Towards flow field measurements around dynamic cross-country skiers

I. A. Sofia Larsson*[1], Henrik Lycksam[1], Mats Ainegren[2]

[1] Division of Fluid and Experimental Mechanics, Luleå University of Technology, Luleå, Sweden
[2] Sports Tech Research Centre, Department of Engineering, Mathematics, and Science Education, Mid Sweden University, Östersund, Sweden

* sofia.larsson@ltu.se

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ABSTRACT

Flow field measurements around cross-country (XC) skiers are lacking in the literature to date. The aim was therefore to investigate the possibility of using particle tracking velocimetry for visualization and measurement of the flow field around XC skiers roller skiing on a treadmill in a wind tunnel. The airflow was seeded with neutrally buoyant helium-filled soap bubbles as tracer particles, following the flow without affecting it. As illumination, two different approaches were tested: first, a laser in the cameras' line of sight (sagittal plane), then a LED unit directed vertically in a narrow slice, clearly limiting the depth of the measurement volume in the cameras' line of sight. The flow field was studied at various speeds (3-7 m/s) around a single skier as well as around two skiers in line with the streaming airflow. It was found that the experimental approach has the potential to provide detailed insights, both qualitatively and quantitatively, into the flow field dynamics. The main challenges regarding setup, illumination, seeding, and cameras were identified, and possible improvements to streamline the experimental methodology were discussed.

Keywords

cross-country skiing, flow field visualization, particle tracking velocimetry, wind tunnel, aerodynamics

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Introduction

Aerodynamics is the study of air flowing around solid bodies, where the link between velocity and pressure distribution and the resulting loads are of special interest. When it comes to sports, aerodynamics plays a crucial role since the drag force is one of the resistive forces opposing the motion in several different disciplines, cross-country (XC) skiing being one of them (Ainegren et al., 2022).

Research on XC skiing has mainly focused on the resulting forces and the link to physiological and biomechanical parameters, not on the flow field itself (Ainegren et al., 2022; Ainegren & Jonsson, 2018; Bilodeau et al., 1994a, 1994b; Brownlie, 2020; Fruhwirth & Ainegren, 2019; Leirdal et al., 2006; Spring et al., 1988). Understanding the motion of air around XC skiers would provide a deeper knowledge of how the aerodynamic loads on the athletes are formed and potentially help to minimize the negative effects of these forces. However, there is still a lack of published flow field results around XC skiers, possibly due to the challenges connected to direct measurements.

When measuring the flow field, non-intrusive, optical techniques are preferably used as long as there is optical access and the fluid is transparent. The fluid is seeded with particles following the flow without affecting it, and the region of interest (ROI) is illuminated using a light source, either in a thin plane or in a volume. The particles reflect the light and the ROI is imaged by one or several cameras depending on the desired result (2D planar, 2D stereoscopic, or 3D volumetric measurements). The acquired images are processed, and either individual particles are tracked (Particle Tracking Velocimetry, PTV) or particle patterns are compared between subsequent images (Particle Image Velocimetry, PIV) to determine the particle translation. The end result is a vector field where the flow velocity and other related parameters can be determined.

For flow field measurements in the context of sports aerodynamics, two different approaches are generally used. The first approach is a multi-camera system integrated into a compact housing with the laser light supplied coaxially through a fiber optic cable. Everything is mounted on a robotic arm to improve the degrees of freedom to be able to easily scan the flow field around the object. Assuming a stationary flow, several measurement positions can then be merged into a large field of view. It should though be noted that the merged result is time averaged. This approach is mainly used in wind tunnels with static models (Jux et al., 2018; Terra et al., 2020) since it simplifies the measurements.

When the flow field around moving athletes has been studied, mainly another approach referred to as the Ring of Fire (Sciacchitano et al., 2015; Spoelstra et al., 2019), has been applied with separate cameras and illumination. The results are direct large-scale PIV/PTV measurements of the flow field. The Ring of Fire approach relies on the object moving through the measurement region containing stationary (relative to the cameras) seeding particles, so it is not suitable for confined wind tunnel testing. Instead, the measurements have been performed on-site on training tracks for cyclists and ice skaters providing more race-like flow conditions. A disadvantage of this approach is that it is difficult to study a continuous dynamic process because the athlete quickly passes through the measurement region and fully controlling the body position during each passage is impossible.

