Flow Profiling in a Windshaper for Testing Free-Flying Drones in Adverse Winds

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Drones will soon fill our aerial ecosystem in the field of imaging/cartography, parcel delivery, and passenger transport, and will need to operate around the clock in arbitrary atmospheric conditions, especially in adverse weather conditions during emergency situations. Drones are much smaller than conventional aircraft and are thus more sensitive to weather conditions. In order to test drones in various and controllable atmospheric conditions, a real weather simulator was developed. The wind and weather facility (windshaper) consists of an array of a large number of fans that may be arranged in various patterns on demand. It subjects drones to winds of variable intensity and direction as well as various weather conditions (such as rain, snow, hail, fog etc.) that reflect real world situations. These tests can rate drones according to their capacity in maintaining a proper flight attitude and tackling flight perturbations in an urban, countryside, or high altitude environment. For this work, various time-independent flow morphologies are generated with a windshaper and measurements are performed at a certain distance in order to see whether the output at the measurement station matches the input at the surface plane of the windshaper.

I. Introduction - Why drones need to be tested and certified

Drones are aerial vehicles that fly without an onboard pilot. In the past, the terminology *drone* was restricted to military platforms. The word *drone* is today accepted worldwide to refer to both military and civilian systems. If they are unmanned, they are classified officially by the FAA (Federal Aviation Administration) and the ICAO (International Civil Aviation Organization) as Unmanned Aircraft Systems or UAS (which also include associated ground systems), although they are also commonly called Unmanned Aerial Vehicles (UAV). If they carry a handful of passengers, drones are known as Urban Air Mobility (UAM) aircrafts or drone-taxis (although no official label yet exists since these vehicles are still experimental). UAVs are used nowadays for multiple applications, from recreational to industrial and commercial activities such as mapping/cartography/inspection and delivery. In turn, UAMs are expected to thrive in the coming decade through the efforts of traditional aircraft or helicopter manufacturers as well as a number of burgeoning startups.

Drones can be remotely piloted (as in traditional recreational radio-controlled flyers), but the trend is towards fully *autonomous* systems, whether for unmanned or manned drones. However, such automation entails a number of risks and challenges that need to be mitigated.

Similarly to the aircraft industry, the performance of drones needs to be assessed in order to minimize the occurrence of accidents. Nowadays, it is natural for most drone manufacturers to run operational demonstrators or obtain waivers for specific operations but in the near future this industry will need to rely on performance and safety standards. Such standards will facilitate the development of drones and reduce the time to market. Various international regulatory agencies are in the process of setting up regulations for the safe operation of drones. Drones will have to pass official testing procedure (as it is the case today for traditional transportation systems), and will be rated according to their ability to tackle realistic scenarios (Figure 1), and in particular, adverse weather conditions (shear flows, gusts, rain, snow, hail etc.).

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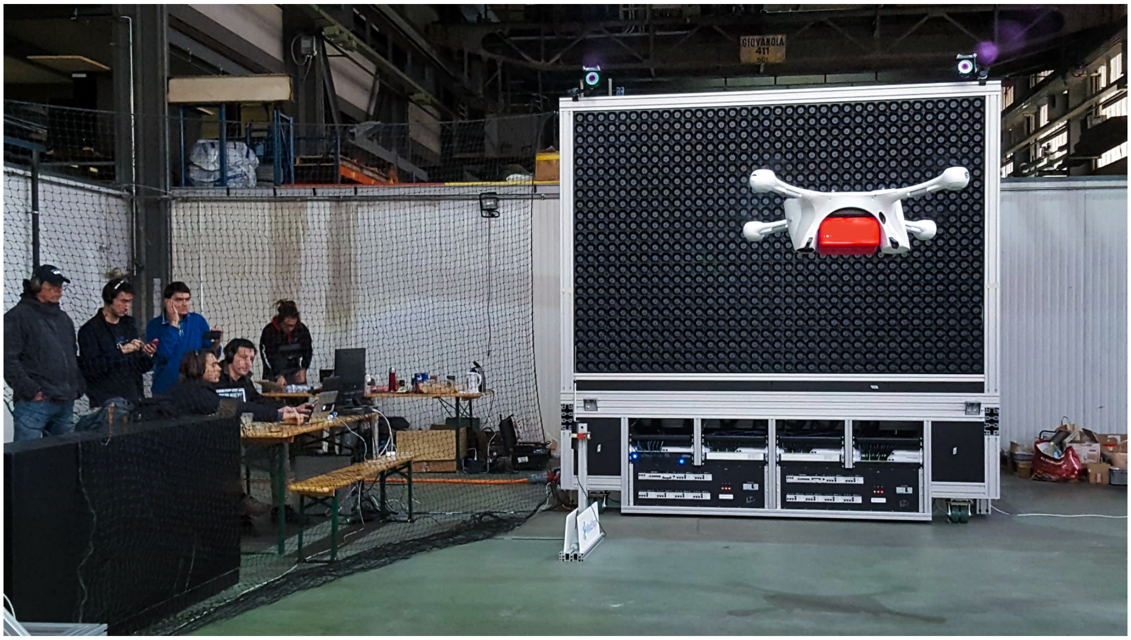


