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Triple-lidar observations of flow around a bridge deck

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SUMMARY:
The paper presents results of a lidar measurement campaign investigating the wind at a bridge site and its interaction with a suspension bridge girder. The measurements, carried out at the Lysefjord Bridge wind and vibrations laboratory in Norway, build on a former study with a dual lidar WindScanner system. The novelty of the present investigation is the deployment of three synchronized lidars, two on the deck and one close to the foundation of the bridge tower, enabling a three-dimensional characterization of the turbulent flow. The scanning patterns are tailored to explore the spatiotemporal characteristics of the wind field upstream of the bridge, as well as the disturbed flow downstream of the bridge deck. The lidar wind velocity records are verified against sonic anemometer data recorded on the bridge. The local wind characteristics around the bridge deck, derived from the lidar measurements, provide new insight into the wind-bridge interaction in the natural wind, in a complex fjord topography.

Keywords: Wind turbulence, Lidar measurements, Suspension bridge, Full-scale.

1. INTRODUCTION

The potential of remote wind sensing using lidars (light detection and ranging) to complement measurements at a bridge site, traditionally performed with anemometers fixed to a measurement mast, has been explored by Cheynet et al. (2016), Cheynet et al. (2017a), and Nafisifard et al. (2021). The data in Cheynet et al. (2016) was acquired by a dual-lidar system installed at the Lysefjord bridge in Norway during a one-week period. The present work introduces a new lidar measurement setup on the bridge using a triple-lidar system to resolve all three turbulence components. The triple-lidar campaign took place over a three-month period, from August to October 2021.

2. INSTRUMENTATION AND METHOD

In Fig. 1, the measurement setup with three lidars is visualized, together with the adopted scanning patterns. Two of the lidars are deployed on the bridge deck, 36 m apart, and a third lidar is close to the tower foundation 38 m below the bridge deck, 10.5 m from the vertical plane defined by the two deck lidars. The bridge girder is formed as a hexagonal closed-box in steel, with a width-to-depth ratio of $B/D = 4.6$, where $B = 12.3$ m and $D = 2.7$ m.

The WindScanner lidar system (Angelou et al., 2021) synchronizes the line-of-sight measurements by three lidar units, which target a common steerable measurement "point". Three scanning patterns adopted as part of a scanning cycle repeated once every 90 minutes are illustrated in Fig. 1. The 20 m long vertical and horizontal scanning lines are separated from the nose of the bridge deck by 11 m, and a bow-tie pattern in a vertical plane parallel to the bridge axis by 39 m from the deck leading/trailing edge. The bow-tie pattern has a 60-meter-long vertical part, an 80-meter-long horizontal part and two inclined segments, all enabling a study of turbulence characteristics for separations of different sizes and orientations.

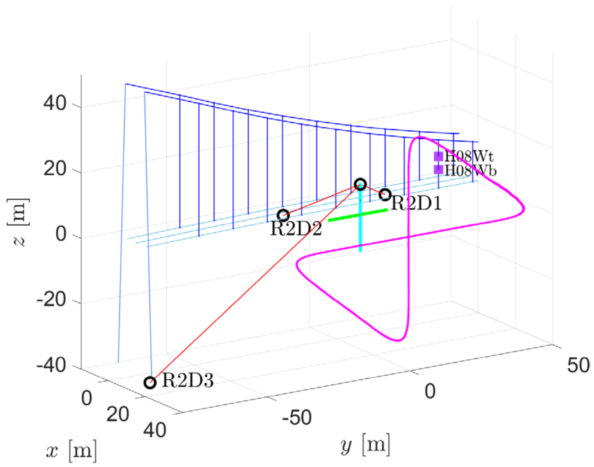

Figure 1. Lidar measurement setup.

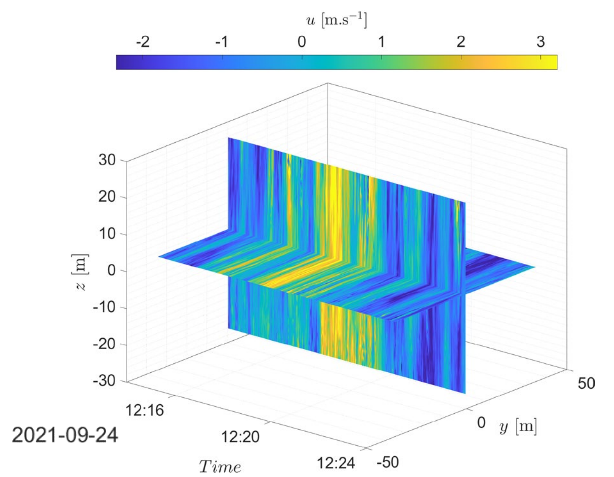

Figure 2. Along-wind turbulence 39 m upstream of the bridge recorded on 24.9.2021.

