Observation of Flow Downstream of a Bridge Deck Model Using Cobra Probe and Lidars

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Abstract. Application of lidars in civil engineering is evolving in many areas, for instance in planning and estimating design loads for long-span bridges. The use of the lidar technology in the wind tunnel provides a new option for turbulence measurements around model scale structures. The paper presents a wind tunnel test campaign using a combination of two continuous wave lidars and Cobra probes to study the flow conditions downstream of a bridge deck model, within and outside of the wake region. The measurements took place in a boundary layer flow at the wind tunnel facility of Politecnico di Milano where the performance of the two lidars for studying bridge aerodynamics was tested and is herein validated by reference Cobra probe measurements. The wake characteristics around the bridge deck are explored with the aim of improving the understanding of the nature of the wind forces acting on a bridge girder and demonstrating the potential of the remote sensing technology for wind tunnel studies relevant to bridge design.

Keywords: Wind Tunnel Tests · Bridge Deck Section · Continuous-Wave Lidar · Cobra Probes

1 Introduction

Wind tunnel studies of long-span bridges are essential for a comprehensive insight into the aerodynamic loading of bridges in the atmospheric flow. Time-averaged force coefficients are commonly measured with static bridge deck models, using various types of force transducers. Occasionally, surface pressure measurements are performed to increase the understanding of the interaction of the airflow with a bridge deck, both with a fixed and a moving model (Rocchi et al., 2015; Argentini et al., 2012).

Wake flow characteristics of streamlined closed-box bridge girders have been investigated in wind tunnels by the means of surface pressure measurements (Ricciardelli and

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Hangan, 2001), high-resolution particle image velocimetry (PIV) (Chen et al., 2014), and numerical flow simulations (Kuroda, 1997; Fransos and Bruno, 2010; Kusano et al., 2021). In full-scale, pressure measurements on a bridge deck surface have been performed in a limited number of studies (Daniotti, 2022). The work of Daniotti (2022) also includes turbulence measurements by sonic anemometers in a point upstream and a point downstream of the bridge, at deck level. The use of remote sensing technology (Cheynet et al., 2017a) makes it possible to survey a much larger flow domain around a bridge structure than practically feasible using anemometers.

The present work introduces the potential use of lidars in wind tunnel investigations of bridge decks. Remote sensing of a wind field by continuous wave lidars inside a wind tunnel is a relatively unexplored subject. Previous lidar investigations in wind tunnels are limited to the validation of mean wind speed measurements by Pedersen et al. (2012), a study of the effect of droplets in an icy wind tunnel on the high-frequency velocity data by Sjöholm et al. (2017), and measurements downstream of wind turbine models by Dooren et al. (2017) and Sjöholm et al. (2017).

Herein, the lidars, in parallel with Cobra probes, are used to investigate the flow around a bridge deck model in the wind tunnel. The case studied concerns a suspension bridge across the Lysefjord in Norway, which is instrumented by an array of sonic anemometers for long-term wind monitoring (Snæbjörnsson et al., 2017). Several lidar measurement campaigns have also been performed at the bridge site (Cheynet et al., 2017a; Cheynet et al., 2016; Cheynet et al., 2017b; Nafisifard et al., 2021; Nafisifard et al., 2023a; Nafisifard et al., 2023b) motivating the present study.

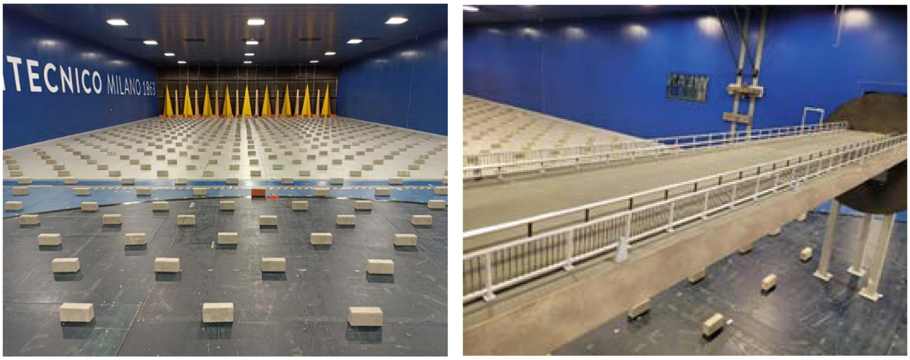
An investigation of the flow conditions around the bridge deck model, as performed in the present study, aims to improve the understanding of the nature of the wind forces acting on a bridge girder.

