The Development of a Large-Scale Particle Tracking Velocimetry System for Wake Analysis of Wind-Loaded Structures

B. la Bastide, G. A. Rosi and D. E. Rival

Abstract. The current study examines the capabilities of large-scale particle tracking velocimetry (LS-PTV) in fully resolving the wake behind a wind-loaded structure. LS-PTV measurements within a 16m$^3$ volume were acquired behind a 0.75m diameter sphere. The study uses a spherical obstruction as a base case to prove the feasibility of measuring wind-turbine wakes. The Reynolds number of the flow was approximately $Re = 1 \times 10^5$. The temporal longevity of paths increased at a rate of 0.0073D/U$_0$ per sphere diameter, indicating that the seeding particles have the ability to withstand the shear forces present in the wake. Furthermore, the mean freestream-velocity deficit profiles, the streamwise Reynolds stress profile, and the wake-deficit decay obtained using the LS-PTV system agreed with studies performed by Amoura et al. [1] and Eames et al. [2], thereby demonstrating the system’s ability to accurately quantify the mean flow. Finally, steady-flow, ramp-up and ramp-down events were identified within the data from the time trace of the freestream flow. The corresponding wake structures behind the sphere during the three events were characterized using the real-time spatial measurements achievable by the LS-PTV system. During steady-flow conditions, pathlines exhibited high mixing and high curvature within one diameter downstream of the sphere, whereas pathlines further downstream were comparatively straight. In contrast, the straightening of pathlines occurred further upstream during ramp-up and ramp-down events, indicating that high freestream-velocity events such as gusts have an organizing effect on the wake, which attenuates shedding structures.

1 Introduction

Current computational models used for characterizing the wakes of wind-loaded structures, such as wind turbines, use artificial representations of the incoming wind. For example, in numerical studies of wakes conducted by Suzuki [3] and Vermeer et al. [4], the incoming wind is assumed to be steady and parallel, or represented using a synthetic turbulence model. Synthetic turbulence models as developed by Mann [5] are limited in their ability to accurately represent the oncoming flow field. The limitations are due to the assumptions required to develop the models, such as artificial eddy lifetimes and assigned geometric structure. It is uncertain if such models accurately recreate actual wind conditions, which are characterized by unsteadiness and abrupt changes such as gusts. Although the aforementioned studies recreate accurate representations of the phase-averaged mean, they are incapable of quantifying how the wake of an structure responds to unsteady flow phenomena, such as wind turbulence or coherent wind structures.
An alternative to wake analysis via computational modelling is the direct measurement of wakes through experiments. Current direct wind-measurement techniques utilize either point measurements as in Medici and Alfredsons [6], or mapping devices such as LIDAR as can be seen in Schlipf et al. [7]. The advantage to direct wind measurements over computational models is that they represent real-life wind conditions. However, in spite of this advantage over computational models, direct wind measurements also suffer from a lack of real-time spatial resolution within large measurement domains. It is impossible to resolve a flow over a large domain in real-time via single-point measurements and consequentially single-point measurements are unable to resolve turbulent flow structures. Although anemometer rakes have shown to be effective in resolving certain structures such as *very large-scale motions* (Hutchins and Marusic [8]), such methods provide insufficient spatial resolution to definitively identify vortical structures; see Rosi et al. [9], Scarabino et al. [10]. A solution to the poor spatial resolution of such anemometer rakes would be to increase the number of anemometers within the measurement domain. However, there is a limit as to how many anemometers may be placed within a specific measurement domain before the rake itself begins to alter the wind flow. Furthermore, although LIDAR techniques are non-intrusive, such systems do not provide the necessary real-time spatial resolution to resolve turbulent structures within a wake.

A substitute to anemometers and LIDAR in measuring wind-loaded structure wakes is large-scale particle tracking velocimetry (LS-PTV). The method is a non-intrusive measurement technique that tracks the motions of tracer particles with sizes on the order of centimetres within a measurement domain on the order of metres. LS-PTV produces simultaneous, Lagrangian, velocity measurements over a large spatial domain at high sampling rates, which is unachievable via current wind-measurement methods. The technique is typically used indoors and involves complex, facility-specific setups; see Lobutova [11], Biwole et al. [12], Machacek [13] and Sun and Zhang [14]. The complexity and facility-specificity of LS-PTV had rendered the technique inappropriate for outdoor use. However, a recent article by Rosi et al. (online first) [15] demonstrated the practicality of three-dimensional LS-PTV for outdoor wind measurements. The system produced measurements within a 16m$^3$ volume by tracking the motions of fog-filled soap bubbles. Not only did the system accurately resolve the mean wind profile and Reynolds stresses throughout the measurement volume, it also produced novel measurements such as Lagrangian acceleration and pathlines of the wind flow. However, the study did not attempt to measure the wake behind an obstruction, nor did the study consider how susceptible the tracers were to bursting due to the increased shear stresses near the obstruction’s surface.