Fig. 1 In November 2019, WindShape tested Matternet drone in various wind conditions within a windshaper.

Currently, there are no solutions for testing drones and single-passenger aircraft in various wind/weather configurations. Due to the lack of testing solutions, **manufacturers have no choice other than testing their flying vehicles in the outdoors**. However, this testing methodology suffers from many drawbacks, including poor accuracy, lack of reproducibility, dependence on day-by-day weather forecast, unknown and non-controllable flow conditions, short test times, large distance between drone and tester. Under such conditions it is difficult to assess and evaluate drone aerodynamics and provide robust measures of their airworthiness.

II. Traditional test facilities

Over the last century, aircrafts have been tested in wind tunnels, pioneered by Eiffel in 1908 [1] and Prandtl in 1909 [2]. These test facilities were intended for aircrafts (Figure 2), which either fly in relatively quiet atmospheric conditions (for example at 30'000 ft flight levels) or are so large and heavy that they are largely unaffected by turbulence scales that are small relatively to the size of the craft.

(a) **(b)**

Fig. 2 The aerodynamic development of ***senseFly eBeeX*** **was performed in a traditional wind facility setup (a) at the ETH Zürich wind tunnel, and (b) in a WindShape facility used as a traditional wind facility, with uniform, low turbulence flow (with screens and honeycombs) and the drone tightly attached to a robotic arm.**

Wind Tunnel	Fan Size	Fan Array
WindShaper1 (Caltech, US) [21]	**8 cm**	**36 x 36**
Oklahoma State University (US) [20]	8 cm	10 x 11
Caltech (US) [18, 19]	12 cm	10 x 10
Louisiana State University (US) [22]	12 cm	5 x 3
University of Fukuoka (Japan) [23]	12.2 cm	5 x 10 (x 2)
Tianjin University (China) [24, 25]	14 cm	6 x (2 x 4)
University of Tokyo (Japan) [26]	18 cm	1 x 6
Jiao Tong University (Shanghai, China) [27]	22 cm	8 x 10
University of Florida [28, 29]	23 cm	25 x 7 + 24 x 6
University of Miyazaki (Japan) [16]	27 cm	9 x 11
Tongji University (Shanghai, China) [30]	27 cm	10 x 12
University of Florida [31]	30 cm	3 x 7
WindEEE (Western University, Canada)	0.8 m	15 x 4
IBHS (South Carolina, US) ([32]	1.68 m	15 x 7
Florida International University Wall of Wind (WoW)	1.8 m	6 x 2

Table 1 Multiple-fan wind facilities around the world

However, such wind tunnels are inadequate for the study of low-altitude phenomena or technologies, such as wind turbines, atmospheric boundary layer (ABL) flows, or drones. Laminar, low turbulence, steady, and flat-profile winds are not representative of atmospheric conditions near the ground.

In such tunnels, spatial and temporal wind gradients can only be produced with added perturbations, either passive (grids, roughness elements) or active (vibrating 2D blades, active grids).

Passive elements These flow obstructions offer little control, only reproduce time-averaged statistics of atmospheric turbulence, or generate overly simplified canonical flows, such as shear layers [3]. In addition, modification of the flow morphology requires a physical interchange of the hardware (grids or screens).

Louvers Louvers are blades that can be made to oscillate at arbitrary frequencies. They can only produce 2D perturbations in a flowfield [3, 4].

Active grids In recent years, active grids have been proposed as alternative solutions to passive grid elements and louvers. First introduced by Makita *et al.* 1991, they consist of two planes of horizontal and vertical rods, with a large number of paddles along each rod. Each rod is activated independently of the others. Such systems have been extensively used for producing homogeneous shear turbulence and turbulent boundary layers with adjustable properties [6, 7]. Overall, active grid systems are pressure-drop systems, thus lowering the effective flow energy in the wind facility. Aside from one example of independently activated blades [8], which requires some complex engineering, all active grid setups are based on 2D oscillated rods.

