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Design and construction of an open-circuit wind tunnel with specific measurement equipment for cycling

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Abstract

In order to overcome resistance a cyclist has to deliver a total power output of which 90% is necessary to overcome the aerodynamic drag [1,2]. In order to perform research in this aerodynamic drag a wind tunnel has been built by the Belgium company Flanders' Bike Valley. This wind tunnel is designed using classical design rules and with specific cycling requirements an open-circuit wind tunnel is designed. This wind tunnel, containing a test section in which two cyclist can be positioned in succession, contains three main measurement systems to investigate the aerodynamic drag of a cyclist. A balance is used for the measurements of aerodynamic forces acting on the model, a bikefitting test is included to have a perfect fit between cyclist and bike and finally a PIV system is installed to investigate the flow behaviour.

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Keywords: Wind tunnel, aerodynamics, bikefitting, PIV.

1. Introduction

Rules and regulations of the Union Cycliste International (UCI) bound the design spectrum of sports engineers concerning the global shapes of bicycles and cycling gear. As about 90% of the total power output delivered by the cyclist is needed to overcome the aerodynamic drag the focus lies on the reduction of this resistive force [1,2]. In order to gain profits the aerodynamics and attitudes of cyclists and their gear must be investigated.

Examinations of the aerodynamics (on both macro and microscopic scales) of cycling clothing and bicycles and the attitude of the athletes on their bikes are part of the research goals of Flanders' Bike Valley. This cluster collaboration therefore invested in building a cycling wind tunnel. Next to the wind tunnel tests the company, which is founded by Ridley Race Productions, BioRacer, Lazer Sport, Voxdale and Flanders' Drive, strives for open innovation in the cycling industry. By hosting an incubation centre Flanders' Bike Valley encourages the joint go-to-market strategies of multiple companies to bring new and innovative products on the market.

This paper will discuss the detail design of the Flanders' Bike Valley wind tunnel and focuses especially on the test section with its measurement devices.

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2. Design of the wind tunnel

The design of a wind tunnel starts with determining the top-level requirements and the size of the test section [3]. The test section size and shape determine the overall size and the power input of the wind tunnel.

2.1. Requirements

A wind tunnel can be classified by its type, specialisation, size, operating speed, etcetera, and requirements for the design were given within these classes. From a conceptual wind tunnel study performed in 2012 it became clear that an open-circuit wind tunnel would be optimal for the given requirements. An open-circuit wind tunnel has an inlet and an exit and uses atmospheric air through the wind tunnel. Open-circuit wind tunnels save construction costs and a lot of space as a return circuit is not needed. This type of wind tunnel is usually placed in a sealed building and for that reason it can be seen as a closed-circuit wind tunnel with a less efficient return circuit [4].

The wind tunnel test section must be able to host multiple cyclists in line and the hydraulic diameter of the test section must be at least $2.2m$. This minimum cross-sectional dimension ensures that the blockage factor will not exceed 10%, which is a maximum for liable results [3]. This blockage factor is defined by dividing the frontal area of the test object by the cross-sectional area of the test section.

The maximum speed of the wind tunnel is reached in the test section and was required to be $30m/s$. This velocity is substantially higher than a cyclist reaches in normal conditions (ca. $15m/s$ in time trial mode), but in order to extend the versatility of the wind tunnel the upper speed limit is increased. This versatility creates a possibility for the wind tunnel, which is intended for cycling research, to be used in multidisciplinary research areas. Further it is aimed to have a laminar flow with a turbulence intensity below 0.1% as suggested by [3].

2.2. Wind tunnel configuration

The design of a wind tunnel is an iterative process which starts with dimensioning the test section. The test section was designed to be squared with a width of $2.5m$. A circular test section shows better flow properties, but the construction and mounting of the test object is more straightforward in a straight walled tunnel. The $2.5m$ width leads to a blockage factor of 6.1%, with a frontal area of $0.38m^2$ for an average cyclist in time trial position, in the test section [1]. A larger blockage factor leads to increased uncertainty with the formulation of the blockage correction factor. A lower blockage factor would be favourable; however, a lower blockage would mean a larger test section and therefore a larger wind tunnel which was impossible within the space constraints.

The requirement to include more than one cyclist in the test section resulted in a test section length of $6.5m$. With this test section size the wind tunnel is capable op hosting two cyclists in succession. At the inlet and outlet of the test section $1.25m$ and $1.5m$ respectively of empty space is needed to stabilise the flow and to 'close' the separated region behind the second cyclist [3,4].