Current wind-turbine wake analyses, such as the LIDAR experiments conducted by Smalikho et al. [16], calculate time-averaged quantities to develop parameters that describe wind-turbine wakes. However, this averaging method is not capable of resolving the transient flow experienced by downstream turbines, and consequently cannot resolve the fluctuating loads acting on the turbines. The spatial- and time-resolved data obtained using LS-PTV will allow for the quantification of coherent structures, which can be subsequently used to characterize the fluctuating loads experienced by wind turbines.

The focus of the current study is to ascertain the suitability of the LS-PTV system discussed in Rosi et al. [15] in measuring the wakes of wind-loaded structures such as wind turbines. Specifically, the study measures the wake behind a sphere immersed in an unsteady wind flow. The sphere has been selected due to it being a symmetric canonical obstruction. The manuscript begins by briefly reviewing relevant literature of sphere wakes that will be compared to the results of the current study. The LS-PTV system, as well as the test site are then discussed. The results section begins by quantifying the susceptibility of tracers to burst by considering the length of pathlines as a function of radial distance from the sphere. The wake-deficit and streamwise Reynolds-stress profiles are then plotted at various downstream distances from the sphere and compared to results from literature. Finally, pathline plots for various wind events...
are discussed, demonstrating the novelty of the system in characterizing wind-loaded structure wakes.

2 Background
The areas of specific interest for the current study are: the radial wake profile developed behind a sphere, the evolution of the Reynolds stresses along the wake flow path, and the rate of velocity deficit decay. The wake developed behind a sphere in turbulent inflow conditions has been recently observed by teams such Amoura et al. [1] and Eames et al. [2]. Amoura et al. [1] presented a wake-deficit profile for a sphere in turbulent inflow (>20% turbulence intensity) at varying Reynolds numbers. It was concluded that the wake of a sphere starts to become independent of Reynolds numbers for \( Re > 230 \). Based on the velocity profile developed by Amoura et al. [1] it can be seen that the velocity deficit in the sphere wake approaches zero at approximately \( x/D = 1 \), where \( x \) is downstream distance from the sphere measured from the sphere’s centre, while \( D \) is the sphere diameter. Amoura et al.[1] also presented the Reynolds-stress profiles found in a sphere wake. It was observed that peak streamwise Reynolds-stress occurred at a distance of approximately \( x/D = 1.5 \). Eames et al. [2] examined the decay of the velocity deficit behind a sphere in turbulent conditions and determined that the velocity deficit decays at a rate \( x^{-2} \) relative to the distance downstream of the sphere.

3 Experimental Methods
On October 7, 2013, wake measurements behind an inflatable polyvinyl-chloride sphere were acquired using an LS-PTV system designed for outdoor use. The measurements were performed in an open field on the University of Calgary campus. An aerial view of the test site is shown in Fig. 1(a). The LS-PTV system and sphere were located in a 10m \( \times \) 10m square in the northern section of the field. During the measurement campaign, the wind blew primarily from the southeast. The nearest obstructions to the wind flow were a five-story building located 60m south of the LS-PTV system and a row of trees 25m east of the LS-PTV system.

Fig. 1(b) shows a schematic of the LS-PTV system. The LS-PTV system uses fog-filled soap bubbles as tracers. The tracers, which are illuminated by sunlight and are contrasted against blue sky, are seeded into the wind by a particle seeder located 15m upstream of the measurement volume. The seeder consists of a commercial bubble generator mounted onto a steel tube. Fog and soap fluid is delivered to the bubble generator via a manifold system. After dispersing downstream, the tracers are tracked by four digital cameras positioned on a 10m \( \times \) 10m square. Each camera is equipped with a 50mm lens. Videos are captured at 60Hz and at a resolution of 1280 \( \times \) 720 pixels. The cameras are synchronized using a custom radio to infra-red remote. Further details regarding the LS-PTV system can be found in Rosi et al. [15]. The sphere was elevated such that the height of its centre was 3m off the ground, and was positioned just outside the southern limit of the control volume. To achieve this elevation, the sphere was secured onto an aluminium tube that was braced by a wooden A-frame. During the tests 6.5 minutes of test data was collected at a Reynolds number of \( Re \approx 1 \times 10^5 \).