Multiple jets In 1975, Teunissen [9] used 64 independently activated jets placed in a 8 x 8 array for simulating planetary boundary layers. Because of the required pneumatic connections, such a facility cannot be scaled up.

Small number of fans In Japan, the University of Miyazaki introduced the concept of multi-fan wind tunnels for simulating atmospheric boundary layers [10–12]. The wind tunnel consisted of an array of 6 x 11 fans. Later, the wind tunnel was enlarged to accomodate an array of 99 fans in a 9 x 11 configuration [13–17]. The fans can be activated independently and over the years the University of Miyazaki has been able to successfully reproduce several of the characteristics proper to atmospheric boundary layers. The University of Miyazaki wind tunnel is permanent and cannot be modified, and shows the challenge of stacking multiple fans with its associated electrical wiring.

Other multi-fan facilities exist worldwide (Table 1). They have been used to generate gusts and shears around pliable structures [18, 19] or micro-air vehicles (MAVs) [20], but just like the one at the University of Miyazaki, the number of fans is limited, and the architecture is neither scalable (they cannot be made bigger) nor modular (they cannot be modified into shapes other than flat walls).

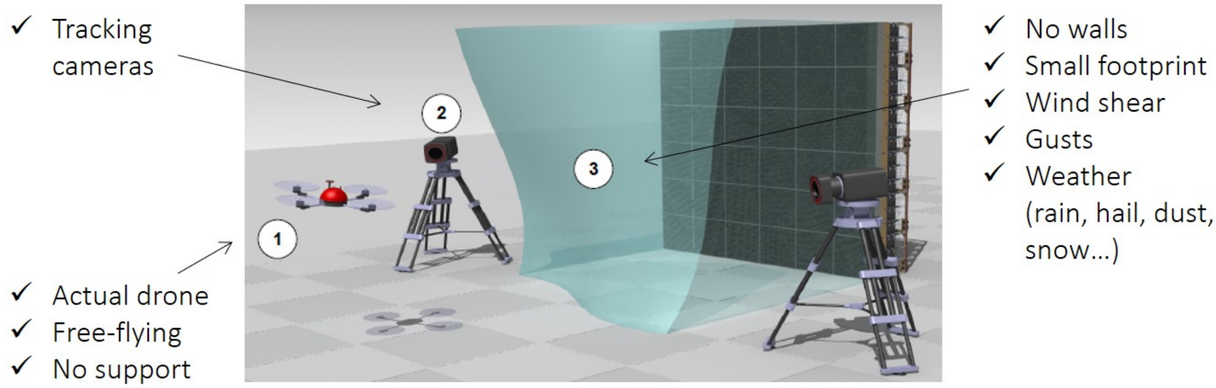


Fig. 3 Wind facility for drone-testing based on multiple-fan technology [33].

III. Background - WindShape technology

A. General description

In order to resolve the issues associated with traditional wind tunnels or outdoor testing protocols, we have developed a real wind and weather simulator [21, 33] for testing flying vehicles in various and controllable atmospheric conditions, including arbitrary wind speed, temperature and direction (even vertical flow for simulating landing/descent configurations), as well as turbulence, hail, rain, snow, and sandstorms. The novel wind facility allows free-flight maneuvering, is completely modular, can be assembled in any desired geometry, and can be made as large as desired while maintaining a small footprint. It is capable of generating gusts (temporally varying winds) and arbitrary wind profiles (shear flows) in any direction. Foremost, the flyer is always at hands-reach from the tester while performing actual flight maneuvers. A motion tracking system (motion capture cameras or mocap) is integrated into the facility in order to measure the drone position and attitude (Figure 3).

The product has been designed and is being commercialized by a Swiss company, WindShape*. The first such facility was purchased by the Aeronautics Department at the California Institute of Technology (Caltech) and inaugurated on October 24, 2017, within its new Center for Autonomous Systems and Technologies (CAST†).

