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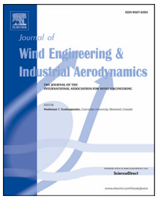

Evaluation of mast measurements and wind tunnel terrain models to describe spatially variable wind field characteristics for long-span bridge design

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ABSTRACT

The quality of the information about the wind field characteristics is crucial for accurately predicting the structural response of a long-span bridge subjected to dynamic wind loads. In this paper, in situ mast measurements and terrain model wind tunnel tests are compared with full-scale measurements of the wind field along the Hardanger Bridge girder. The aim is to investigate the performance of mast measurements and wind tunnel terrain model tests in predicting the wind field characteristics for long-span bridges in complex terrains. Wind field spatial variations and statistical distributions for the mean wind velocity and turbulence intensity are investigated. Extreme value statistics have been applied to compare the mean wind velocity recordings from two different measurement periods. Results showing terrain-induced effects on the wind directions, turbulence intensities and mean wind velocities are presented. Simultaneous spanwise wind profiles for the mean wind velocity and along-wind turbulence intensity are compared between the terrain model wind tunnel tests and the full-scale measurements, and large nonuniformities are identified. The extreme profiles of the turbulence intensities vary as much as 100% along the span, and the mean wind velocity profiles vary up to 50% along the span.

1. Introduction

The Norwegian government is planning a new highway along the west coast of Norway to reduce traveling time between four of the largest cities. The Norwegian west coast is dominated by a terrain with deep fjords and tall, steep mountains, and a highway in this complex terrain demands crossing fjords as wide as 5000 m and as deep as 1300 m with fixed bridge connections. Other extreme crossings are also being proposed around the world, such as the Messina Strait and the Strait of Gibraltar, which pose large engineering challenges. The design for dynamic environmental loads is critical for such structures, and some of the methods used for the design of past bridge structures may not account for the challenges of these extreme projects.

For long-span bridges where the response from dynamic wind loading is dominating the load effects relevant for design, the quality of the information about the wind field characteristics available for the design calculations will govern the achieved structural reliability. In complex inhomogeneous terrain, the spatial variability of the statistical distributions for the wind field parameters can be large. In situ mast measurements and wind tunnel terrain model tests are currently the main approaches used to investigate the local wind field characteristics for long-span bridge design purposes. Other methods such as computational fluid dynamics (CFD) and LIDAR technology are also becoming increasingly attractive as computer performance is increasing and further development is progressing, but the traditional methods will also be important in the future. Mast measurements can be used to record the variability of the local wind field at a single point, and wind tunnel terrain model tests can be used to investigate the spatial transfer of the turbulence characteristics from the mast position to the bridge span. There are a few wind tunnel terrain model experiments for bridge design purposes presented in the literature (Hui et al., 2009a, 2009b, Li et al., 2010, 2015), but there is still a need to investigate this method's ability to spatially transfer mast measurements to the bridge span through studies comparing terrain model results with full-scale measurements, especially in complex terrain.

Design calculations of the dynamic bridge response due to stochastic wind loads are still mainly based on the buffeting theory first introduced by (Davenport, 1962) and improved by (Scanlan, 1978a, 1978b; Scanlan

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and Tomko, 1971). Many full-scale bridge measurement campaigns have been performed to verify the performance of the buffeting theory (Bietry et al., 1995; Brownjohn et al., 1994; Cheynet et al., 2016; Cross et al., 2013; Fenerci et al., 2017; Fenerci and Øiseth, 2018, 2017; Macdonald, 2003; Miyata et al., 2002; Wang et al., 2011, 2013; Xu, 2013), with some campaigns finding good agreement and others finding significant discrepancies. In traditional design approaches, based on a short-term stationary and homogeneous wind field assumption, the turbulence characteristics are commonly chosen as deterministic parameters, although a significant variability in the measured wind field characteristics and bridge responses are presented in several of the referred full-scale measurement campaigns (Fenerci et al., 2017). have shown that it is possible to account for most of the measured response scatter if detailed information about the variability in the wind field parameters is available. More advanced methods such as probabilistic design approaches (Ciampoli et al., 2011; Davenport, 1983; Kareem, 1988; Pagnini, 2010; Pagnini and Solari, 2002; Solari, 1997; Spence and Kareem, 2014; Zhang et al., 2008) or long-term extreme response analysis (Xu et al., 2017) are able to account for the variability in the load to a greater extent, but these methods rely on a more complete statistical description of the load than that used in the traditional methods. Without the bridge in place, the statistical distributions for the wind field parameters can be achieved by mast measurements close to the bridge span, but this approach will rely on the ability to spatially transfer the full statistical distributions to the bridge span.