2 Wind Tunnel Test Setup and Measurement Equipment

The tests were performed in the boundary layer test section of the closed-circuit wind tunnel at the Politecnico di Milano. The test section is 13.84 m wide, 3.84 m high, and 35 m long and the facility can generate mean wind speeds up to 16 m/s. The boundary layer flow was created by spires and floor roughness elements (Fig. 1a). The horizontal turbulence intensity was about 10%, which is relevant for a prototype bridge. A 4 m long section model of the bridge deck, which is 12.3 m wide and 2.76 m tall in full-scale, was fabricated in a 1:15 scale (Fig. 1b) and tested at a zero-pitch angle. A Pitot tube was used to monitor the wind velocity in the tunnel at deck level, 4.5 deck widths upwind from the leading edge of the bridge deck.

The lidar measurement equipment was provided by the Technical University of Denmark (DTU) in the form of two 2-inch-wide optical telescopes that were connected to a single continuous-wave laser (Fig. 2a) (Sjöholm et al., 2017). Special clamps were designed and 3D-printed at DTU, to fix the telescopes to a supporting aluminum beam. The telescopes could slide along the beam as well as rotate about a fixed axis. The beam was attached to a specially designed frame, providing support for the lidars in different measurement configurations (Fig. 2b). An aerosol generator was used to generate droplets of sufficient concentration for the lidar measurements (Fig. 2c).

The bridge deck wake characteristics were monitored by an array of four 4-hole Cobra probes manufactured by Turbulent Flow Instrumentation distributed at lateral distances up to 1B, where B = 820 mm is the model deck width. A traversing mechanism was used to obtain wake profiles at distances 0.16B, 0.5B, 1B, and 3.25B (profiles W1, W2, W3, and W4) downstream from the trailing edge of the deck model, see Fig. 3a and Fig. 5. The Cobra probe data was recorded with a sampling frequency of 2 kHz.



(a) Spires and floor roughness elements upstream of the model.

(b) The 1/15 scale bridge deck section model.

Fig. 1. The bridge deck model setup in the wind tunnel.

(a) Lidar telescopes.

(b) Aluminium supporting frame.

(c) Aerosol seeding system.

Fig. 2. Lidar measurement setup.

The wake profiles (mean wind speeds and turbulence) were also measured by dual lidar, in front of strip B (Point C, in Fig. 5) at several heights including five points above the trailing edge level (667 mm, 500 mm, 313 mm, 133 mm, and 53 mm), a point at the trailing edge level, and four points below the trailing edge level (−60 mm, −123 mm, −303 mm, and −480 mm). Lidar data 1B downstream from the trailing edge of the deck model (section W3, in Fig. 5) is presented herein.

(a) Array of four Cobra probes fixed to a traverse.

(b) Two lidar telescopes fixed to a traverse.

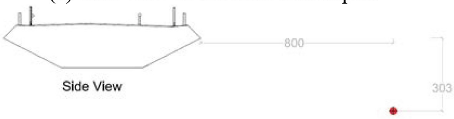
Fig. 3. Wake measurement setup.

As illustrated in Fig. 3b, the two telescopes were orientated at an angle of ± 31° from the horizontal, to provide information on the turbulent flow in the vertical plane. The measurement volume in this configuration was 3 cm (full width at half maximum, FWHM).