4 Results
This section will first examine the ability of the tracers to withstand and shear forces by discussing the mean lifespan of pathlines obtained as a function of absolute distance from the sphere. Secondly, mean flow characteristics will be quantified and compared to previous studies to validate the results obtained by the LS-PTV system. Finally novel, spatially resolved instantaneous wake structures are presented and discussed for steady flow, ramp up, and ramp down events.
4.1 Pathline longevity
In order for the LS-PTV system to be viable, the tracers must be able to withstand high levels of shear found in wakes. The mean lifespan of pathlines as a function of absolute distance from the sphere gives an indication of the tracers’ ability to withstand shear forces. Figure 2 shows the dimensionless lifespan of pathlines, \( \frac{U_0 t}{D} \), as a function of absolute distance of the pathline from the sphere, \( \frac{r}{D} \). Here, \( U_0 \), \( t \) and \( r \) represent the mean freestream velocity, time and absolute distance from the sphere’s centre, respectively. The mean lifespan obtained during the experiment is dependent on two factors. The first factor is the lifetime of the tracer particle. The second factor is the ability of the camera to distinguish the tracer particles from the background. The relationship between the normalized path length and the distance from the sphere observed in Figure 2 shows a slight increase in longevity proportional to the distance from the sphere. The overall trend has a relationship of 0.0073\( D/U_0 \) per sphere diameter. This trend has a smaller magnitude than the fluctuations observed between the individual recorded values. The standard deviations in the pathline lifespan found for each absolute distance fell between 0.047 and 0.049 when normalized by \( d/D \). The magnitude of the standard deviations are significant relative to the fluctuations and overall trend observed in Figure 2. This indicates that the pathline lifespan is not strongly correlated with the absolute distance between the particle and the sphere.

4.2 Mean-wake measurements
Time averaged velocity deficit profiles were developed over the wake of the sphere. Figure 3(a) shows the radial profiles of the velocity deficit at three points downstream of the sphere: \( x/D = 1 \), \( x/D = 2 \) and \( x/D = 3 \). The velocity deficit is defined as \( u - U_0 \) normalized by \( U_0 \). Here, \( u \) represents the mean streamwise velocity. The radial distance is defined as the distance of the particle from a line parallel to \( U_0 \) intersecting the centre of the sphere. The particle distance is then normalized by the diameter of the sphere. The data points falling in the positive portion of \( r/D \) were obtained from particles located in the upper half of the wake and the negative data points were found from particles located in the lower half. The segregation of the data points between the upper and lower half of the wake was done in order to observe the symmetry of the profile and therefore demonstrate any ground effects acting on the flow field. As can be seen
in Figure 3(a) ground effects were present. However, they had a minimal impact on the velocity profile modifying the external flow velocity by $\approx 5\%$. Also, the velocity deficit presented in Figure 3(a) for $x/D = 1$ has a similar relationship to that observed by Amoura et al. [1]. However, the amplitude of the deficit obtained from the LS-PTV system is $70\%$ as large as the deficit found by Amoura et al. [1] at the same downstream distance. The non-conformity could be due to a difference in the $U_0$ turbulence intensity which would result in a change in momentum transfer. The downstream velocity deficit decays as a function of $x^{-1.9}$ at $r/D = 0$, which agrees with the conclusions developed by Eames et al. [2] who observed a wake deficit decay on the order of $x^{-2}$ in highly turbulent flows. Finally, Figure 3(b) shows the square root of streamwise Reynolds stress $\sqrt{(u - U_0)^2}$ normalized by $U_0$ as a function of $x/D$. It can be observed that the Reynolds stress reaches a maximum at $x = 1.25D$. This is consistent with the results obtained by Amoura et al.[1] where peak Reynolds stresses were achieved at approximately $x = 1.5D$.

4.3 Instantaneous wake structure

As stated previously, LS-PTV is capable of producing simultaneous, Lagrangian, velocity measurements over a large spatial domain and at high sampling rates. Thus, LS-PTV is capable of resolving the wakes of wind-loaded structures in real time, opposed to traditional direct wind-measurement techniques that can only resolve the mean statistics. The following sections highlights this capability by exploring the wake structure of the sphere as measured by the LS-PTV system during a period of steady flow, as well as during a ramp-up and a ramp-down event.