Nowadays, however, there exist wind tunnels with a moving ground plane, which provides realistic and controllable conditions for testing athletes in motion, in this study specifically XC skiers during dynamic roller skiing. These types of facilities enable continuous visualization and measurement of a dynamic process where the flow field is more realistic compared to the flow field around stationary objects. The aim of this study was to explore the possibilities and challenges associated with visualizing and measuring the flow field, using PTV, around XC skiers roller skiing in a unique climatic wind tunnel with a moving ground (Ainegren et al., 2019). Such measurements will provide a quantitative visualization of the flow field, where flow features can be related to measured aerodynamic loads (Sciacchitano et al., 2015). In this work, the focus is on the time-averaged wake forming behind the skier. In all applications where drag plays a major role, the wake is of special interest. The characteristics of the wake – flow, size, pressure, etc. – affect the total amount of drag generated. The drag acting on an object can be obtained from the mean velocity deficit in the wake (Anderson, 2017).

Methods

Participants

Two male XC skiers competing at a high national level participated in the experiments. The skiers were dressed in tight clothing normally worn during XC skiing, a face mask covering the mouth and nose, protective goggles, roller skis, and regular racing boots and poles. Before the experiments started, the skiers gave their written consent to participate in the study, which was approved by the Swedish Ethical Review Authority (No. 2022-01049-01).

Experimental setup

The experiments were carried out with the skiers roller skiing using the double poling technique on a treadmill in a climatic wind tunnel (Ainegren et al., 2019). The flow field at various speeds (3-7 m/s) around a single skier as well as around two skiers in line with the streaming airflow was studied to investigate the flow field interaction in a drafting situation. The distance between the skiers was approximately 2 m, which is a general length of cross-country skis and hence a typical distance during competition. As visual support for the skiers to keep the distance and their positions on the treadmill, a wide colored tape was used and stuck on the side of the treadmill next to the leading skier.

The airflow was seeded with neutrally buoyant helium-filled soap bubbles (HFSB) as tracer particles (300 μm in diameter), following the flow without affecting it. The seeding system (LaVision GmbH) consisted of four aerodynamic rakes with a total of 80 nozzles over an area (height x width) of 1 x 0.25 m^2. The flow field was initially visualized and recorded in the sagittal plane (using an iPhone 13 Pro 4K resolution at 60 fps), and then processed in Matlab. Continuous LED light fixtures mounted in the ceiling provided illumination. Figure 1 shows images from the visualization.

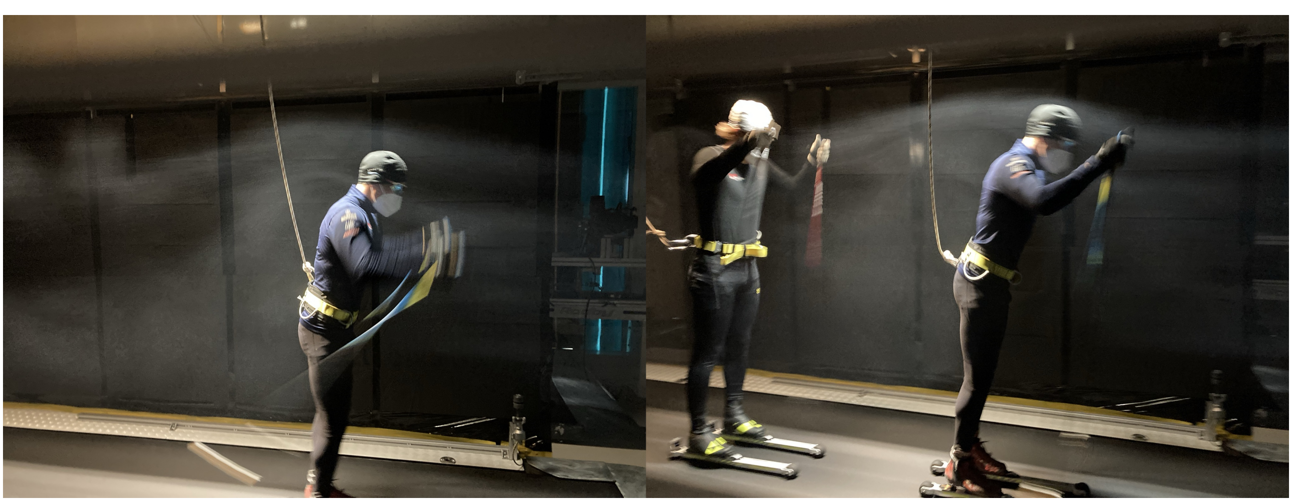

Figure 1 Images from the flow field visualization.

The flow measurements were carried out using PTV, which is a non-intrusive optical experimental technique for measurements of velocity fields, as described in the introduction (Dabiri & Pecora, 2019; Jux et al., 2018; Schanz et al., 2016; Sciacchitano et al., 2015; Spoelstra et al., 2019; Terra et al., 2020). In these types of dynamic applications where the flow field is (at least locally) highly three-dimensional, volume illumination is preferable to avoid decorrelation in the particle images due to large out-of-plane velocities.

