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Full-scale to model-scale comparison of flow conditions downstream of a bridge girder

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SUMMARY:
The paper compares results from two novel measurement campaigns, where lidars are used to study the wake of a suspension bridge deck. In full-scale, a system of three synchronised lidars is deployed to monitor flow conditions one and four deck widths downstream of the deck trailing edge. Corresponding wake measurements are carried out in a boundary layer flow around a 1:15 section model of the bridge girder, exploring the potential of a dual lidar measurement setup for remote wind sensing in a wind tunnel. In full-scale, the lidar wind velocity records are verified against sonic anemometer data, while at model scale, an array of four Cobra probes provides reference measurements. The measurements provide new insights into the wind-bridge interaction, especially in full-scale. Despite some differences between the wind conditions at the bridge site and in the wind tunnel, which influence the bridge aerodynamics, the two experiments demonstrate an overall similarity between the observed wake characteristics in full- and model scale.

Keywords: Continuous-wave wind lidar measurements; Full-scale suspension bridge; Model-scale bridge deck.

1. INTRODUCTION

Remote optical wind sensing technology in recent decades has been mainly developed and applied within the field of wind energy (Hassager and Sjöholm, 2019). This has gradually led to the application of remote sensing to other fields of wind monitoring, including bridge engineering. A promising potential of continuous-wave lidars (light detection and ranging) in resolving wind fields upstream or downstream of the bridge deck has been demonstrated by Cheynet et al., (2016), Cheynet et al. (2017) and Nafisifard et al. (2021). However, a comparison between lidar measurements in a wind tunnel on a model-scale structure (Dooren et al., 2017; Sjöholm et al., 2017; Nafisifard et al., 2023) and its full-scale counterpart has not been done before, which is the motivation of this study.

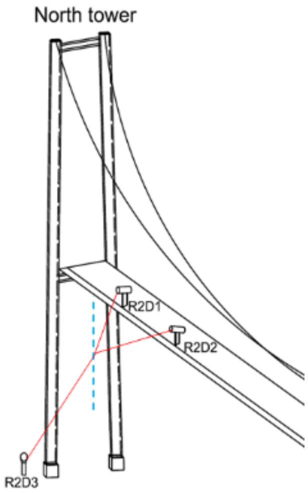
2. INSTRUMENTATIONS AND METHOD

2.1. Full-scale measurements

The measurement setup with three lidars, and a vertical scanning pattern for wake measurements, are illustrated in Fig. 1a. On the bridge deck, two lidars are deployed 36 m apart, while a third lidar is installed 38 m underneath the bridge deck (Fig. 1b), 10.5 m away from the vertical plane with two deck lidars. The hexagonal steel closed-box girder has a width-to-depth ratio of B/D = 4.6 with a width of B = 12.3 m and a depth of D = 2.7 m. The WindScanner system synchronizes the three line-of-sight measurements on a 20-meter-long vertical line separated from the bridge deck's nose by 11 meters. The sampling frequency of 322 Hz is “distributed” throughout a scanning cycle, which corresponds to a sampling frequency of 2 Hz or more for each measurement volume. Data along the vertical line are recorded over an interval of 20 minutes.

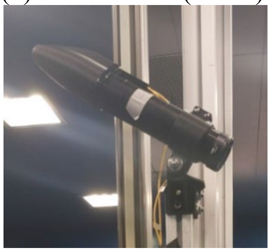
2.2 Model-scale measurements

The 4-m long rigid section model of the bridge deck was fabricated in 1:15 scale, suitable for wake measurements in the large boundary layer wind tunnel of Politecnico di Milano. Spires at the inlet and roughness elements on the floor were used to generate a boundary layer flow with a horizontal turbulence intensity of approximately 10%. Two 2-inch-wide optical telescopes and a single continuous-wave laser were integrated into a dual-lidar system (Fig. 1c and 1d). A traversing mechanism was used to obtain the wake profile one deck width downstream from the trailing edge of the deck model. The flow velocity was measured at several heights above the bridge model trailing edge (3.7H, 2.78H, 1.74H, 0.74H, and 0.3H), at a point at the trailing edge level, and at four points below the trailing edge level (-0.33H, -0.68H, -1.68H, and -2.66H) where H =180 mm is the model deck height. An aerosol generator was used to seed the air with droplets of sufficient concentration required for lidar observations.

