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A Study of an Inverted Wing with Endplates in Ground Effect

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Abstract

The aerodynamics of an inverted wing with endplates in ground effect has been investigated using experimental methods. A wind tunnel containing a moving belt was used to reproduce the effect of the ground on the flow field and the measurements were made using Laser Doppler Anemometry (LDA). Flow visualization showed that the implementation of an endplate on a wing yields the formation of two co-rotating vortices originating from the top and the bottom of the endplate. Initially the effect of the size of the endplate and the height of the wing above the ground on the vortices behaviour was studied. Then, the most relevant configuration of the wing was studied using LDA measurements.

Introduction

One of the most common applications for inverted wings close to the ground is in Formula 1 aerodynamics. It has its importance as the wake of the front wing is directly interacting with the front wheels of the car and can spoil the wake behind the wheel. Many studies have been carried out to understand and explain the ground effect on wings, either on up-lift or downforce producing wings. Barber et al [3] presented a review on different experimental and numerical studies and pointed out the importance of the effect of the boundary conditions on the results. It was proved that the most accurate way to experimentally investigate ground effect is to run measurements in a wind tunnel containing a moving belt to simulate the relative velocity of the ground to the wing.

The effect of the closeness of the ground is that both the drag and the downforce increase. Their values evolve as the wing gets closer to the ground such that the lift to drag ratio increases until the distance between the wing to the ground gets around 0.8 wing chord (0.8c) [7]. Endplates are attached to wings to make the flow as two-dimensional on the surfaces as possible, and to avoid the formation of the tip vortex, induced by the pressure difference between the surfaces. Therefore, the presence of endplates increases the downforce acting on the wing. However, the difference of pressure produces two co-rotating vortices to form at the top and bottom sides of the endplate. Flow visualisation experiments suggested that the behaviour of the vortices depends on the size of the endplate used and indicated that the length of the endplate seems to affect the shape of the vortices while the width seems to influence the path of the vortices downstream. Indeed, the use of endplates having a width greater than half of the chord of the wing makes the vortices travel separately while a smaller width makes them interact and merge with each other. As the merging process is interesting to study, a small endplate was used in this investigation.

Further flow visualization was conducted to study the influence of the height of the wing, which is defined by the distance between the lowest point of the wing and the ground. As the wing gets closer to the ground, the vortex coming from the bottom side of the endplate is weakened. The height used for this study was chosen to have the strongest vortices as possible. However, the height has to be small enough in order to have a ground effect predominant; the height used was then 0.5c.

The paper is organized as follows. First, the experimental facilities proceedings are described. Then, the experimental results are presented. A brief discussion follows about the flow visualisation made using smoke and then the LDA measurements. The results will focus on the velocity field and the comparison between two different height of the wing from the ground. Finally, the turbulent character of the wake and the frequency analysis will be presented.

Apparatus and Instrumentation

The wing used during the experiments was the NACA 4412 made in Perspex with a chord length c of 75mm and a span of 130mm. All the experiments were run with a far field velocity of 10.5 m/s so the Reynolds number based on the chord length was around 50,000. The endplate was also made in Perspex and had a rectangular section, with a length of 100mm, a width of 20mm and a thickness of 1mm. The endplate was set perpendicular to the ground, with the wing in a downforce position (the lift being directed toward the ground) at an angle of 10°. The origin of the coordinate system used is attached to the trailing edge of the wing, at the intersection with the endplate. The x component is in the flow direction and the z toward the ground as it is common to do in ground effect studies (figure 1).

The measurements were made in the wind tunnel designed and built at the University of New South Wales [5]. The section of the wind tunnel has a width of 228mm, a height of 485mm (figure 2) and contains a moving belt running at the same speed of the air, reproducing the ground effect. The wing was mounted on a side wall of the wind tunnel, the span being more than 1.5c. In these conditions, the boundary layer on the wall is too small relative to the span to alter the vortices behaviour.