Figure 4 summarizes the measurements taken by the LS-PTV system during a period of steady flow over the sphere. Figure 4(a) shows the time-trace of the freestream velocity $U$ normalized by the mean freestream velocity of the data set $U_0$ where $U_0 = 2.8\text{m/sec}$. $U/U_0$ is plotted against dimensionless time, $t/(D/U_0)$. $U$ and $U_0$ were determined from measurements along pathlines that were an absolute distance of $r/D > 2$ away from the centre of the sphere. The time-trace demonstrates that during this section of data, the freestream velocity remained constant and roughly matched the freestream velocity of the data set. To gain insight into the wake...
structure behind the sphere during the constant-flow event, the pathlines that were concurrently measured can be considered. The pathlines are shown in Figure 4(b). The pathlines have been colored with time according to the colorbar in the top-right corner of the figure. Along the surface of the sphere, the pathlines exhibit high levels of curvature. Approximately one diameter downstream of the sphere, pathlines above and beneath the sphere’s equator tend to generally curve downwards and upwards, respectively, towards the central axis of the sphere. However, the shapes of the pathlines within this region exhibit high levels of mixing, indicating a high level of turbulent stresses within this region. This is in agreement with Figure 3(b), that indicated a peak in turbulent stresses at $X/D = 1.25$. Further downstream at $X/D = 3$, the pathlines have straightened substantially compared to the flow upstream. The straightening of pathlines indicate a drop in turbulent stresses, which also agrees with Figure 3(b).

To compare against the steady-flow case, the wake structure behind the sphere during ramp-up and ramp-down events can also be considered. Figure 5 shows the time-trace of $U/U_0$ where $U_0 = 2.7 \text{m/sec}$, as well as the pathlines that were measured concurrently behind the sphere during the ramp-up event. The time-trace shown in Figure 5(a) indicates that during the ramp-up event, the freestream velocity increased from approximately $0.7U_0$ to $1.3U_0$. Similar to the constant velocity case, the pathlines that pass over the sphere move towards the central axis of the sphere. However, the high level of mixing in the pathlines that was observed at $X/D = 1$ is less prevalent during the ramp-up event. Specifically, the reorganization of pathlines that occurred at $X/D = 3$ during the steady-flow case has moved upstream and the pathlines have straightened by $X/D = 2$. The result suggest that events such as gusts act to organize the flow,
Figure 4: (a) The time trace of $U/U_0$ where $U_0 = 2.8 \text{ m/sec}$ during a steady-flow event. The event is plotted against dimensionless time $t/(D/U_0)$, while the time trace is colored with time according to the colorbar in (b). (b) Pathlines measured in the wake of the sphere. Pathlines are colored with time according to the colorbar, and the sphere has been drawn into the figure.

and greatly attenuate the coherent structures that shed off of wind-loaded structures. However, further data must be collected during ramp-up events to quantify and validate this result.

As a final case, a ramp-down event is considered. Figure 6 shows the time-trace of $U/U_0$ where $U_0 = 1.95 \text{ m/sec}$, as well as the pathlines that were measured concurrently behind the sphere during a ramp-down event. During the ramp-down event, the freestream velocity dropped from approximately $1.5U_0$ to $0.8U_0$. Similar to the ramp-up event, the reorganization of pathlines has moved upstream, especially during the first half of the ramp-down event, i.e. $0 \leq t/(D/U_0) \leq 7$. However, during the second half of the ramp-down event, i.e. $7 \leq t/(D/U_0)$, high-curvature pathlines that exhibit sporadic motions begin to reappear one diameter downstream of the sphere, similar to those observed during the steady-flow case. The result suggests that ramp-down events are the termination of the organizing effect brought on by the high streamwise velocity that preceded them. Thus, the wake of the wind-loaded structure becomes more prevalent in the flow. Again, more ramp-down events must recorded to quantify and validate this result.

5 Conclusions

Wind flow around a sphere with a diameter of 0.75m was investigated using an LS-PTV system developed by Rosi et al. [15]. The objectives of the investigation were: to validate the measurement technique based on current literature; and to demonstrate the potential of the system to spatially resolve the wakes of wind loaded-structures, such as wind turbines, in real-time, as opposed to obtaining the mean statistics. Time-averaged statistics, as well as real-time wake measurements were presented in order to accomplish these goals.