The measurement system is a commercially available 3D system from LaVision GmbH, consisting of a Minishaker Aero (four CMOS cameras in an aerodynamic casing, 2.5 MP, 10 bit, 4.8 x 4.8 μm pixel size, 8 mm f/11 lenses), mounted on a robotic arm (UR5e, six degrees of freedom, Universal Robots A/S) which translates and rotates the optical probe. The probe has a working distance of approximately 40 cm.

Regarding illumination, two different approaches were tested. First, a laser (Nd-YAG, 532 nm, 100 Hz, 50 mJ from Litron Lasers Ltd) was used as light source, providing coaxial illumination in the cameras' line of sight (sagittal plane), see Figure 2. The resulting measurement volume was conically shaped with a diameter increasing from 250 to 330 mm over a depth of 80 mm.

As a second approach, to avoid issues with out-of-focus particles close to the cameras (which will be further discussed in the next section), a pulsed LED unit (LED-Flashlight 300 blue, LaVision GmbH) was used as light source directed vertically downwards from the ceiling, from a position superior and posterior to the skiers and in line with their median plane, which clearly limited the depth of the measurement volume in the cameras' line of sight. The LED consisted of 72 individual high-power, high-efficiency LEDs arranged in an array of size 300 x 100 mm.

Images were taken at 343 Hz for 15 seconds (sensor size 1,184 x 748 px), and a total of 5,000 images were captured in each measuring position. The size of the measurement volume was approximately 240 x 160 x 95 mm (width x height x depth). The focus was on the flow in the wake behind the torso of the (leading) skier, where the probe was moved both horizontally and vertically to measure in six different positions. The results were merged into two separate measurement regions (three vertical measurements in two horizontal positions), each spanning 240 x 480 x 95 mm.

Figure 2 Image from the measurements with the Minishaker Aero (blue probe) with coaxial laser illumination (green light) mounted on the robotic arm. The seeding rakes with the nozzles producing the helium-filled soap bubbles can be seen in front of the skiers.

The illumination and the cameras were synchronized using a timing unit, and the system was controlled from a computer using Davis 10 software (LaVision GmbH).

Data processing

A calibration was performed where a mapping function between image and physical volume coordinates was obtained. A volume self-calibration procedure (Wieneke, 2008) was then applied to correct and improve the mapping. This was followed by determining the optical transfer function (OTF) which was necessary for the Lagrangian particle tracking using the Shake-the-Box algorithm (Schanz et al., 2016).

The acquired images were preprocessed using a combination of time and spatial filters to remove background and image noise. The particle intensity was normalized to the first frame and locally smoothed. The Shake-the-Box particle tracking algorithm in Davis 10 returned the particle translations and the flow field information.

The datasets were merged into one volume spanning approximately 240 x 445 x 95 mm, and a spatial median filter was applied before the particle tracks were converted to a Cartesian grid, resulting in a time-averaged velocity field.

Results and discussion

The visualizations directly provided an overview of the transient flow field, see Figure 3. The helium-filled soap bubbles were excellent seeding particles, showing where separation occurs and vortices are generated. From the visualizations, it was also possible to determine suitable areas for quantitative measurements where the skiers did not block the cameras' views with parts of their bodies.

Figure 3 Instantaneous results from visualization of the flow field around a single and leading and drafting skier at 5 m/s. The figures show a complete double poling motion cycle.

To enhance the visualizations, the contrast between seeding particles and the background needs to be improved through better illumination, preferably focused in a thinner light sheet. Further, the frame rate of the camera should be increased to better capture details of the flow, at least doubled or preferably more. Also, the number of seeding nozzles and the position of the seeding rakes can be further optimized for the intended setup. There were some disturbances noted in the flow in front of the leading skier, possibly depending on the flow around the seeding system itself and differences in the velocity of the seeding particles out of the nozzles versus the velocity of the airflow.

Moreover, a disadvantage for the skiers is the need to use both a face mask and goggles to protect the airways and eyes from the helium-filled soap bubbles. However, for the skiers who participated in this study, no adverse effects were noted in the respiratory tract or eyes either acutely or in the days following the completion of the experiments.