The part of the wind tunnel preceding the test section serves the purpose of 'catching', stabilising and accelerating the flow. The flow enters the inlet of the wind tunnel and is captured by a bellmouth intake. This elliptical intake, with an axis ratio of 1:3, increases the intake efficiency and prevents *vena contracta*. This phenomena describes the excessive contraction of the flow in the inlet of a straight duct which increases the energy losses in the flow and can initiate separation [5].

The flow entering the wind tunnel is subjected to turbulence and velocity variations and has to be stabilised in order to produce a laminar flow in the test section. After the inlet the settling chamber is positioned which hosts flow manipulators to produce a steady and uniform flow. Honeycomb structures and screens are used in wind tunnels to manipulate the flow. A combination of both is preferred since the honeycomb structure is most effective in reducing swirl and lateral irregularities in the flow and screens are more effective in reducing the axial turbulence [6,7]. These flow straighteners produce a pressure drop, which causes additional drag, and are therefore placed in the settling chamber. The low velocity in this wind tunnel section causes these disadvantageous effects to be minimised.

Several screens are placed behind the aluminium honeycomb structure in the $4m$ long settling chamber. The number of screens is depending on the level of turbulence that has to be reached in the test section. A screen produces a pressure drop which contributes in the reduction of velocity variations and turbulence and after the screen the static pressure returns to constant without an appreciable loss in total pressure [6]. This pressure drop is depending on the porosity of the screens and therefore on the wire diameter and the mesh size. Multiple screens can be used to reduce the turbulence intensity [6,8,9].

The smaller the wire diameter, the better the flow properties after the screen. However a lower limit arises when the fragility is taken into account. The screen parameters were chosen according to those of comparable facilities such as the open-jet facility at the Delft University of Technology. Five of these stainless steel screens are placed behind the honeycomb structure with a spacing of $450mm$, which must be sufficient to reach an acceptable turbulence level in the test section. In order to keep the number of potential screen suppliers as high as possible, as the weaving width is a limiting factor, the maximum screen width, and therefore the settling chamber width, was determined to be $5.625m$.

After the settling chamber the contraction zone accelerates the flow. The converging shape of this section, where the inlet cross sectional area is larger than the outlet, causes the flow velocity to increase and the power requirement to decrease. Due to the velocity increase a percentage-wise reduction in velocity deviations of the flow is achieved. According to references [3], [4] and [10] the optimal contraction ratio for small, low speed wind tunnels ranges from six to nine. However, the limitations in available space and construction limitations, especially when the flow straighteners are taken into account, define the contraction ratio of larger tunnels. The shape of the convergent duct can cause adverse velocity gradients on the wall which causes the danger of boundary layer separation [6]. The boundary layer of the contraction experiences a destabilising effect due to the concave shape at the inlet and a stabilising effect due to the convex structure near the exit [10]. In order to have no separation the shape of the contraction should be changing gradually which can be acquired by a long contraction zone, causing excessive boundary layer growth in the tunnel. Therefore a rule of thumb is that the length of a nozzle should be around 1.25 times the inlet diameter [8]. A lot of research has been performed to find an optimal contraction shape. Most early work on contraction shapes were done by designing by eye, after which studies on pressure distributions and gradients in the contraction zone showed better flow behaviour and better designs. Recent studies done at the MTL wind-tunnel optimised the pressure gradients along the contraction walls resulting in a polynomial defining the contraction shape [11]. With an inlet width of $5.625m$ and a test section width of $2.5m$ the contraction ratio is 5.09 and the length of the nozzle is taken to be $7m$.

The part of the tunnel succeeding the test section serve the purpose to decelerate and stabilise the flow before the flow encounters the fan section. During this deceleration the flow achieves pressure recovery which reduces the power needed in the wind tunnel. This pressure recovery process must take place at minimum energy loss in order to decrease the required power [3,10]. In order to have minimum energy losses, the angle of divergence is not allowed to be large as this will cause flow separation.

The overall shape of the tunnel is squared as this reduces the construction difficulties. In order to have no interference of the wall flows the corners of the squared cross sections are filled. These triangular fillets are designed to remain above the boundary layer such that interference is minimised.

The fan section contains four axial fans ($\varnothing 1600mm$) placed in a squared configuration to overcome the pressure losses in the tunnel. Each section of the wind tunnel originates a pressure loss and the highest contribution comes from the settling chamber, the test section and the exit. The pressure loss in the settling chamber is caused by the pressure drop used by the flow straighteners to stabilise the flow. In the test section an object is placed in the flow and since the velocity is highest in this section the pressure losses are largest in this section. The exit causes a pressure loss as the airflow from the tunnel is 'dumped' in static air. The wind tunnel will have a total length of $35.5m$ and is visualised in Figure 1a.