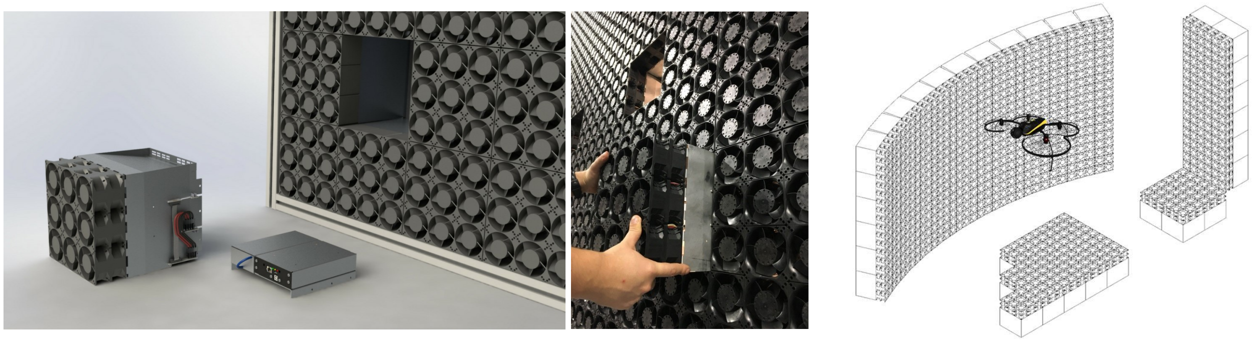
B. Multiple-fan technology

The wind facility is based on a multiple-fan technology, which is not novel in itself. One hundred years ago, the single-fan technology used by Eiffel and Prandtl was not novel either (the Wright brothers and others had experimented with similar devices), but the tunnels they designed were a unique and innovative tool for the aircraft industry. Similarly, WindShape technology is distinctive as it addresses the needs of the drone industry. In particular, the patented modular fan system [33] enables the stacking of an unlimited number of fans (1'296 for the Caltech facility) for high resolution and fast response, as well as arbitrary wind-generating geometries that can be modified at will and over time.

C. Wind pixels

The technology consists of an array of a large number of fans (approximately 150 fans per square meter) stacked in arbitrary fashion. Each single fan can be controlled independently and can, thus, be assimilated to a wind pixel (wpx). WindShape wind walls are composed of a great number of wind pixels (12.5 wpx/m in the Caltech configuration). This feature allows fine control over the generated wind properties, which in traditional tunnels requires extra flow management devices (proper nozzle geometry, flow control devices, vanes etc.). In addition, the low inertia of small-size fans enables fast changes in wind speed. Gusts of wind and shear flows can be faithfully reproduced. Laminar wind conditions, with a turbulence intensity below 1 %, can be achieved by adding screens and honeycombs in front of the fans, while preserving the independent character of every single wind pixel. Alternatively, traditional wind testing can be performed by placing the model on the aspiration side and by integrating appropriate tunnel walls.

*`http://www.windshape.ch`
†`http://cast.caltech.edu`



(a) (b) (c)

Fig. 4 (a) The basis of WindShape technology is what we call a wind module – a wind generation unit composed of nine small fans with integrated power, which acts like a building brick or Lego^{TM} block. (b) These modules can be rapidly assembled into an array to shape surfaces of fans. (c) Wind modules can be stacked into arbitrary shapes and sizes, thus enabling the testing of drones of various dimensions, from small UAVs up to drone-taxis, in arbitrary wind configurations (cruise flight, descent, cross-winds etc.).

D. Wind modules

The basis of the product is what we call a wind module – a wind generation unit composed of nine small fans (Figure 4a), acting like a building brick or Lego^{TM} block. These modules are designed to be assembled manually into an array to shape surfaces of fans (Figure 4b). These modules can be arranged onto surfaces of any shapes (Figure 4c). One current version of the module has a square section of 0.058 m^2, can generate winds up to 16 m/s, and requires about 1.1 kW of electrical power at maximum output.

The facility being highly modular, thus, lends itself to an unlimited variety of wind configurations, spatially or temporally (Figure 4b): a wind wall can be enlarged simply by adding more modules to the wall; by moving the modules around, one can change the aspect of the wall (rectangular, square, etc.); the wall orientation can be easily modified: for instance, one can recreate the apparent wind of the descent (landing) phase of a multirotor by choosing to place the wind modules in a horizontal plane.