The region of interest in these measurements was the flow field in the sagittal plane behind a single skier and between a leading and a drafting skier, as can be seen in the visualization images. Due to the short working distance of the optical probe, the probe needed to be quite close to the skiers. One of the drawbacks of coaxial illumination is that the volume illuminated is not limited in depth. Most of the cameras' line of sight is hence illuminated (see Figure 2), meaning that large, out-of-focus particles can block part of the view of the measurement volume. This happened in these experiments as the seeding particles were deflected by the leading skier and pushed closer to the optical probe, see Figure 4. This had a very detrimental effect on the measurement result.

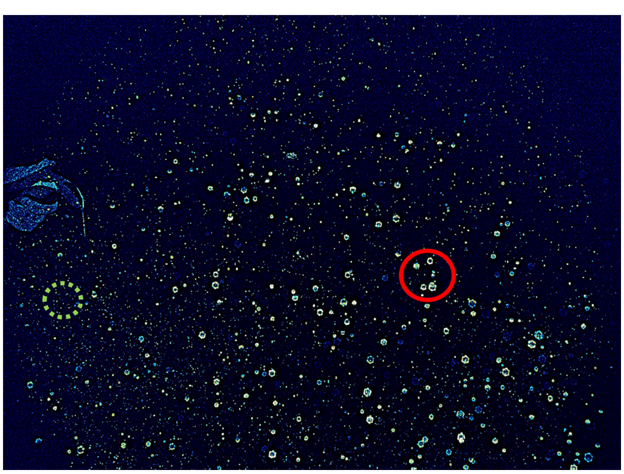

Figure 4 Particle image illustrating the large, out-of-focus particles disturbing the measurements. The green, dashed circle shows a region with good-sized particles in focus while the red, solid circle shows a region with too large, out-of-focus particles.

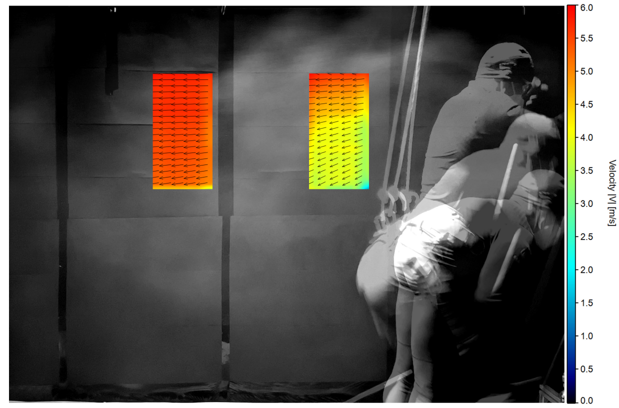

Figure 5 Time-averaged velocity measurement results from a part of the wake behind a single skier at 7 m/s. The results are superimposed on the corresponding visualization of the flow field.

To be able to obtain some quantitative data, another approach was therefore tested using pulsed LED illumination. Since the cameras and the LED were not moving together, the position of the measurement volume in the streamwise direction was not so flexible and also hard to maintain relative to the skiers when they were moving. They accelerate during the push-off phase and decelerate during the rolling phase, which causes them to move 0.1-0.2 m forwards and backwards on the treadmill for each motion cycle. This was a drawback, and the resulting data can therefore only be used to show trends in a limited part of the ROI, see Figure 5. The positions were chosen based on the visualizations – as close to the skiers as possible without anything blocking the view in the measurement region, and the same measurement positions for both a single skier and two skiers in line. Due to the reasons mentioned above, it should be noted that the position of the measurement volumes in relation to the skiers is approximate. As can be seen in Figure 3, the upper body of the skiers also moves up and down during each motion cycle, this affects the extent and position of the wake. Figure 5 therefore highlights that the velocity measurement results are time-averaged over several motion cycles through the visualization image in the background.

Looking closer at the full measurement volume immediately behind the leading skier (Figure 6) it can be

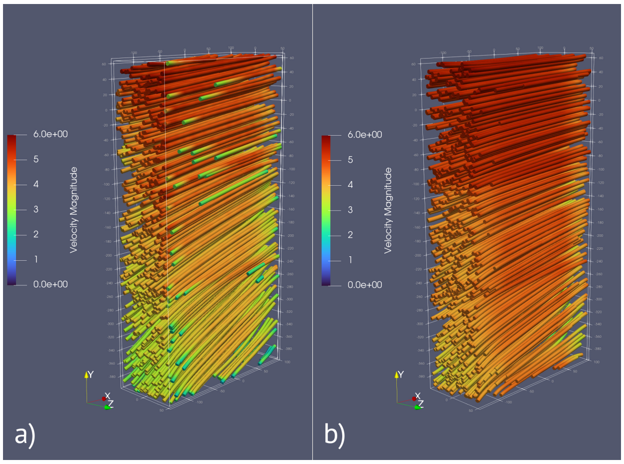

Figure 6 Velocity streamlines in the volume closest behind the leading skier at 7 m/s, a) part of the wake behind the leading skier skiing alone, and b) the same position behind the leading skier with the drafting skier skiing approximately 2 m behind.