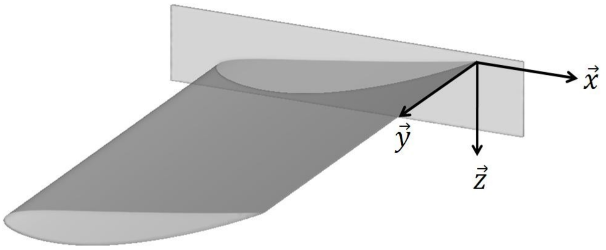


Figure 1. The wing and the endplate with the origin and coordinate system.

The tunnel works by aspirating the air, powered by a Donaldson Torit 10Kw vacuum box. Two honeycomb sheets are positioned at the entrance of the wind tunnel so the potential coherent structures in the flow are broken; the turbulence level was measured and is less than 1% at the entrance of the wind tunnel.

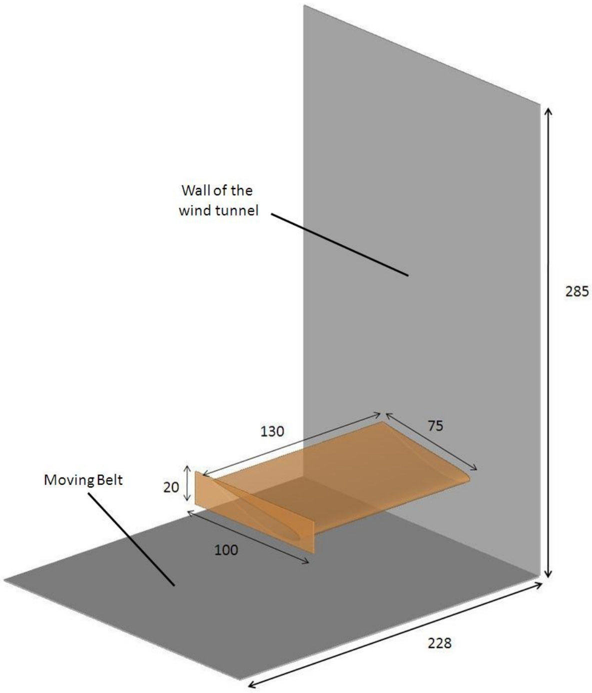


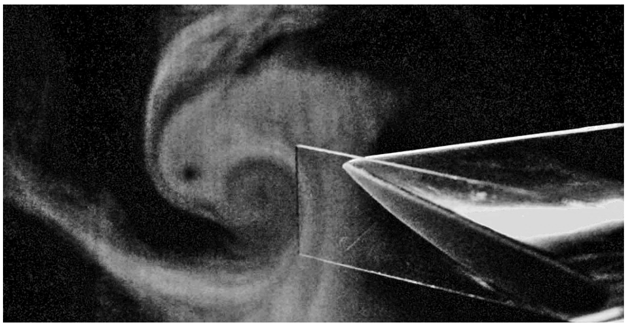
Figure 2. Dimensions in of the wing and the section of the wind tunnel in millimetre.

The LDA system used was a Dantec 5W Argon-ion laser beam which is split in three component pairs, so the three components of the velocity field could be measured. The seeding was made by using atomized vegetable oil stored in a pressurised tank of 2 bar.

Experimental Procedure

Flow Visualisation

Flow visualization was the first step of the study as it is an easy way to determine the position and the evolving of the vortices. By setting a laser sheet perpendicular to the flow direction and by introducing dense smoke at the entrance of the wind tunnel the vortices are visible (Picture 1). A scale is first positioned in the wind tunnel and an image is recorded. A comparison between the scale and a vortex image allows quantitative information about the vortex location and size to be determined. This procedure was used to determine the best configuration to study, i.e., the endplate size (20mm*100mm), the wing angle of attack (10°) and the height from the ground (0.5c).



Picture 1. Interaction of the vortices using an endplate of 20mm visualized with smoke and laser sheet.

Measurements using LDA

The measurements were made on planes perpendicular to the flow direction, from x=4/15c to x=4c, and every 1/15c. The first measurements were made using a coarse grid, with 5mm spacing, and made on planes having a width of 0.8c and a height of 0.6c. Subsequently, further measurements centred on the vortex location were made on the same planes but using a finer grid, with a 2mm spacing. The data acquisition was set such that 2000 samples were acquired of each measurement point. The behaviour of the wake is shown via contours of dimensionless longitudinal velocity in the following figure.