IV. Experiments

A. Methodology

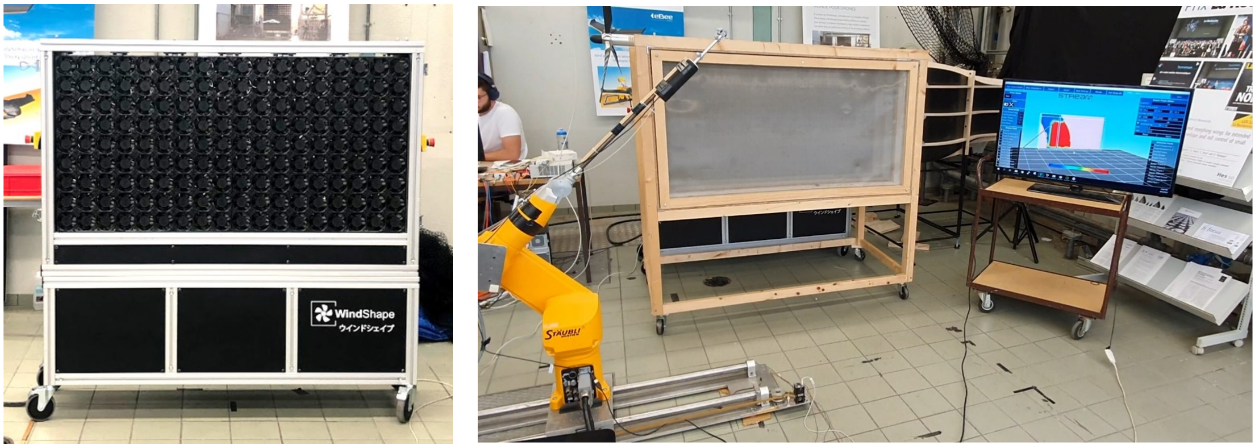
Traditional wind tunnels have test sections that can come in two configurations: open flow (or open jet) and closed (or ducted) flow. Open configurations are convenient for avoiding blockage effects and facilitating hardware installation, but are prone to shear layer perturbations at the edges of the flow jet. Closed or ducted test sections remove the potential disturbances of shear layers, but introduce spurious blockage effects and dramatically complicates installation. Moreover, one of the motivations for open flow configurations is the ability to fly drones freely without any risk of wall collisions (Figure 1). Thus, it is of interest to be able to use windshapers in open configurations and see how they fare with their ducted counterparts.

1. Windshaper

A windshaper with 3x6 modules (9x18 fans) is used (Figure 5a). The size of the flow generation plane is 1.50 m x 0.75 m. The windshaper is used in conjunction with a flow management device, which consists of a honeycomb used as a flow straightener and four rows of screens for turbulence management (Figure 5b). The depth of the flow management device is 0.95 m, and allows maximum flow speeds around 11 m/s and turbulence levels below 1 %.

Fans are controlled via a computer-controlled interface. They can be individually controlled manually (Figure 6a) or through a Python script (Figure 6b). The windshaper surface can also be represented as a Y-Z plane (Y is the coordinate along the windshaper breadth, Z along the height). The fan rotational speed can then be programmed with an arbitrary mathematical function of the coordinates Y and Z. A temporal coordinate can also be introduced for time-varying flows.

Rotational speeds are given as percentage of maximum Pulse Width Modulation (PWM). It is to be noted that



(a) (b)

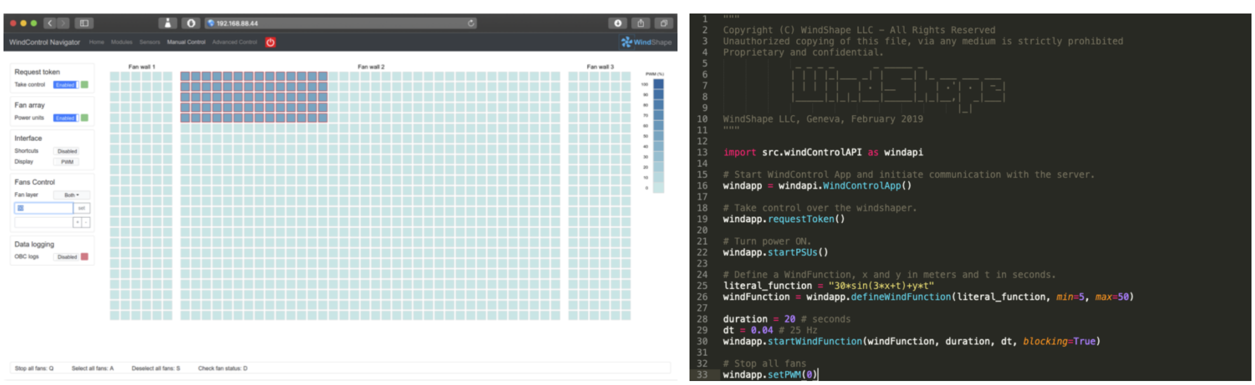
Fig. 5 (a) Windshaper with 18 x 9 fans; (b) Windshaper with flow management screens and multihole probe system on robotic arm, tracked by motion capture cameras, with ProCap software (from Streamwise GmbH) for flow measurements.

windshaper fans actually come as a counter-rotating pair, with an upstream fan and a downstream fan, whose rotational speeds can be programmed separately.

