the frequency increases. The reduction in wake length when introducing the oscillation is also significant here, it can be up to 36% compared to not using flaps and up to 22% compared to the case where stationary flaps are set at 20 degrees.

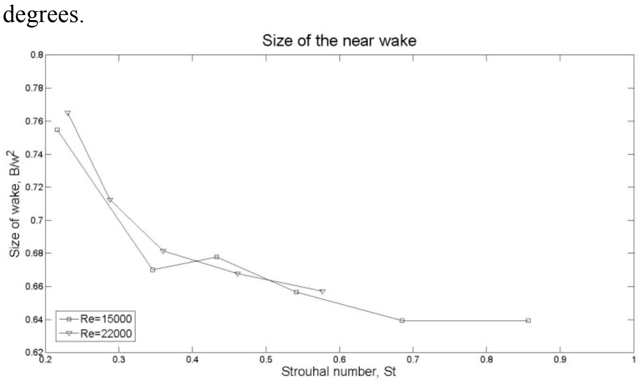

Fig. 5. Comparison of the size of the wake for two different Reynolds numbers at varying frequencies oscillating at 10-30 degrees.

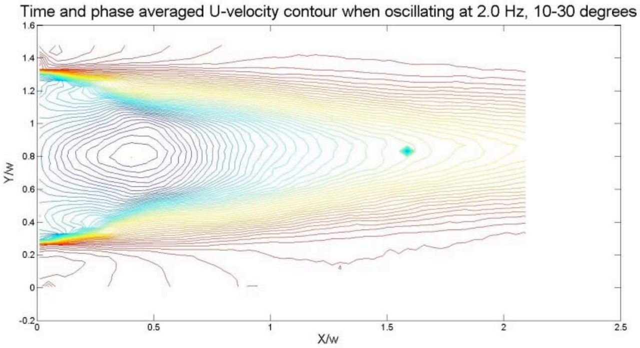

Fig. 6. Time and phase averaged U-velocity contour when oscillating at 2.0 Hz, 10-30 degrees.

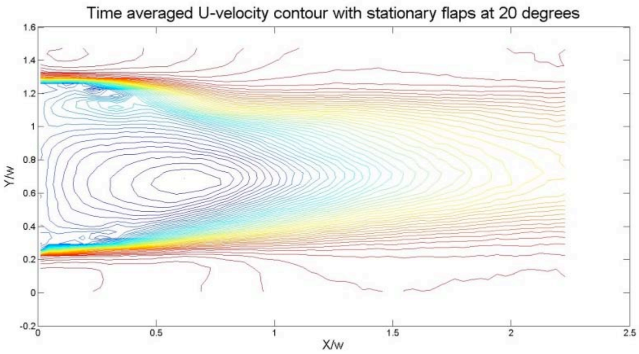

Fig. 7. Time averaged U-velocity contour with stationary flaps at 20 degrees.

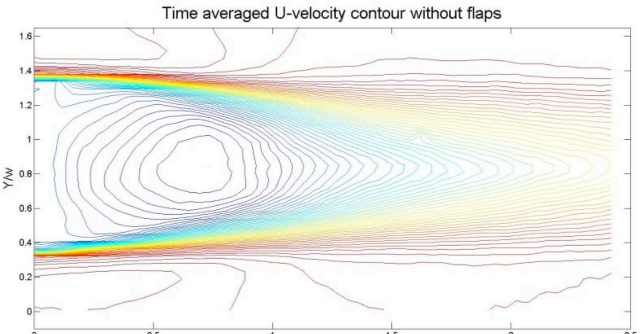

Fig. 8. Time averaged U-velocity contour without flaps.

The experiments were repeated at another velocity (Re = 22000) and are plotted in Fig. 5 for comparison against the results shown in Fig. 4 (Re = 15000). These show that the cases at the two Re follow the same trend, with a strong decrease in wake length that then levels out at higher Strouhal numbers. This is an indication that the expected Reynolds number independence occurs, providing some confidence that one can scale down a model and conditions to simplify the acquisition of data, which can then be rescaled back to real life conditions.