Measurements using Cobra probes and lidars were performed in separate runs, ensuring that the lidar measurements were free of any interference from the Cobra probe setup in the proximity of the target volume. However, a co-location of Cobra probes and lidars was also included for a single case, where simultaneous measurements by lidars and a Cobra probe were carried out, to enable a direct comparison of the turbulence time-series acquired by the two types of sensors. This setup is shown in Fig. 4, with the lidars focusing on a point 303 mm below the deck trailing edge, 800 mm downstream of the 820 mm wide bridge deck model (see Fig. 4a and 4b). Simultaneously, a Cobra probe was deployed at a lateral distance of 100 mm from the focus point of the lidars (see Fig. 4c).

Measurements of the lateral coherence, in both the disturbed and the undisturbed flow regions, were also undertaken by Cobra probes. Lateral coherence was also studied using lidars, with the two telescopes in a side-by-side arrangement, as shown in Fig. 2a. Simultaneous measurements by two lidars were carried out at three different inclination angles (−30°, 0°, and 30°), to enable the estimation of the lateral coherence of the u- and w-turbulence components. The two line-of-sight velocities were sampled at a frequency of approximately 600 Hz. Figure 5 outlines the experimental plan showing the location of the measurement points in sections across (Fig. 5a) and along (Fig. 5b) the deck.

(a) Side view of the lidar telescopes.



(b) Schematic of tailored scanning.

(c) Closeup front view of the instruments.

Fig. 4. Co-location measurement setup. For clarity, the laser beams are illustrated by red solid lines. Target points of lidars and Cobra probe are marked by red and green circles, respectively.

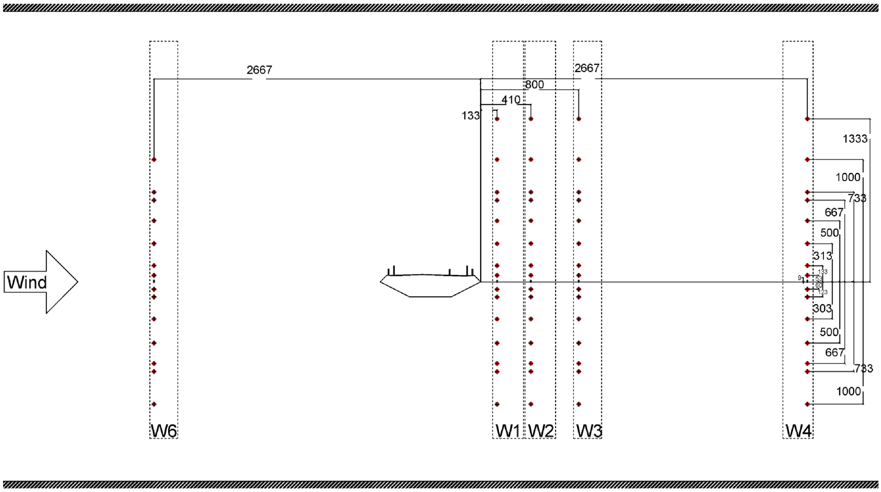
3 Data Analysis and Measurement Results

3.1 Cobra Probe Data Quality and Orientation

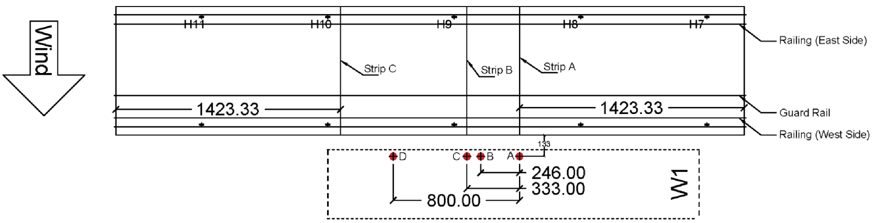
Two main steps were adopted in the initial processing of the Cobra probes recordings. The first one concerns the quality control of data to eliminate erroneous observations of the occasional flow directions outside the interval $\pm 45°$ from the Cobra probe x-axis, which Cobra probes cannot resolve properly. This kind of flow is relevant to vortices due to the flow-model interaction. This has been investigated by introducing a data quality factor Q:

$$Q = \frac{N_o}{N_{total}} \tag{1}$$

where N_o is the number of observations with zero value recorded by a Cobra probe and N_{total} is the total number of observations. The results in Fig. 6 show that, as expected, the poorest data quality is seen within $\pm$ 60 mm ($\pm$0.3H where H $=$ 184 mm is the model height) from the trailing edge of the bridge deck, at sections W1 and W2. For the other measurement locations, further downstream of the bridge, the data quality from the Cobra probes was good, with Q factor values higher than 95%.

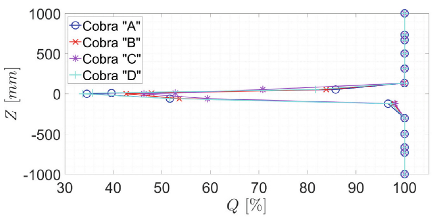


(a) Side view of target points.

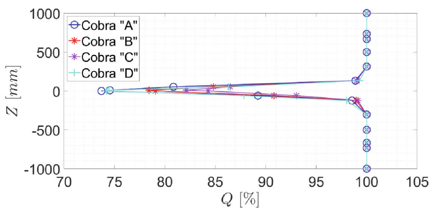


(b) Top view of target points. For sake of simplicity, only the W1 case is illustrated in the drawing.

Fig. 5. Target points for flow measurements.



(a) the W1 case.



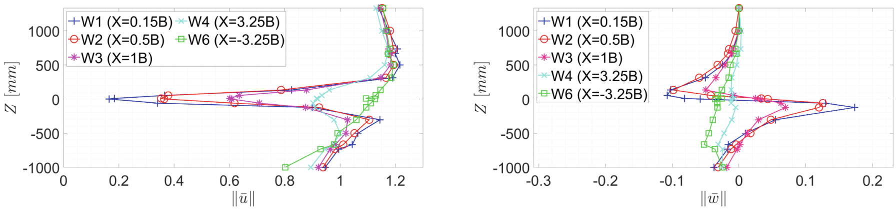
(b) the W2 case.

Fig. 6. The data quality factor, Q, at different heights, Z, from the leading/trailing edge, for data recorded 0.15B (case W1) and 0.5B (case W2) downstream of the trailing edge of a B = 820 mm wide deck model.

The second consideration is the adjustment of slight misalignments of the Cobra probes, in such a way that the rotation of the turbulence data into a re-aligned coordinate system yields zero-mean v- and w- values at the top of the boundary layer in the wind tunnel. The recordings at the highest profile measurement point (1333 mm above the deck leading/trailing edge) were used to establish the pitch and yaw angles needed for the correction.

3.2 Wake Study

An illustration of the results from the wake measurements is given in Fig. 7, in terms of the mean wind speed profiles observed by a Cobra probe, in comparison to the profile upstream of the model (section W6 in Fig. 5). Around the trailing edge level, data values equal to 0 are disregarded in the calculations as discussed in Sect. 3.1.



(a) Mean along wind speed normalized by pitot velocity.

(b) Mean vertical wind speed normalized by pitot velocity.

Fig. 7. Normalized mean wind velocities recorded by Cobra probe A, at several distances X from the deck trailing edge.

The values are normalized by the horizontal mean wind speed recorded by the Pitot tube upstream of the model. The horizontal wind profiles clearly demonstrate the velocity deficit in the wake embedded in the boundary layer flow.

In Fig. 8, the associated turbulence intensities are displayed. At the three shortest distances from the model (sections W1, W2, and W3), both the horizontal and the vertical turbulence intensities exceed 30% at the trailing edge level. This is a triple and a fivefold increase compared to the turbulence level of the undisturbed flow (sections W4 and W6) for the two velocity components, respectively.