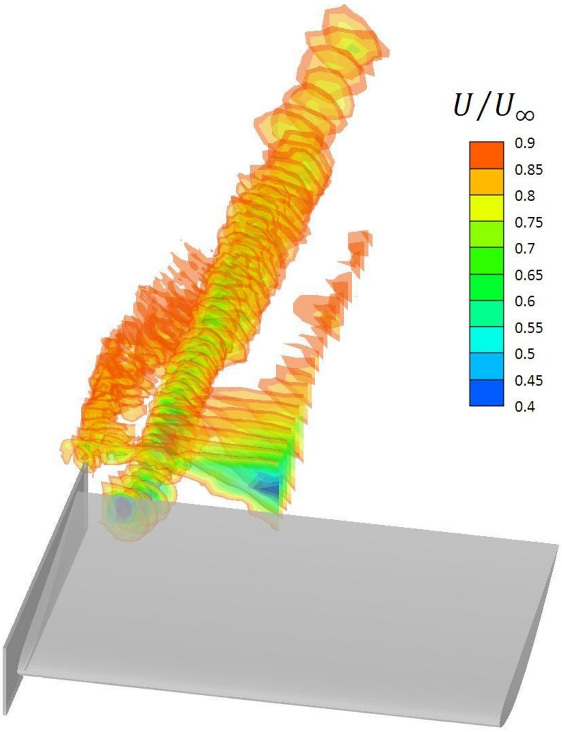


Figure 3. Visualisation of the merging process via the the dimensionless longitudinal velocity.

Experimental Results

The velocity field

Figure 3 shows that the velocity in the vortices is lower that the freestream. This deficiency comes from the fact that the high rate of rotation produces a low pressure at its core where the air is slowed in the longitudinal direction. One can assume then that the lower the velocity is at the core, the stronger is the vortex.

It is interesting to notice that some studies, quoted by Devenport et al [4], investigated tip vortex measurements and showed a core velocity immediately higher the freestream, with this effect reversed a few chords behind the wing so the core velocity was deficient.

The velocity field shows that the lower vortex coming from the endplate is much stronger than the upper one. Its velocity reaches 30% of the freestream at its core directly after the wing while the core velocity of the upper one is around 90% of the freestream.

The next figure is a comparison of the velocity field directly behind the wing between the heights 0.5c and 0.1c. It indicates that the lower vortex is much weaker in the second case. Indeed, the closeness of the ground alters the development of the recirculation. As the lower vortex develops in the case with the greater height, it also perturbs the wake and shorten its width close to the endplate. The streamlines are also plotted, producing a useful means to locate the vortices. Even though the location of the strongest vortex is well located by the longitudinal velocity, this is not always the case for the upper one.

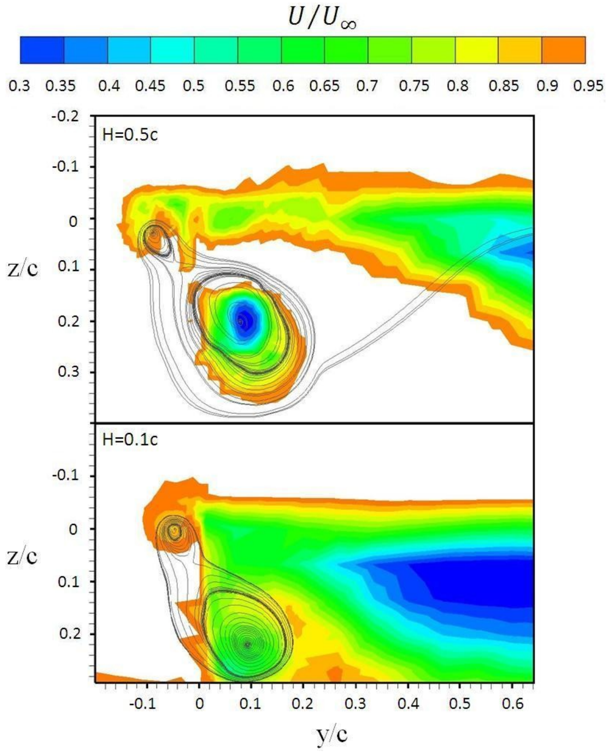


Figure 4. Comparison of the dimensionless longitudinal velocity for two heights on the plane located at x= 4/15.