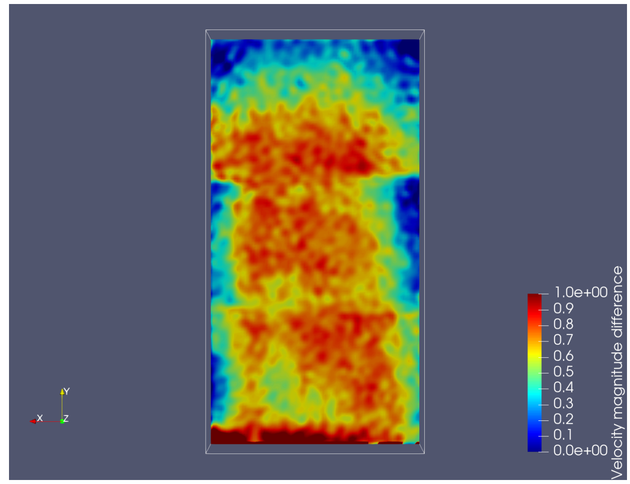

Figure 7 Velocity difference between the two cases shown in Figure 6. The result is shown in a plane in the middle of the measurement volume.

seen that there is a slight mean velocity difference when comparing a single skier (Figure 6a) with two skiers in line (Figure 6b). Figure 7 shows the velocity difference in a plane in the middle of the measurement volume for easier comparison. When the drafting skier is present, the mean velocity in the measured wake region increases. This implies a lower velocity deficit (oncoming freestream velocity minus wake velocity) and a resulting decrease in drag for the leading skier. However, measurements of the entire wake are required to quantitatively confirm this observation.

Measurements around moving objects are connected to several challenges regarding the optical access for both cameras and illumination, as was noted in the experiments. It was clear that coaxial illumination is not suitable in this particular case and hence the illumination needs to be separated from the camera probe. Since the measurements involved people, the safety aspects were of utmost importance. A trade-off needed to be accepted between correctly measuring the ROI and not disturbing the skiers and being in their way while they were moving. The use of the multi-sensor system can therefore be questioned in this type of measurement.

One way to instead enable direct large-scale measurements of the flow field to better investigate instantaneous and time-averaged dynamics is to use large-scale PIV/PTV with fixed, separate cameras and illumination rather than a moving multi-sensor system. The entire field of view is illuminated and imaged directly and can hence be increased as long as there is enough light, but the optical access issues still remain. In contrast to the Ring of Fire approach where the athletes move through the measurement region, the athletes in the wind tunnel are moving but stay in the same position due to the moving ground. This allows for continuous measurements with the possibility to record several motion cycles in succession to follow how the flow field is affected by body position. Careful experimental setup is though required so that the entire region of interest can be clearly viewed by all cameras without the moving object shadowing it. The added complexity of several separate cameras regarding setup, viewing angles, and calibration also needs to be taken into consideration.

The multi-sensor system used in this study offered a quite straightforward way to investigate the challenges of flow field measurements around XC skiers in motion. It was therefore chosen instead of large-scale PIV/PTV as a first step due to the relatively quick and easy setup of the system as the access to the wind tunnel and especially the athletes was very limited in time.

Conclusions and future work

The study showed that the tested experimental approach has the potential to provide detailed insights, both qualitatively and quantitatively, into the flow field dynamics and the connection to drag. The main improvements required to streamline the experimental methodology were identified and discussed.

No measurement or estimation was performed to quantify the aerodynamic interference of the seeding system, robotic arm, LED unit, and optical probe. This needs to be done in future studies to know how much the measurement equipment affects the flow and where it is possible to measure with minimal disturbance.

Finally, setting up and testing large-scale PIV/PTV to directly obtain large field of view flow field measurement results would also be interesting future work to fully utilize the potential of the wind tunnel. These types of measurements can be seen as a quantitative visualization that provides both a visual, detailed overview of the flow field as well as quantitative data on key flow-related parameters. When measuring a larger flow field directly, it will also be possible to average the results over a longer period of time as there is no need to measure in several positions to get the full information. The quality of the mean data and consequently the drag prediction will hence improve. Accurate measurement of the flow velocity around the skier will enable estimation of the drag generated, making it possible to translate the results to skiing practice for performance optimization.

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Competing interests

The authors have declared that no competing interests exist.

Data availability statement

All relevant data are within the paper.