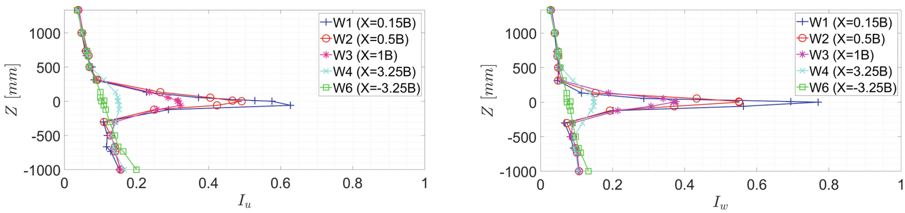
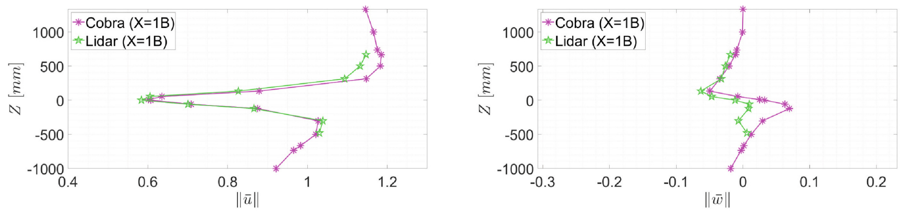


Fig. 8. Turbulence intensity of u- and w- components recorded by Cobra probe A.

In Fig. 9 a comparison between the wake results obtained by the Cobra probe and the lidars, one deck width downstream of the model trailing edge is given. It can be seen that Cobra and lidar profiles are in good agreement with each other except for few locations. In particular, for the vertical wind velocity profile some discrepancies can be seen close to the wake center, below the deck. A slight discrepancy in the along wind velocity is also noticeable above the deck. This can potentially be attributed to the finite sampling volume combined with a steep spatial gradient. Difference may also be related to irregularities in the wake pattern in crosswise direction due to the objects on the deck surface (posts, railings etc.). The profiles were not recorded simultaneously and using a different traversing positioning system, which may also affect the comparison in terms of the accuracy in the probe/lidar position and interference with the probe stands. Furthermore, the velocity in the tunnel was reduced during the lidar measurements, to improve performance, as higher wind velocities caused higher dispersion of the smoke required. A difference in the dynamic pressure by a factor of 2.4 between the lidar and the Cobra probe measurements may have also contributed to a slightly different flow-model interaction, especially just above the deck where railings and hanger posts disturb the flow pattern.



(a) Mean along wind speed normalized by pitot velocity.

(b) Mean vertical wind speed normalized by pitot velocity.

Fig. 9. Normalized mean wind velocities recorded by lidars and Cobra probe at one deck width downstream of the model trailing edge.

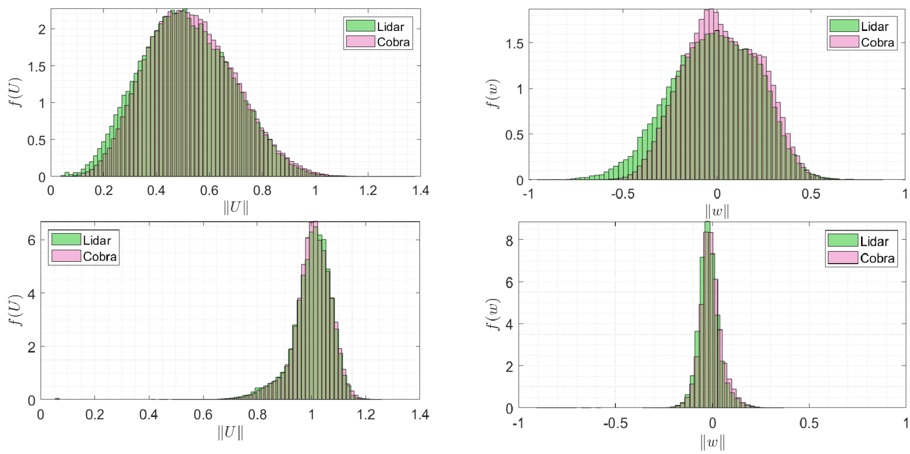
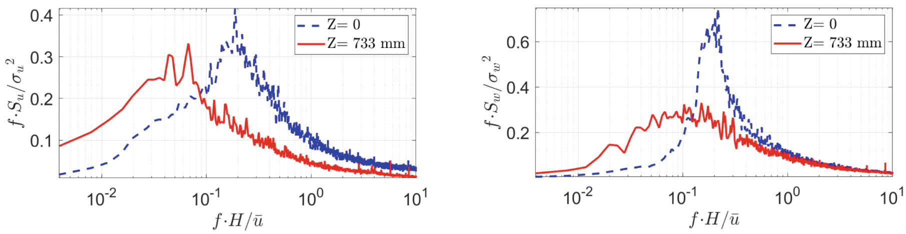