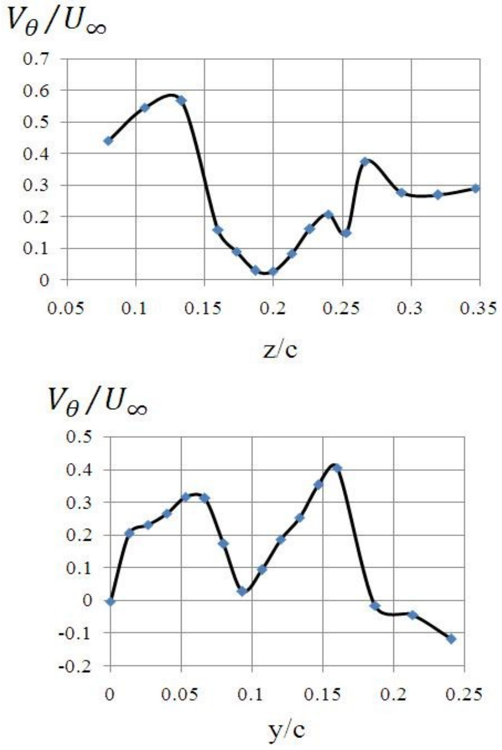


Figure 5. Variation of the dimensionless angular velocity around the lower vortex.

In both cases, the shape of the vortex seems to be stretched in the direction of the other vortex. By calculating the angular velocity and by observing the variation of it around a vortex, the radius of the core vortex can be estimated as it is the distance between the centre of the vortex and the point where the angular velocity is a maximum [2].

Figure 5 indicates the variation of the dimensionless angular velocity in the horizontal and vertical direction of the lower vortex.

Besides confirming the fact that the shape of the vortex is not symmetric, it also suggests that it is not homogeneous as the distribution of the angular velocity is not regular in both directions. The highest angular velocity, which is located close to the other vortex, reaches 60% of the freestream. The average of the diameter of the lower vortex is estimated to be 0.12c while the average diameter of the upper one is 0.05c. At x=4c, the vortex resulting from the merging has a mean radius of 0.5c.

The next figure shows the evolution of the longitudinal velocity measured at the core of the vortices at varying distance behind the wing. The lower vortex velocity significantly increases with the distance while the upper velocity does not seem to vary significantly.

It is difficult to get the velocity at the upper vortex during the merging process because it is difficult to locate its centre. Also, the fluctuating character of the curves comes from the fact that the centre of a vortex is determined from the vector field of velocity, which is not always an accurate method.

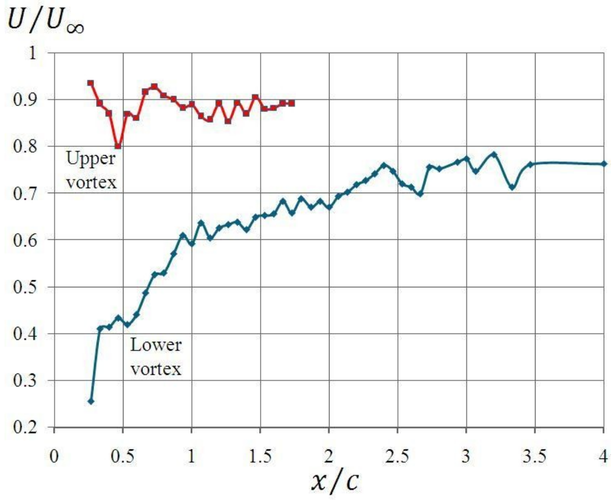


Figure 6. Evolution of the x component velocity at the core of the vortices.