In Fig. 6 – Fig. 13 the rear end of the body is placed just outside the left side of the figures so that the back plate of the trailer is at X/w = 0.

Fig. 6 – Fig. 8 show the velocity profile in the wake behind the trailer. They reveal the significant changes the oscillating flaps introduce. As has been shown in Fig. 3 and Fig. 4 it is also obvious here that both the size of the wake and the reattachment length are largely reduced. Also, the shear layer is shown to be stepwise weakened when introducing flaps and then oscillating them. Further downstream the wake is narrower due to the fact that the flow is kept attached to the flaps and directed inwards before the separation point. By comparing the recirculation zone for the three cases there is a significant difference in intensity, with the oscillating case having the largest velocities inside the wake. Higher flow velocities suggest there is a larger exchange between the flow inside and outside of the wake i.e. higher entrainment. This will have an effect on the pressure inside the wake, which is directly coupled to the base pressure coefficient and hence drag coefficient. This relationship is, however, complex as discussed by Roshko [18] and Balachandar [19], and while the drag is clearly affected the detail of the extent of this is yet to be determined.

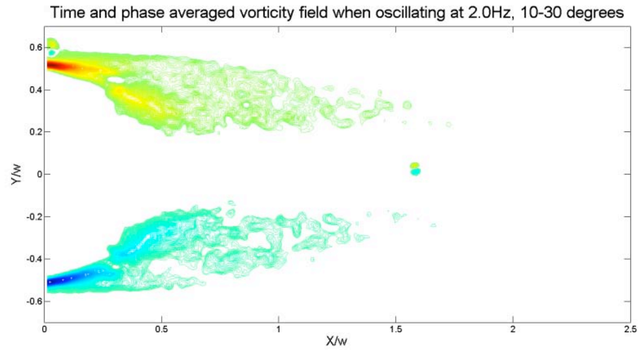

Fig. 9. Time and phase averaged vorticity field when oscillating at 2.0 Hz, 10-30 degrees.

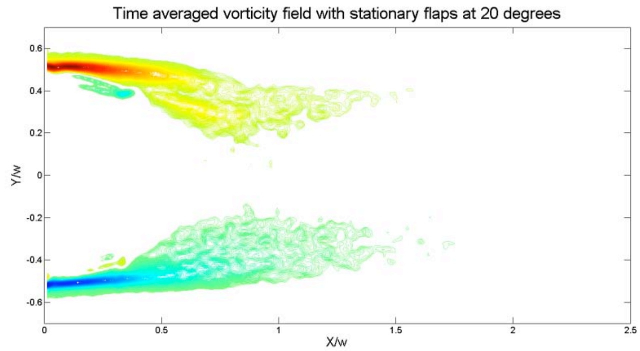

Fig. 10. Time averaged vorticity field with stationary flaps at 20 degrees.

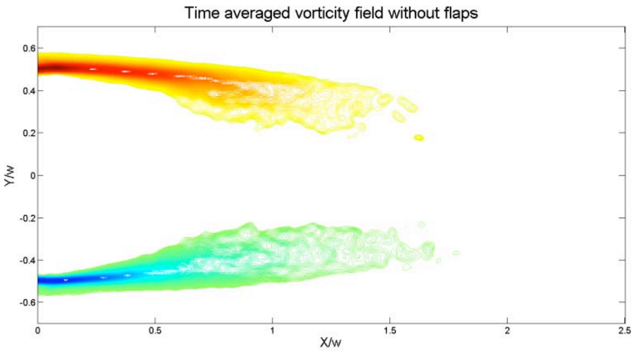

Fig. 11. Time averaged vorticity field without flaps.

Fig. 9 – Fig. 11 replicate the above sequence of figures but present the data in the form of vorticity. These make the arguments stated above even more evident. The strong shear layers appearing in the case without flaps can be seen in Fig. 11. The more inward directed flow appearing in Fig. 9 when the flaps are oscillated can be explained by the vorticity roll up on the flap during the cycle of oscillation, which is more evident here. The presence of the large-scale Kármán vortices affects the development of the shear layers and the entrainment, as previously mentioned.