Fig. 10. Histogram of normalized along-wind (U) and vertical (w) velocity components recorded by Cobra probe D and lidar, for heights Z = 0 mm (top panels) and Z = 667 mm (bottom panels) at 800 mm (1B) downstream from the trailing edge.

The histograms of the along-wind (U) and vertical (w) velocity components measured by Cobra probe D and the lidars, inside (Z = 0 mm) and outside of the wake (Z = 667 mm), are displayed in Fig. 10. The velocities, monitored one deck width downstream of the model, are normalized by the along-wind mean speed at Z = 667 mm. In the nearly undisturbed flow at Z = 667 mm, turbulence variations are confined to a relatively small range of velocity values compared to the distributions at the trailing edge height (Z = 0 mm). A broader range of values at the trailing edge level is consistent with the elevated turbulence levels in the wake presented in Fig. 8. They also indicate an increased variability in the local flow directions within the wake, e.g., in relation to the vortex shedding process. In line with the results shown in Fig. 8, the average along-wind velocity is considerably reduced at the trailing edge height compared to the undisturbed mean wind velocity.

The frequency content of turbulence within and outside of the wake, one deck width from the trailing edge (line W3) is presented in Fig. 11. At the trailing edge level (Z = 0 mm), the spectral peak has a higher frequency (smaller scale turbulence), compared to that at Z = 733 mm, which indicates a flow-deck interaction. In particular, the vertical turbulence spectrum is more narrow-banded in the wake than outside the wake, indicating a vortex shedding process. The spectrum is centered at a Strouhal number, $St = \frac{fH}{U}$, close to 0.2. In full scale, St values from 0.15 to 0.25 have been observed, for turbulence intensities, I_u, ranging from 0.06 to 0.27 (Daniotti, 2022).



(a) u- component. (b) w- component.

Fig. 11. The turbulence spectra outside and within the deck model wake recorded by Cobra probes 0.98B downstream of trailing edge. Dashed lines belong to Z = 0 mm and solid lines belong to Z = 733 mm.

3.3 Comparison of Measurements by Collocated Cobra Probe and Lidars

The results from the simultaneous measurements by the collocated Cobra probe and the lidars obtained with the setup shown in Fig. 4, are provided in Table 1. The tests were carried out at wind tunnel power of 40%, at which the quality of the lidar measurements was found to be better than at higher wind speeds. At higher power, a lower number of aerosols was encountered in the measurement volume during the recording interval. The results show an overall good agreement but the results for the mean vertical velocity (w_m), are sensitive to the alignment of the instruments relative to the mean along wind velocity (U_m). Since the along wind component is in the order of 30 times larger than the vertical component, the difference of 0.12 m/s for the mean vertical velocity between the Cobra probe and the lidar results could correspond to an un-accounted for misalignment between the instruments of 1°. In the wake analysis, the Cobra probe misalignment was corrected by assuming that the mean vertical and transversal velocities were zero at the top measurement height of the profile, which rendered tilt corrections between 0.2° and 1.3° for the four Cobra probes at the four different downstream locations. Since the co-location setup was only based on one measurement point within the influence area of the surface roughness, such alignment correction was not possible. As the lidar data is based on two laser beams in a vertical plane, vertical misalignment should not be an issue, however, a minor horizontal misalignment is possible for the lidar setup. It is noteworthy that the standard deviation of the vertical velocity component is the same from both lidars and Cobra probe.