2. Instrumentation

For flow measurement, a ProCap system (`https://www.streamwise.ch/procap/`) was used. ProCap uses a multihole (5-hole) probe, which has the particularity of being tracked by a Motion Capture camera system (OptiTrack camera system made by NaturalPoint). A software (Motive) analyzes the captured images from each camera, which can detect the optical trackers installed on the probe. With these trackers, the spatial position of the multihole probe is recorded in real time (Figure 5b). The purpose of ProCap is to coordinate in real time the measured values of the multihole probe with the probe position (linear and angular). The probe is mounted on a 6-axis robotic arm, which is itself on a Y-traverse to allow the probe to scan the full flow section. The multihole probe can measure all three velocity components, but only the time-averaged component (X) perpendicular to the windshaper plane is shown in the results.

ProCap is a volume-measuring technique, and flow measurements are taken within a voxel. Voxels were chosen between 1.00 cm and 1.50 cm on the side, depending on the needed resolution.



(a) (b)

Fig. 6 A windshaper can be controlled (a) manually by selecting individual fans and their respective rotational speeds, or (b) with a script that inputs fan rotational speed as a mathematical function of the windshaper plane coordinates (and the time coordinate for temporally varying flows).

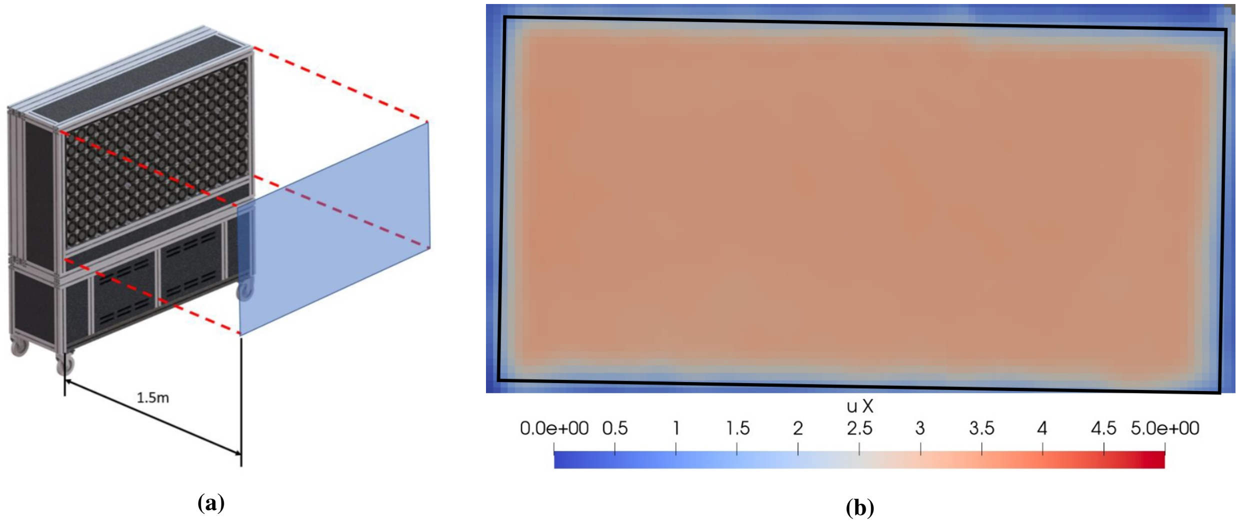


Fig. 7 (a) Measurement plane parallel to and at 1.50 m from the windshaper surface (the flow management device has been omitted from the picture for clarity, but is present during the measurements); (b) Magnitude of flow velocity component perpendicular to the windshaper plane (velocity scale in m/s), with the black bounding box representing the windshaper actual exit flow area.

B. Results

1. Data collection

Flow profile measurements were performed at a distance of 1.50 m from the windshaper surface (Figure 7a). Note that the flow management device was present in all experiments. As the flow management device is 0.95 m deep, a measurement plane located 1.50 m from the windshaper plane signifies that flow measurements are taken 0.55 m from the exit plane of the flow management device.

2. Uniform flow

Figure 7b shows the result for a uniform flow of about 5 m/s. A closer look reveals the voxelated nature of the ProCap technique. Also, as the windshaper is a mobile platform, the flow direction is dependent upon the windshaper orientation and the laboratory floor unevenness. No particular care was taken to align the windshaper with the robotic arm. This slight misalignment shows up in the data in Figure 7b, which is slightly slanted. Motion Capture cameras can be easily used to locate both the windshaper and the robotic arm (which could also be used as a sting for holding a wind tunnel model), so that both systems can be perfectly aligned with each other.