The turbulence measurements

The next figure shows the relative root mean square (RMS) values. The first presents the contour of the relative RMS in the flow direction while the second shows the contour of the relative RMS in the plane direction. Their amplitudes are much higher in the plane direction, reaching 50% at the core of the lower vortex while the longitudinal ones are only at 20% close to the same vortex. This observation suggests that the core of the lower vortex is made by a turbulent flow, induced by the flow field coming beneath the wing and by the sharpness of the bottom and top sides of the endplate.

A part of the RMS values in the radial direction might also come from the vortex wandering phenomena, which is assumed to be a common wind tunnel effect, and studied among others by Devenport et al [4]. Even though the wandering is present, the high RMS values in the radial direction might demonstrate that the energy transfer is going from the core vortices to the freestream.

Even if the core of the upper vortex is not easily detectable with turbulent or velocity contours on the first plane, it becomes clearer a few planes behind the wing. The vortex path and the merging process is then observable by plotting the contours of the turbulent intensity, which is done for several planes in the wake (figure 8). This illustrates that the position of the lower vortex is not affected by the upper one. Instead of spinning around each other as co-rotating vortices of same strength usually do, the upper vortex is simply “swallowed” by the stronger one. The upper vortex is travelling half the circumference of the stronger one before disappearing.

It is impossible to determine the exact distance from the wing of the merging vortices as the shapes are not clear during the process and the interaction occurs along a distance of two chords. The turbulence intensity is very important at the core of the lower vortex for the first planes behind the wing as it reaches 50% while the remaining of the wake is around 30%.

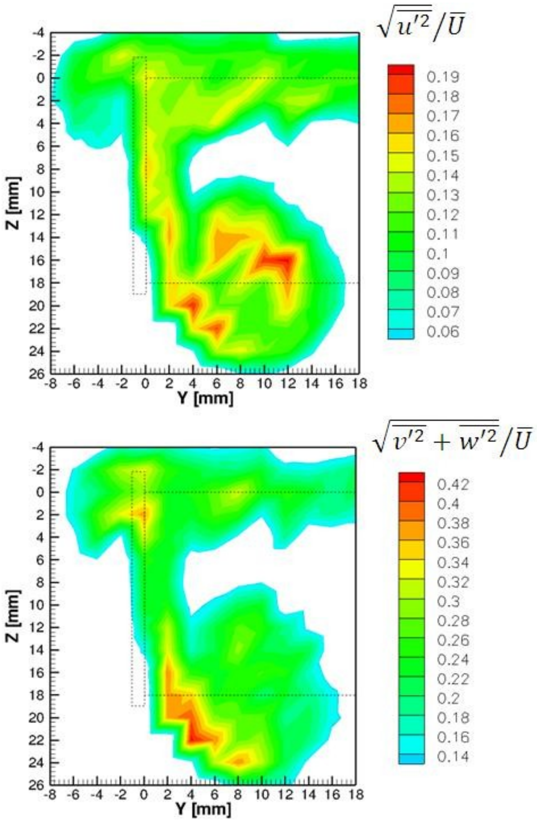


Figure 7. Contours of the longitudinal and radial relative root mean square at the plane x=4/15c.

Going further downstream the turbulence intensity dissipates in the wake but is still around 30% at the core of the vortex for x=2c. It is surprising to notice that the turbulence intensity at the core is the same during more than two chords. The contours spread out from plane x=1.7c and x=2.3 which might suggest the effect of the diffusion of the turbulence among the wake.