Table 1. Flow characterization by Cobra and Lidar at the co-location point for 40% power in the wind tunnel.

Sensor	Mean velocity (m/s)		Standard deviation (m/s)		Turbulence intensity		Reynolds shear stress (N/m2)
	U_m	w_m	σ_u	σ_w	I_u	I_w	r_{uw}
Cobra	6.27	0.12	0.89	0.54	0.141	0.086	−0.0376
Lidar	6.16	0.24	0.76	0.52	0.124	0.084	−0.0625

3.4 Correlation Study

Simultaneous measurements by four Cobra probes enabled the estimation of the flow correlation at six different lateral separations (see Fig. 5). In Fig. 12, the lateral correlation of the along-wind velocity at the leading/trailing edge height is displayed both for the undisturbed flow upstream of the model (W6) and disturbed flow downstream of the model (W1-W4). The correlation is seen to be strongly reduced in the wake, in which the smaller scale turbulence generated by the bridge deck dominates, which is in line with the reduction of the low frequency content shown in Fig. 11. In the undisturbed flow, the correlation of the along-wind turbulence at lateral separations drops to a value of $\exp^{(-1)}$ at separations corresponding to about one half of the deck width (0.5B). In the wake, one deck width downstream from the trailing edge (W3), the corresponding length scale reduces to about 0.1B.

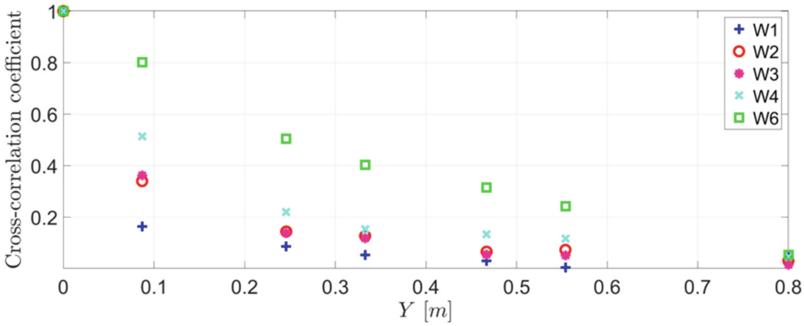


Fig. 12. Cross-correlation coefficient of the along-wind turbulence at the trailing edge height, as a function of lateral separation.

4 Discussion and Conclusion

The comparison of the collocated measurements from the lidars and the Cobra probe shows a good agreement despite a difference observed for the mean vertical velocity component, which is likely linked to the sensitivity of the vertical component to the alignment of the instruments relative to the along wind component.

Some discrepancies between the results from the different instruments can also be seen in the wake profiles which potentially could be attributed to the extended sampling volumes of the lidars in combination with steep gradients in the flow field. However, differences are also seen between the results from the four different Cobra probes indicating that the flow field is varying along the bridge model. This fact, in combination with slightly different measurement locations and separate measurement runs using different tunnel velocity, is also likely to influence the results.

A redistribution of the turbulence spectra due to the flow interaction with the bridge model is illustrated using the Cobra measurement data. In the wake, the deck "signature" turbulence is characterized by higher frequencies and smaller scales compared to those in the inflow. Correspondingly, the observed overall lateral correlation of turbulence is significantly reduced downstream of the model.

The paper describes the measurement campaign and documents an overall good agreement between the flow statistics observed by the Cobra probes and the lidar around a bridge deck model. While more detailed results can be retrieved from the measurement data in future studies, this work demonstrates the potential of lidar remote sensing technology for wind tunnel studies relevant to bridge design.

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