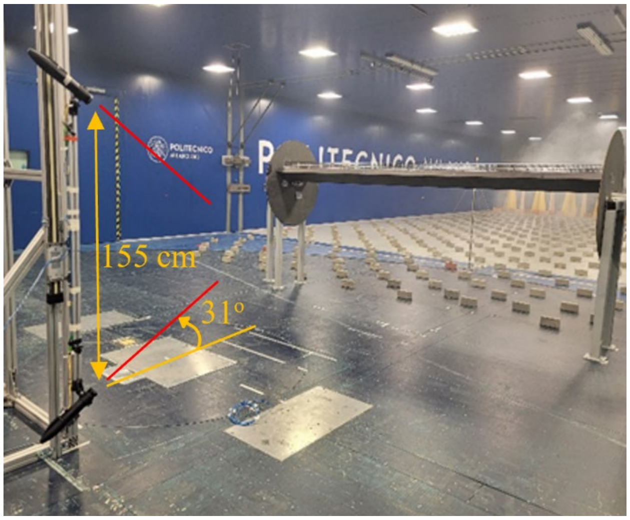


(a) The measurement approach for a vertical line.

(b) Ground lidar (R2D3).



(c) Lidar telescopes.



(d) Two lidar telescopes fixed to a traverse.

Figure 1. Lidar measurement set up in full-scale (a, b) and wind tunnel (c, d).

In the following, the flow characteristics recorded during one selected event in full-scale are compared to the corresponding measurements from the wind tunnel. The wind conditions in the two cases are summarized in Table 1. In full scale, the wind direction has been calculated with respect to the bridge axis, which has a 42° deviation from North.

Table 1. Key parameters for the test cases studied.

Date	Duration	Location	Mean horizontal wind speed	Mean wind direction	Temperature	Along wind turbulence intensity
	(seconds)		$(m.s^{-1})$	(°)	$(°C)$	(%)
2021-09-22	840	Bridge	5.9	63	12.5	9.3
2022-01-13	80	Wind tunnel	6.0	90	20.1	10

3. RESULTS

A comparison between the mean wind velocity profile derived from the lidar data in full scale and model scale, one deck width downstream of the model trailing edge, is given in Fig. 2 (left). In full-scale, a significant downward displacement of the wake centre, associated with a flow inclination angle of -11° is observed, likely due to the influence of the local mountainous terrain. The velocity values are normalized by the horizontal mean wind speed recorded in undisturbed flow at Z = 10 m in full scale which corresponds to Z = 667 mm in model scale. The wake profile in full-scale is seen to be embedded in a more uniform flow, compared to a more sheared boundary layer flow in the wind tunnel. Overall, the mean velocity profiles agree. For a more direct comparison of the velocity deficit regions, the full-scale profile is also shown elevated by 1.5 m in Fig. 2 (right).