3. Tweaking flow uniformity

It should be stressed that, since the windshaper is a pixelated wind facility, *each wind pixel can be tweaked so that flow uniformity can be improved*. This tweaking was applied in this case in order to ensure a desired level of flow uniformity (only a couple of iterations were performed for the present case).

For traditional wind tunnel users, this is a disruptive improvement over laborious procedures for ensuring flow uniformity. In the past, tunnels had to be carefully designed to make sure that flow was uniform in the test section. Yet, additional efforts were in general required to achieve a required tunnel flow quality after it was built. In particular, actual hardware modifications, such as patches added to flow management screens, were needed. After all was said and done, these "improvements" were not to be touched for decades of tunnel usage.

4. Shear flows

Two examples are given, for a simple shear flow (Figure 8a) and for a double-hump flow (Figure 8b). Again, no particular care was taken to ensure flow alignment with the robotic arm.

Contrary to the uniform flow case, gradient flows were not tweaked in order to ensure a perfectly linear gradient

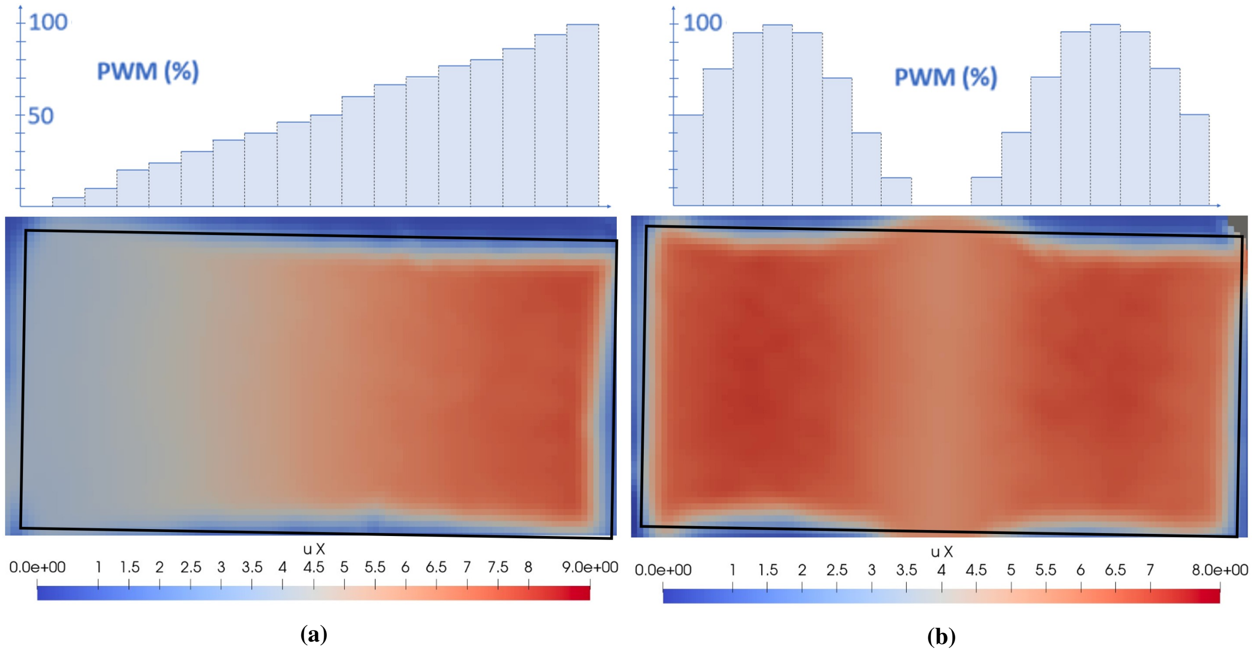


Fig. 8 Fan speed at the windshaper plane (in % PWM) and resulting magnitude of flow velocity component perpendicular to and at $1.5\,m$ from the windshaper plane (velocity scale in m/s): (a) simple shear flow, and (b) double hump, with the black bounding box representing the windshaper actual exit flow area.

(but could easily be done if such need arises). Nonetheless, with a linear distribution of fan rotational speeds, flow gradient linearity downstream of the flow management device was remarkably well preserved (Figure 8a), although speed maxima were slightly reduced and the gradient slope was a bit lower. Without a flow management device, gradient steepness is well maintained, although at the expense of a higher turbulence level.