The wind tunnel is constructed using a steel-EPS structure. This technique uses a unique plus-shaped steel profile with several connectors. Each profile has constant-pitch connector holes which makes the process of connecting the different profiles and building a structure straightforward. The system is already used for the construction of houses and shows a high dimensional accuracy in the order of $\pm 1mm$. In between the profiles EPS-plates (expanded polystyrene) are glued in such a way that a closed structure of both profiles and EPS plates form the wind tunnel walls. The EPS plates can be milled in any desired shape with high accuracy and after installation the entire structure is plastered to form a coherent, and more important leak-free, structure.

This system will introduce a less complicated, and higher accuracy, system which is cheaper than other building solutions. A set-up of the system can be seen in Figure 1b.

After the design of the entire wind tunnel a specific test section is designed for sports research and especially focussing on cycling. The measurement systems used for this type of research are elaborated on in Section 3.

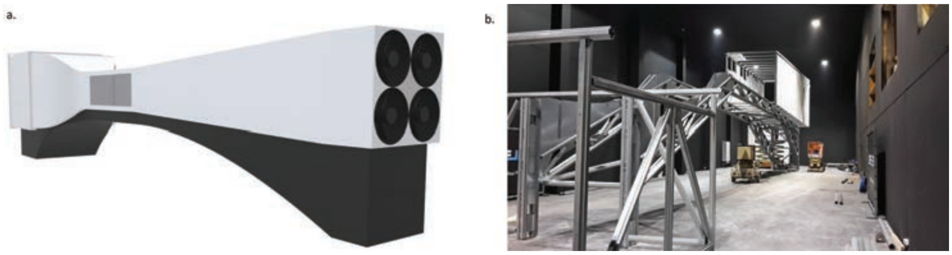

Fig. 1. (a) Visualisation of the wind tunnel; (b) Wind tunnel construction

3. Measurement devices

With an acceptable turbulence level reached in the test section research can be performed. The tests have to be monitored and multiple measurement systems are included to gather data. First of all a balance to measure the weight and drag forces of a pedalling cyclist. Next to the balance a bikefitting system is introduced and a Particle Image Velocimetry (PIV) system is included. These measurement systems will be discussed in this section.

3.1. Balance

The balance included in the test section will be able to determine the forces acting on the test model and consists of a framework connected to five load cells. These load cells measure tension and compression which can be derived to find the aerodynamic drag. This framework contains a bearing on top such that the balance can turn and different angle of attack conditions can be tested. The entire framework can be seen in Figure 2.

The test object is placed on a platform inside the wind tunnel which is elevated 150*mm* in order to introduce a new and fresh boundary layer. This will decrease the level of boundary layer interference. The ground plane has an elliptically shaped leading edge and is left open underneath in order to disturb the flow as little as possible. On top of this platform the bicycle is clamped at the front and rear wheel axles and placed on top of cycle trainers which are calibrated to match the resistance corresponding to the velocities reached during the tests.

The balance is designed to be modular. The entire platform (Figure 2) can be lowered from the test section after which a different test set-up can be included in the test section. This adds to the versatility of the wind tunnel.

3.2. Bikefitting

The second measurement system included in the wind tunnel is a bikefitting set-up. The results from this test can be used to adjust the bike and gear to the athlete in order to reduce injuries and to increase the cyclists performance.

Bikefitting is a very common cycling analysis which is performed in a static manner without forward motion or air resistance. In order to increase the accuracy of these bikefitting tests a more realistic case is presented with a pedalling cyclist encountering wind resistance. The system uses two camera bars on either side of the test section which track infra-red lights on the cyclists key joints. The advantage of two camera bars is that the asymmetry of the athlete on the bike can be seen which is a common cause for injuries. During the effort of the cyclists 200 pictures per second are taken and the behaviour of the cyclist on its bike can be investigated as can be seen in Figure 3.

In the example presented in Figure 3 it can be seen that the cyclists knee moves in a similar fashion throughout the test, which corresponds to a good body attitude. The second (circular) movement contains the rotation of the infra-red

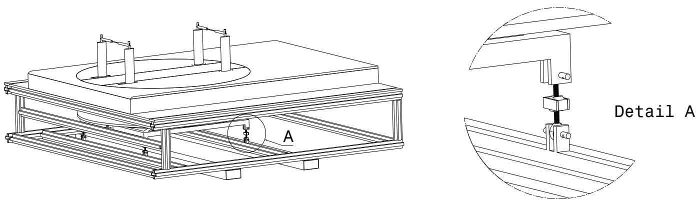

Fig. 2. Balance

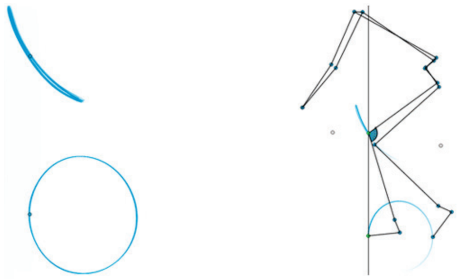

Fig. 3. Bikefitting test showing knee and pedal movement

light connected to the foot just above the pedal. This movement serves as a reference in order to define the accuracy of the test.