Several studies in the literature have undertaken the long-term monitoring of turbulence characteristics, thus contributing to the understanding of wind field characteristics in different topographies. Most of the measurement campaigns have been located in typhoon- and monsoon-dominated areas, such as the work performed by (Cao et al., 2009; Choi, 1978; Li et al., 2015; Wang et al., 2017), and have consisted of full-scale bridge monitoring campaigns such as (Hu et al., 2013; Hui et al., 2009a, 2009b; Miyata et al., 2002; Wang et al., 2013, 2011, 2009, 2014). Additionally, for European conditions, many wind field characterization studies can be found in the literature (Bietry et al., 1995; Bocciolone et al., 1992; Brownjohn et al., 1994; Cheynet et al., 2016; Cross et al., 2013; Fenerci et al., 2017; Fenerci and Øiseth, 2018, 2017; Harstveit, 1996; Macdonald, 2003). Although all these studies provide valuable insights, most of them have been based on very few wind sensors (some only measured the wind field characteristics at a single point) that are unable to describe spatial variations in the wind field (Burlando et al., 2013). address the problem of spatially transferring measured wind velocities to a target site using CFD, but on a less detailed scale than what is necessary for terrains that exhibit extreme complexity. For long-span bridge design purposes, there is still a need for studies investigating spatial variations of wind velocities and turbulence characteristics, especially in complex terrain where terrain-induced variations can be large.

In the years prior to the construction of the Hardanger Bridge, in situ mast measurements and wind tunnel terrain model tests were performed to investigate the local wind field characteristics at the bridge site. Since the opening of the bridge in 2013, the Norwegian University of Science and Technology (NTNU) has been monitoring the wind field along the bridge girder using 8 ultrasonic anemometers. This paper is an extension of the preliminary results presented at the European-African Conference on Wind Engineering in 2017 (Lystad et al., 2017). In this paper, we study the spatial variations in the statistical distributions for mean wind velocity and along-wind turbulence intensity at the Hardanger Bridge site and the performance of the traditional wind field characterization methods for describing these statistical distributions along the bridge span in complex terrain.

In section 2 the measurement campaigns used in this study are introduced, and in section 3 flow patterns at the bridge site are interpreted using wind directionality effects as basis. Section 4 investigates the spatial transfer of the mean wind velocity extreme value distributions and the probability density function of the along-wind turbulence intensity between the mast and along girder anemometers. In section 5, spanwise simultaneously measured profiles for mean wind velocity and along wind turbulence intensity from the full-scale measurements are compared with spanwise profiles identified in the wind tunnel terrain model test. Finally, in section 6 conclusions and some recommendations for the use of the investigated methods are presented.

2. Wind field measurements

The Hardanger Bridge is a suspension bridge with a main span of 1310 m, making it the longest bridge span in Norway. The bridge crosses the Hardanger fjord, which is located in complex terrain surrounded by high, steep mountains. The surrounding terrain is extreme, but it is typical for the fjord landscape along the coastline of Norway.

2.1. *Full-scale monitoring campaign*

After the bridge was opened to the public in 2013, it was instrumented with a state-of-the-art monitoring system measuring wind field characteristics and acceleration responses along the bridge girder. The monitoring system consists of 20 triaxial accelerometers and 9 ultrasonic triaxial anemometers, of which 8 are distributed along the span. An overview of the wind monitoring system is shown in Fig. 2, and the system is described in more detail in (Fenerci et al., 2017).

2.2. *Mast measurements*

During 1988–1992, the Norwegian Meteorological Institute placed a wind measurement mast on the headland Buneset, close to the southern end of the bridge, to measure the local wind field characteristics for the design of the Hardanger Bridge. Buneset is a headland extending into the fjord with an elevation of 110–130 m above mean sea level. As this headland is relatively flat and the surroundings are steep and complex, Buneset was a suitable position for the mast placement. Fig. 1 shows Buneset on the left in the picture (south), and Fig. 3 shows a picture of the bridge taken from the headland. The mast was instrumented with wind sensors at three levels, 10 m, 30 m and 45 m above ground. The results from the mast measurements are reported by (Harstveit, 1994) and discussed further by (Harstveit, 1996). In (Harstveit, 1994), it was concluded that the sensors at the two lowest levels were disturbed by the forest vegetation on the headland, so the results from these sensors were discarded. They noted that some disturbance may also be present for the 45 m sensor, affecting both the recorded turbulence intensity and the mean wind velocity. The results from the 45 m sensor were used for the design of the Hardanger Bridge, and these results are also used in the present study.

The elevation of the highest sensor (approximately 155–175 m above mean sea level) is also a concern for representing the wind field characteristics along the bridge girder (60 m above mean sea level). The effects of relative elevation, wind speed-ups as the wind flows over the headland, and differences in surface roughness are important factors for the spatial transfer of the wind field characteristics from the mast to the bridge girder.

2.3. *Terrain model tests*

To quantify the wind field differences between the mast position and the bridge girder and to investigate the spanwise effects such as wind field profiles and covariance, a 1:2000 scale terraced terrain model of the Hardanger Bridge surroundings was tested in the boundary layer wind tunnel at NTNU. The tests were performed by the Department of Energy and Process Engineering at NTNU in 1991, and the results were reported by (Sætran and Malvik, 1991). The boundary layer wind tunnel at NTNU is a closed-circuit wind tunnel with a test section that is 11 m long, 2.7 m wide and 1.8 m high with a maximum wind speed of 30 m/s. Hot-wire anemometers were used in the experiments to measure the along-wind