The double-hump flow configuration was used to demonstrate that complex gradients can be preserved downstream of flow management devices. Here too velocity maxima were lowered (from about 11 m/s down to 8 m/s) as flow gradients were smoothed out.

Unexpected flow features (that were not investigated) seem to occur at the edges of the open jet. It is likely that entrainment of the surrounding air is modulated by the flow speed at the boundary of the jet.

The evolution of linear gradient flows was also investigated along the main flow direction (Figure 9). The straightness of the jet and the linear gradient is again well preserved downstream of the windshaper. The ability of windshapers to maintain straightness (and avoid jet spreading) is a phenomenon that is currently being investigated.

Another interesting feature of linear gradient flows (coupled with flow management devices) is that the flow tends to veer towards the low speed side, as seen from above (Figure 9b). Without flow management, this phenomenon disappears (jet is normal to the windshaper exit plane).

Linear gradient fields are an enabling environment for studying cornering flows in racing car aerodynamics (relative wind is faster farther away from the rotation center because of the vehicle rotation). Pixelated-wind facilities are being sought by Formula One teams, as they allow for the first time an experimental investigation and optimization of cornering aerodynamics.

V. Summary

WindShape facilities enable an infinite variety of wind profiles. In addition, flow quality (uniformity) can be finely adjusted thanks to the pixelated nature of these facilities.

In the future, temporal flow variations will be captured with fast-response multihole probes as well as hot wires, in order to characterize gust regimes.

Pixelated wind facilities are thus an enabling tool for controlling flows according to needs. Currently, rakes and grids of sensors (hot wires or multi-hole probes), as well as optical mapping techniques, are being used to provide

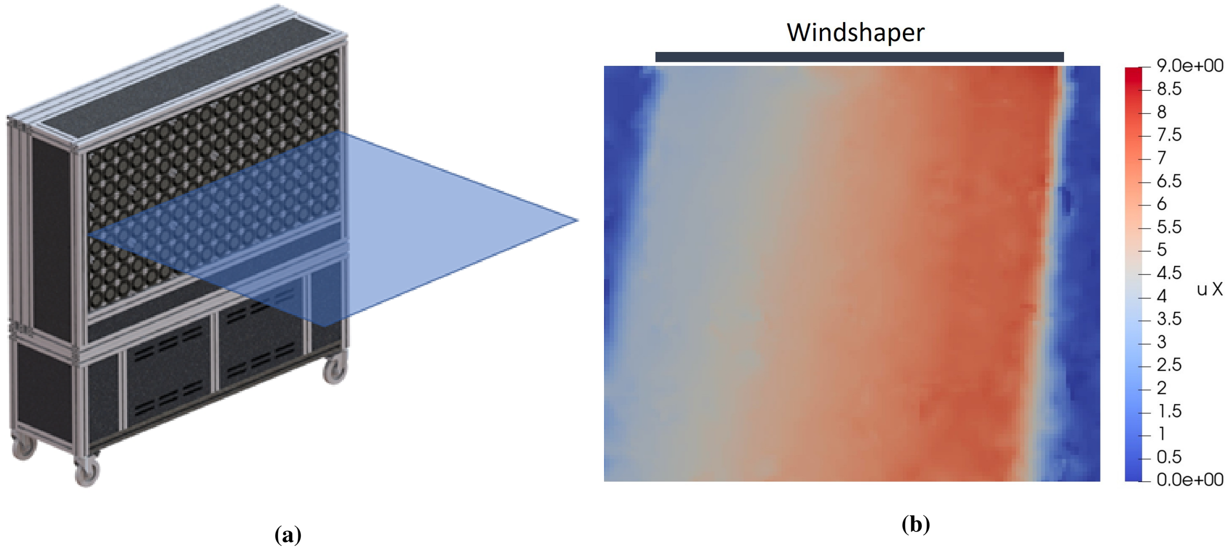


Fig. 9 Simple shear flow: (a) Measurement plane with respect to the windshaper surface (for clarity the flow management device does not appear in the sketch); (b) Magnitude of flow velocity component perpendicular to the windshaper plane (velocity scale in m/s).

feedback signals to windshapers for tuning each pixel and generating desired flow profiles.

An ongoing project is using machine-learning in order to "teach" these windshapers to produce flows on demand, and in particular reproduce natural flows (winds, gusts), especially in urban environments, for testing and certifying autonomous vehicles.

Acknowledgments

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