3.3. Particle image velocimetry (PIV)

The last measurement system included in the wind tunnel is a PIV system. This system can be used to identify the moving flow behaviour. Oil particles will be sprayed in the air flow after which a laser enlightens these particles. A camera, placed perpendicular to the laser beam, captures two images in a small time span. The smoke generator that inserts the oil particles to the airflow will be placed in front of the inlet such that the required particle density is reached within the test section. The movement of the oil particles, and hence the air flow, can be detected and with the time interval known the velocity of the flow can be calculated. After the test the smoke will be ventilated out of the building.

As the laser is very powerful an athlete cannot be tested with this set-up. In order to solve this problem a 3D scan can be made of a cyclist after which a full-scale dummy can be milled and tested in the wind tunnel. This is a powerful tool for especially tests on helmets and cycling clothing as can be seen in Figure 4.

With the use of this PIV system the influence of small geometrical changes on the aerodynamics of both cycling wear and cycling gear can be investigated as well. An example of this type of research can be the addition of a groove in the seatpost of a bicycle in order to decrease the wake behind the seatpost. The addition of the groove reduces the onset of separation resulting in a smaller wake. A smaller wake is beneficial for especially sprinters as the suction effect on the succeeding competitive cyclist is reduced. The reduction in wake size can be seen in Figure 5.

These results are produced in a wind tunnel in Dresden (Figure 4), were the test was performed to first of all gather data on bicycle gear and wear and secondly to evaluate the PIV system. The system used for these tests will be inserted in the Flanders' Bike Valley wind tunnel. As the camera and the laser cannot be included in the test section as this would disturb the flow care must be taken when glass will be inserted in the test section. The laser light is not

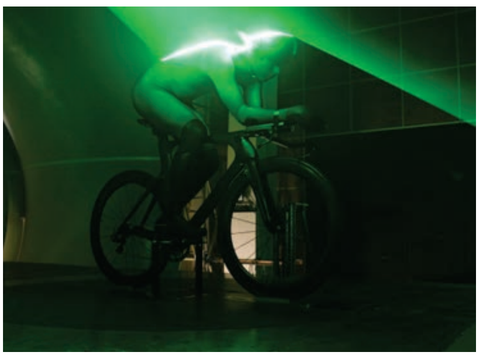

Fig. 4. PIV wind tunnel test in Dresden

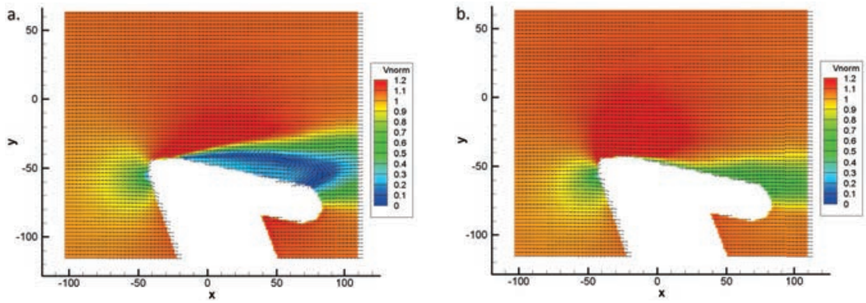

Fig. 5. (a) Seatpost at $50km/hr$; (b) Seatpost with groove at $50km/hr$

allowed to reflect or refract as this will introduce errors in the test results. The PIV test requires the glass to have a transmission of at least 95% at angles up to 45°.

4. Conclusion

The cycling wind tunnel which is designed for the Belgium cluster Flanders' Bike Valley is an advanced construction designed with the use of classic wind tunnel design rules. This resulted in a $35.5m$ long wind tunnel with a squared test section of $6.5m$ length and a width of $2.5m$. This set-up has the advantage that multiple cyclists can be placed in the test section.

The tests that can be performed in the wind tunnel will be measured by three main measurement systems. First of all a balance will be used to measure the drag of the cyclist. Secondly a bikefitting system is included in the test section in order to position the athlete on its bike and to adjust the bike to the cyclist in order to increase performance and prevent injuries. Finally a PIV system is inserted in the design to be able to do test on aerodynamics (on both macro and microscopic scales) and flow behaviour.

The wind tunnel will be operational in 2016.

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