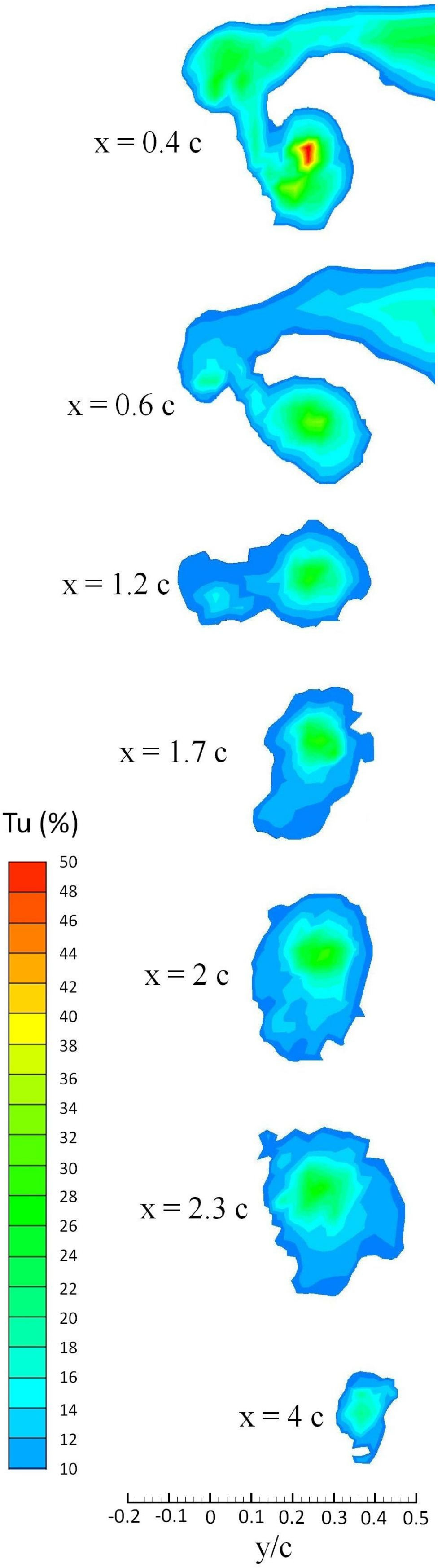


Figure 8. Evolution of the turbulent intensity at several planes behind the wing.

The frequency analysis

Frequency measurements were carried out to study the energy transfer directions. In order to get the highest data rate possible, each laser pair was used separately. The next figure presents the Power Spectrum Density of the signal acquired in the vortex core at 4c, in the flow direction and in the vertical direction. By comparing the slopes, this suggested that the energy transfer mostly occurs in the radial direction as the slope is more pronounced. This supports the suggestion made earlier that the turbulence spreads out from the core of the vortices to the freestream. Note that the second slope of -2.9 on the x component measurement has not any physical significant interpretation as it was caused by the use of the sample and hold technique for data interpolation [1].

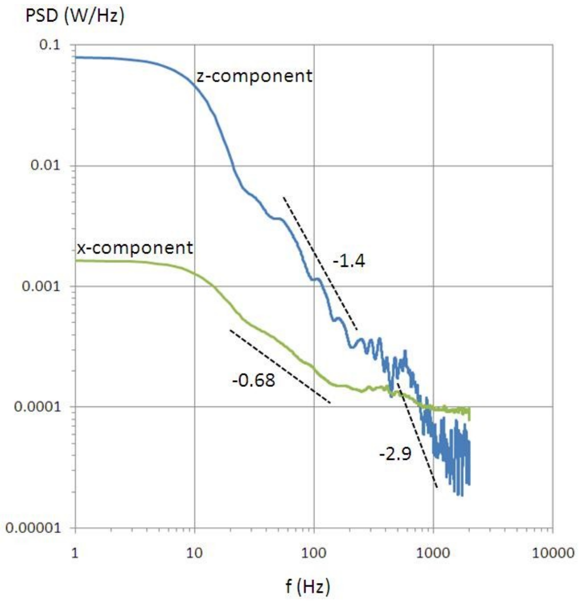


Figure 9. Power spectrum density measured at the core at x= 4c in the longitudinal and vertical directions.

Conclusion

The aerodynamics of an inverted wing with endplate in ground effect has been investigated using Laser Doppler Anemometry measurements. The vortices coming from the top and bottom side of the endplate are quite different as the lower one is much stronger and alters the trajectory of the weaker one. The vortex merging process occurs between one and two chords behind the wing, and was observable from the turbulent intensity evolution. The frequency analysis demonstrates that the likely energy transfer occurs from the core vortices to the freestream. Even though the closeness of the ground does not seem to have any effect on the vortex behaviour, its effect has importance as it increases the downforce on the wing, so the pressure and thus the vortex strength is improved.

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