The pathline lifespan as a function of absolute distance from the sphere was presented in order to demonstrate the ability of the tracers to withstand areas of high shear near the sphere’s surface. No significant relationship between the distance from the sphere and lifespan was observed,
Figure 5: (a) The time-trace of $U/U_0$ where $U_0 = 2.7\text{m/sec}$ during a ramp-up event. The event is plotted against dimensionless time $t/(D/U_0)$, while the time trace is colored with time according to the colorbar in (b). (b) Pathlines measured in the wake of the sphere. Pathlines are colored with time according to the colorbar, and the sphere has been drawn into the figure.

indicating that the tracers are capable of withstanding high-shear regions developed in wakes.

Three aspects of the wake deficit measured by the LS-PTV system were compared to previously conducted investigations. It was found that the velocity-deficit profiles obtained by the LS-PTV system were similar to previous results. The rate of decay of the wake deficit was found to follow the relationship of $x^{-1.9}$, which agrees with Eames et al.’s [2] study conducted in turbulent-flow conditions. The experimentally-obtained streamwise Reynolds-stress profile found as a function of $x/D$ demonstrated a characteristic peak at $x/D = 1.25$. A similar peak has been observed by Amoura et al. [1]. The above results demonstrate the ability of the LS-PTV system to accurately capture the mean characteristics of wakes.

In order to demonstrate the system’s potential in spatially resolving the wakes of wind-loaded structures in real time, three events were identified from the time traces of the freestream flow: steady flow, a ramp-up in flow velocity, and a ramp-down in flow velocity. The corresponding wake structure behind the sphere during the three events were characterized using the real-time spatial measurements achievable by the LS-PTV system. During steady-flow conditions, pathlines exhibited high mixing and high curvature within one diameter downstream of the sphere, whereas pathlines further downstream were comparatively straight. In contrast, the straightening of pathlines occurred further upstream during ramp-up and ramp-down events, indicating that high freestream-velocity events such as gusts have an organizing effect on the flow, thereby attenuating the wake.

In order to increase the number of tracers that are simultaneously tracked, as well as increasing the lifespan of pathlines, two modifications are currently being made to the LS-PTV system. Firstly, the system is being equipped with more seeders in order to increase the production rate of tracers, which would thereby result in a higher seeding density within the measurement volume. Furthermore, a more accurate calibration method is being developed, which would result
in longer path lifespans since fewer tracks would be dropped due to calibration error.

Figure 6: (a) The time trace of $U/U_0$ where $U_0 = 1.95$ m/sec during a ramp-down event. The event is plotted against dimensionless time $t/(D/U_0)$, while the time trace is colored with time according to the colorbar in (b). (b) Pathlines measured in the wake of the sphere. Pathlines are colored with time according to the colorbar, and the sphere has been drawn into the figure.

References
[1] Amoura Z, Roig V, Risso F and Billet A M 2010 Physics of Fluids 22 1–10
[2] Eames I, Johnson P B, Roig V and Risso F 2010 Physics of Fluids 23 1–5
[3] Suzuki A 2000 Dissertation Abstracts International 61
[4] Vermeer L J Sorensen J N and Crespo A 2014 Progress in Aerospace Sciences 39 467–510
[5] Mann J 1994 Fluid Mechanics 273 141–168
[6] Medici D and Alfredsson P H 2005 Wind Energy 9 219–236
[7] Schlipf D, Trabuch D, Bischoff O, Hofsäkm, Mann J, Mikkelsen T, Rettenmeier A, Trujillo J J and Kühn M 2010 15th International Symposium for the Advancement of Boundary Layer Remote Sensing (Paris, France)
[8] Hutchins N and Marcus i 2007 Journal of Fluid Mechanics 579 1–28
[9] Rosi G A, Martinuzzi R J and Rival D E 2013 Journal of Wind Engineering and Industrial Aerodynamics 119
[10] Scarabino A, Sterling M, Richards P J, Baker C J and Hoxey R P 2007 Wind and Structures 10 135–151
[11] Loboutova E, Resagk C and Putze T 2010 Building and Environment 45 3653–3662
[12] Biwole P H, Yan W, Zhang Y and Roux J J 2000 Measurement Science and Technology 20 1–33
[13] Machacek M 2003 A Quantitative Visualization Tool for Large Wind Tunnel Experiments Ph.D. thesis Swiss Federal Institute of Technology
[14] Sun Y and Zhang Y 2003 American Society of Heating, Refrigeration, Air-Conditioning Engineers 09 540–8
[15] Rosi G A, Sherry M, Kinzel M and Rival D E 2014 Experiments in Fluids
[16] Snalikho I N, Pitchugina Y L, Banakh V A and Brewer W A 2012 Russian Physics 55 956–960