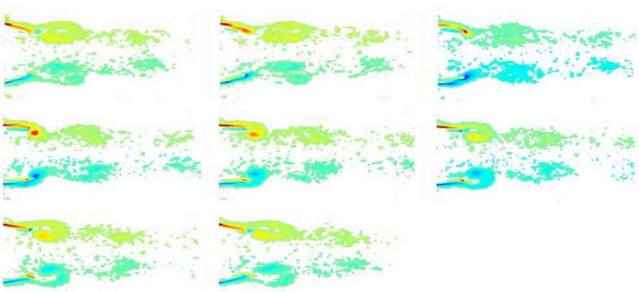

Fig. 12. Vorticity development during one cycle when oscillating at 2.0 Hz, 10-30 degrees, each phase is averaged over 40 instant measurements.

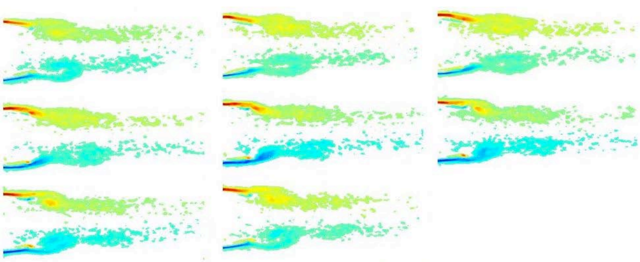

Fig. 13. Vorticity development during one cycle when oscillating at 2.0 Hz, 10-20 degrees, each phase is averaged over 40 instant measurements.

The introduced perturbation from the oscillations of the flaps is so strong that it affects the natural vortex shedding in such a way that they are shed simultaneously on both sides compared to the normal bluff body vortex shedding where they shed one over the other. Accompanying this transition from a sinuous to varicose vortex structure, the frequency of the shedding locks on strongly to the oscillation frequency, as shown in both Fig. 12 and Fig. 13. Here the results of the phase-averaging discussed above are shown. The images are presented in a time sequence from left to right and top to bottom. This clearly shows the wake development with time and the development of the wake vortices in space and time. This also illustrates that the vortex street further downstream of the recirculation area, outside the measured area, will have considerably less transverse fluctuating vorticity field compared with the Kármán vortex street but will instead have one that moves more continuously downstream. The most significant difference between the two set of oscillation parameters studied and presented here, and which can be clearly seen by comparing Fig. 12 and Fig. 13, is the more distinguished shedding of vorticity patches for the larger amplitude in Fig. 12.

CONCLUSIONS

The effects of attaching flaps at the vertical edges of a trailer model and setting them to oscillate have been studied experimentally. By controlling the frequency and amplitude of the oscillation it has been shown that the near wake behind the trailer has been changed significantly in both size and structure. The reattachment length and size of the wake has been shown to be dependent on both the frequency of oscillation and the amplitude, though to a larger extent by the frequency.

When increasing the frequency, both wake size and reattachment length was reduced, although they were starting to level out when Strouhal number rose above 0.55 and beyond, by which time most of the benefit had been realized. Though, this tendency is still to be confirmed by further experiments at higher Strouhal numbers. The most effective of the three amplitudes studied was found to be when the flaps oscillated between 10-30 degrees for all frequencies. There were also large changes shown in the vorticity fields presented, firstly with just using stationary flaps but even further when they were also oscillated. Not only did the shear layer decrease in intensity but the introduced energy into the flow was enough to force the vortices to shed at the oscillation frequency, instead of their natural shedding frequency. This was also the main cause of the reduced reattachment length.

The presented effects of introducing oscillating flaps had their maximum impact when using a frequency of 2.0 Hz (St = 0.88) at the angles 10-30 degrees, though this study is restricted to only a few frequencies and amplitudes. A more extensive investigation is needed before drawing conclusions about these being the most favorable settings. Clearly, at such high Strouhal numbers the possibility of influencing the rolled-up KH vortices becomes an issue. A number of other issues also arise that have not yet been accounted for in this study, such as yaw angle and the forces influencing vehicles travelling either directly or diagonally behind the vehicle in question.

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