3. RESULTS

3.1. Wind field upstream and downstream of the bridge

A view of the along-wind turbulence of the upstream flow is shown in Fig. 2, illustrating the WindScanner data for the horizontal and vertical segments of the bowtie pattern 39 m upstream of the deck, for an 11-minute-long period starting at 12:13 on Sept 24, 2021. The data are found to agree well with the sonic anemometer data simultaneously recorded on the upstream side of the bridge (for brevity, a comparison is not included here). The associated vertical profile of the mean wind speed has a gradient corresponding to a surface roughness of $z_0 = 0.05$ m. The mean wind direction was around 225° from the North, approaching the bridge from the fjord inlet in SW, more or less perpendicularly to the bridge axis.

For an opposite wind direction, the mean flow characteristics observed along the vertical line 11 m downstream of the trailing edge are presented in Fig. 3, in terms of the horizontal velocity component perpendicular (V_x) and parallel to the bridge (V_y), the total wind speed (U) and the vertical wind speed (W). The associated wind directions referring to the bridge axis (γ) and the inclination angle (δ) are also illustrated, as well as the sonic anemometer recordings at $\Delta_x = -11$ m (deck trailing edge position) and $\Delta_y = 36$ m from the vertical scanning line. Excellent agreement between the lidar and the sonic anemometer data is found, except for the mean vertical velocity component and the associated inclination angle. The related data along the bowtie scanning pattern, showed an additional displacement of the wake centre to a lower height, consistent with an inclination angle of -11°. Regarding the wind direction in the horizontal plane (γ), a flow "veering" of about 10° towards the bridge axis (reduction of γ from 60° to 50°) is observed, associated with a larger deficit in the V_x component in the wake relative to that of V_y.

The wind profiles displayed in Fig. 3, illustrate the disturbed flow regions downstream of the bridge deck. The wind-deck interaction is also reflected in terms of increased turbulence intensities in the wake, as well as the coherence, which is different from that in undisturbed flow.

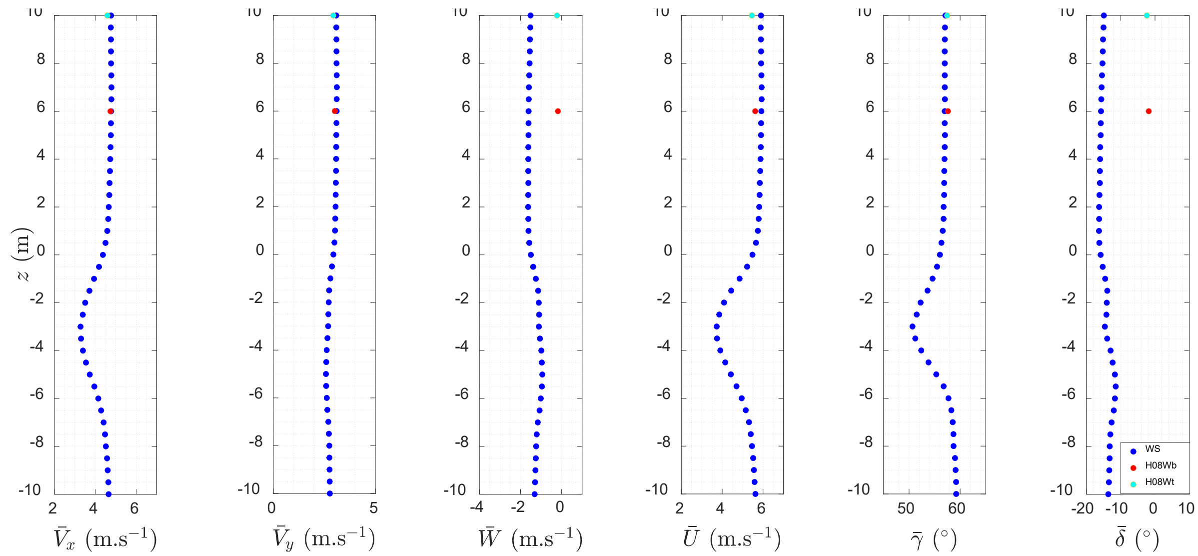

Figure 3. Wind profiles measured by the WindScanners along the vertical line 11 m downstream of the bridge deck compared to the simultaneous sonic anemometer data at Δ_x = -11 m and Δ_y = 36 m from the scanning line.

3.2. Coherence upstream and downstream of the bridge

In Fig. 4, the coherences of the along-wind velocity in two different parts of the vertical scanning line located about 1B downstream of the bridge are compared. The left panels display the coherence for the velocity observed at points inside the wake, at z = -5 m and z = -1 m, while the right panels are for the coherence between velocities outside the wake, at z = 6 m and z = 10 m. The cross-correlation coefficients in the two cases are -0.4 and +0.6 respectively. The coherence values are smoothened by applying a moving average function with a window length of 10 data points. They are displayed as a function of frequencies normalized by the ratio of the deck height (2.76 m) and the undisturbed along wind velocity (6 m/s) recorded by WindScanners at the highest altitude of the scanning line.