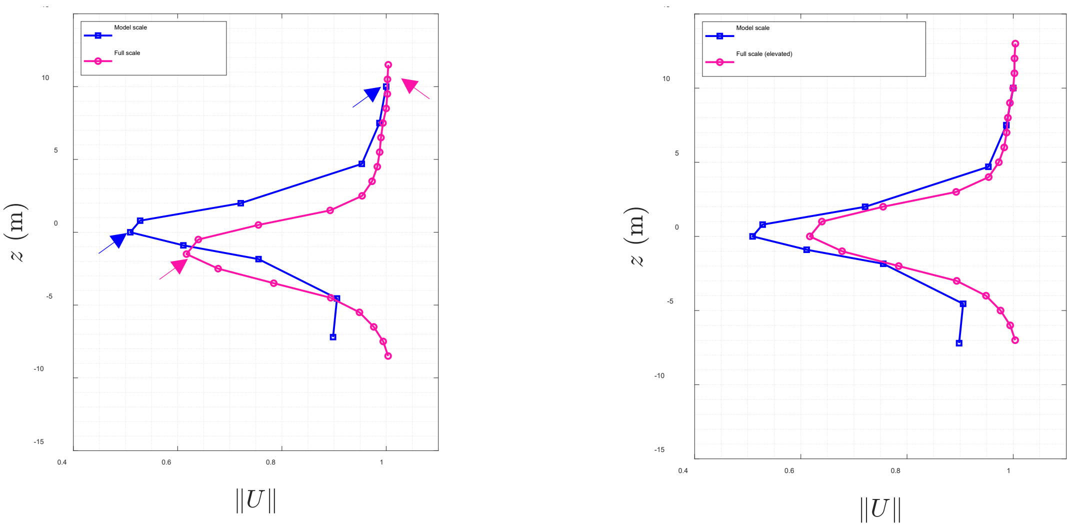
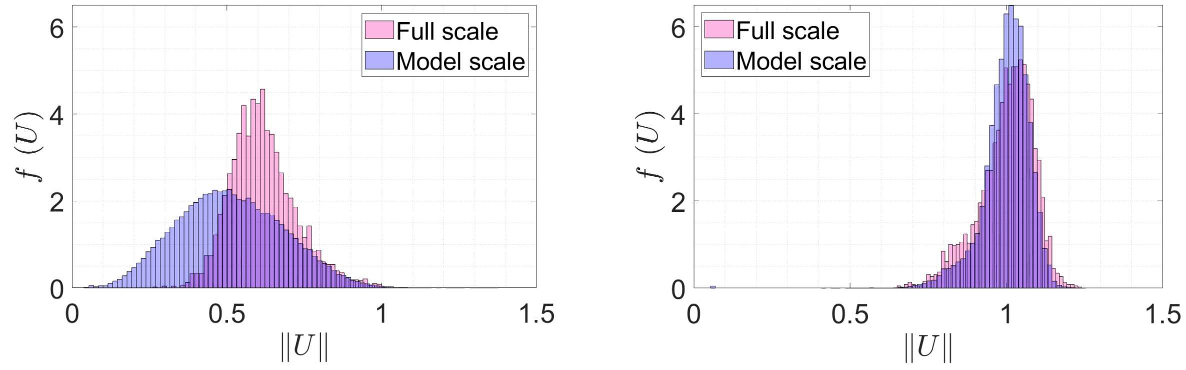


Figure 2. Normalized mean along wind velocities recorded by lidars one deck width downstream of the bridge/model trailing edge. The arrows indicate the locations used for the velocity distributions shown in Fig 3.

The histograms of the along-wind (U) velocity components measured by lidars, inside (disturbed flow) and outside of the wake (undisturbed flow), are displayed in Fig. 3. The corresponding points are marked by arrows in Fig 2 (left panel). The velocities are normalized by the along-wind mean speed at Z = 3.6H (10 m) in full-scale and Z = 3.7H (667 mm) in model-scale, respectively. In the undisturbed flow, turbulence variations are confined to a relatively small range of velocity values compared to the distributions for the disturbed flow. A broader range of values in the disturbed flow indicates an increased variability in the local flow velocities in the wake, related to unstable shear layers and a vortex-shedding process.



(a) (b)

Figure 3. Histogram of normalized along-wind (U) velocity components recorded in full-scale and model-scale, for the disturbed flow (a) and undisturbed flow (b) one deck width downstream from the trailing edge.

4. CONCLUSIONS

In this study, the WindScanner system was successfully used to study the 3D turbulence past a suspension bridge deck in full-scale and a corresponding dual-lidar system used for 2D studies in model-scale. While this unique comparison indicates an overall consistency between the wake conditions at the two scales, more importantly, it demonstrates a valuable potential of remote wind sensing for bridge aerodynamics studies, particularly in full-scale.

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