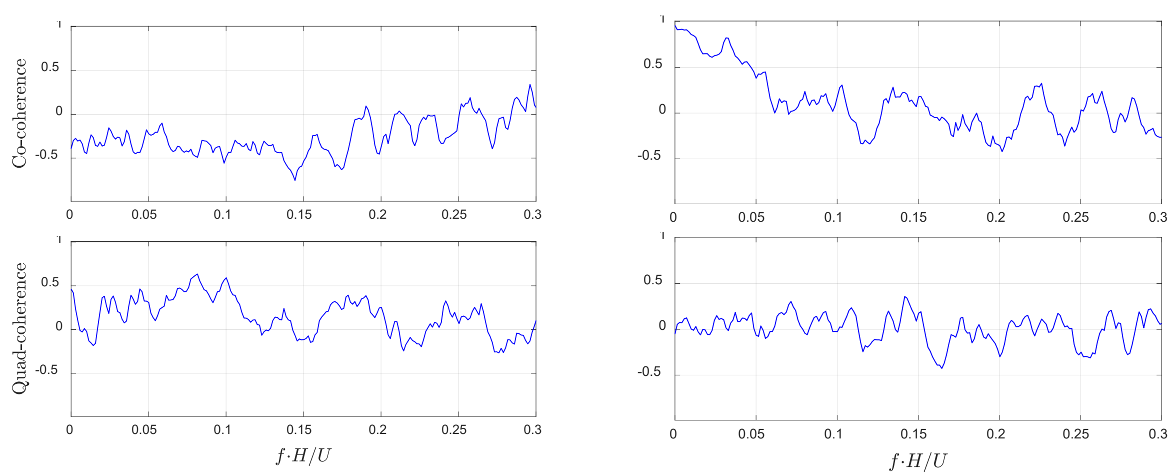

Figure 4. Co-coherence (top), Quad-coherence (bottom) of the along-wind velocity inside the wake (left panels) and outside the wake (right panels), measured by the WindScanners line ~1B downstream of the bridge.

Inside the wake, the co-coherence is negative at reduced frequencies up to 0.2, indicating an alternate increase and decrease of the velocities in upper and lower part of the wake, whereas the wake-free region at the top of the scanning pattern has a positive co-coherence at small reduced frequencies. The wake can also be distinguished by looking at quad-coherence, which shows positive values for wake-embedded heights up to reduced frequencies of 0.2, whereas the quad-coherence for undisturbed flow fluctuates around zero for the lower reduced frequency range.
The co-coherence in the undisturbed part of the vertical line one deck-width downstream of the bridge is comparable to the one estimated during the event shown in Fig. 2. This is demonstrated in Fig. 5, which displays the average lateral and vertical co-coherence of the inflow along-wind turbulence for a 15-m-long separatism-each direction of the bow-tie pattern. The vertical coherence appears to be slightly lower than the lateral one, but further data analysis is needed to establish a more reliable trend. For comparison, the coherence function provided in NEK IEC 61400-1, 2007 associated with an exponential decay coefficient of -12 is included.

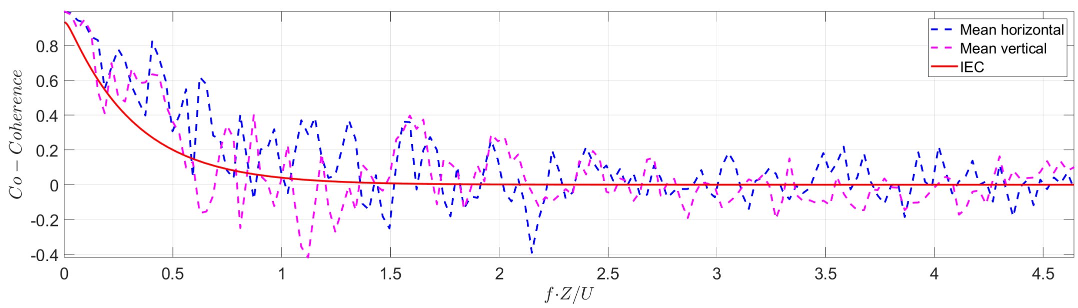

Figure 5. Co-coherence of the along-wind turbulence 39 m upstream (3.6B) of the bridge deck.

4. CONCLUSIONS

A system of three synchronized continuous-wave lidars was successfully implemented to study the 3D turbulence around a suspension bridge deck in a complex fjord terrain. The recorded data give new insight into the approaching flow characteristics as well as the interaction between the wind flow at the bridge site and the bridge deck. One bridge deck width downstream of the bridge girder, the mean velocity deficit is clearly identified, associated with increased turbulence levels and a negative co-coherence.

ACKNOWLEDGEMENTS

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