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Strong wind characteristics and dynamic response of a long-span suspension bridge during a storm

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ABSTRACT

As Storm Tor struck the western coast of Norway, wind speeds and bridge deck accelerations along the Hardanger Bridge girder were recorded by the monitoring system installed on the bridge. Using 13.5 h of data, mean wind speed, turbulence intensities, gust factor, turbulence length scales, angle-of-attack, and one-point and two-point turbulence spectra are studied using 10-minute stationary averaging intervals. Using the measured turbulence statistics as inputs, the buffeting response of the bridge deck is calculated in the frequency domain. The calculated response is compared with the measured response in terms of the root-mean-square (RMS) of acceleration and displacement components and the power spectral density of the acceleration response. Significant discrepancies are found in the case of the vertical response. Predicting the spectral response is found to be more difficult than predicting the RMS response, in particular for high-frequency responses. Considering the spanwise non-uniformity of turbulence statistics did not affect the predictions significantly.

1. Introduction

In Norway, Coastal Highway E39 lies along the western coast and connects Trondheim to Kristiansand in southern Norway, eventually reaching Aalborg in Denmark. Today, a drive on the 1100 km highway from Trondheim to Kristiansand is interrupted by seven ferries, which results in a travel time of approximately 21 h. The western coast is the most economically active region of Norway, where the majority of export goods are transported along the E39 route. Therefore, it is desirable to decrease travel time by replacing the ferry connections with bridges or subsea tunnels. This would involve crossing seven fjords ranging between 1500 and 5000 meters wide and between 600 and 1500 meters deep; for this purpose, bridges of unmatched scale would have to be built. Feasibility studies concerning such large scale bridge projects are being conducted by the Norwegian Public Roads Administration (NPRA) (Ellevset and Skorpa, 2011). The focus is mainly given to the largest crossings (Sognefjørden 3.7 km, Bjørnafjørden 5 km). Different bridge concepts such as super long-span suspension bridges, multi-span suspension bridges with floating towers and pontoon bridges are being considered for the crossings. As the global demand for longer span cable-supported bridges grows, design of such structures against wind effects becomes increasingly important.

Field measurements of mean wind speed and turbulence are indispensable in characterization of the wind turbulence field for design of long-span bridges against gusty wind action. Owing to the increasing number of measurement campaigns (Brownjohn et al., 1994; Cao et al., 2009; Cheynet et al., 2016; Choi, 1978; Cross et al., 2013; Hui et al., 2009a,b; Macdonald, 2003; Miyata et al., 2002; Wang et al., 2017) and structural health monitoring projects with wind measurements (Wang et al., 2009, 2011, 2013, 2014; Xu, 2013) around the world, more and more data on wind turbulence characteristics have been presented by researchers (Harstveit, 1996; He et al., 2013; Hu and Ou, 2013; Li et al., 2015; Peng et al., 2013). Such works provide valuable information on the general characteristics of the wind field (stationarity, homogeneity, and one-point and two-point statistics) at specific sites. Information regarding site-specific features, terrain effects and variability of the wind field are also beneficial in understanding the nature of gust loading on such structures (Pagnini and Solari, 2002; Solari and Piccardo, 2001). However, most of the listed studies concentrate on the Asia and Pacific with a focus on typhoon winds. Therefore, more data on the strong wind characteristics of European windstorms from relevant sites, such as Norwegian fjords, are required.

Stochastic dynamic analysis of wind-induced vibrations of cable-supported bridges was first introduced by Davenport (1962) and then improved by Scanlan (1978) with the introduction of flutter derivatives in the description of self-excited forces (Scanlan and Tomko, 1971).

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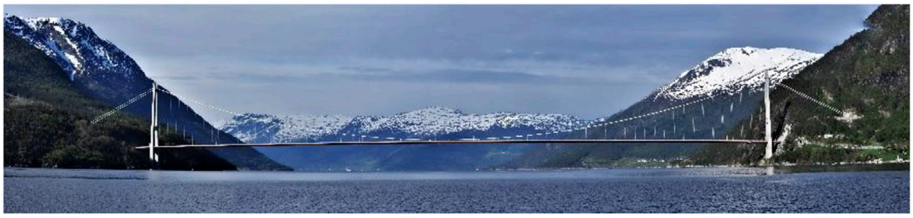

Fig. 1. Panoramic view of the Hardanger Bridge toward the west (photograph by Aksel Fenerci/NTNU).

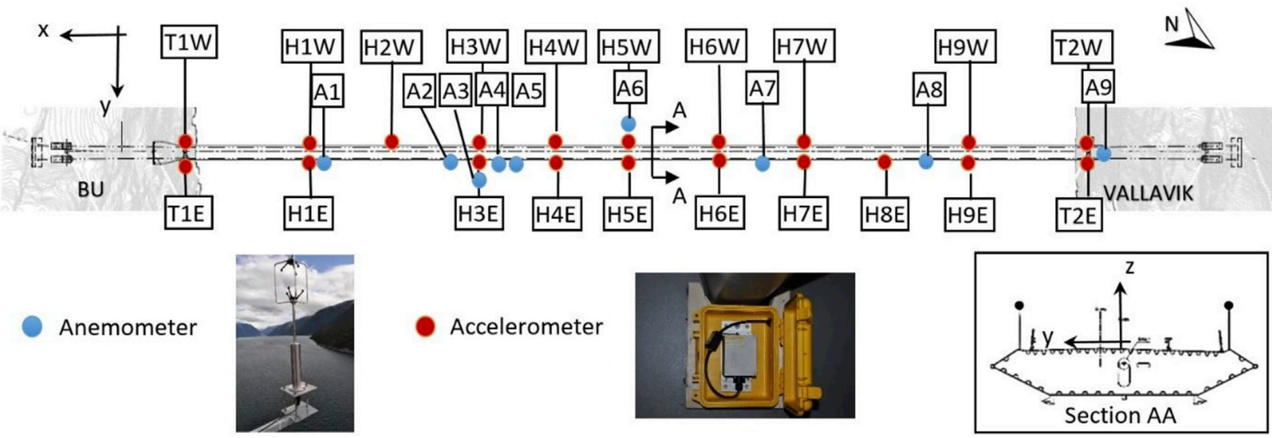

Fig. 2. The sensor layout.

Today, a multimode coupled approach (Chen et al., 2001; Jain et al., 1996; Katsuchi et al., 1998; Øiseth et al., 2010; Xu et al., 2000) is commonly used, where analysis may be conducted in either the frequency or time domain. Analyses considering skew-winds (Kimura and Tanaka, 1992; Wang et al., 2011; Xie et al., 1991; Xu et al., 2003; Xu and Zhu, 2005a; Zhu and Xu, 2005), full-bridge models (Xu et al., 2000) and spanwise non-uniform winds (Hu et al., 2017) were conducted by researchers. In recent years, non-stationary wind models have also been adopted by many (Chen et al., 2007; Chen, 2015; Hu et al., 2013, 2017; McCullough et al., 2014; Tao et al., 2017; Wang et al., 2016; Xu and Chen, 2004). Despite analytical efforts, few attempts have been made toward validation of these methods using full-scale measurements (Bietry et al., 1995; Cheynet et al., 2016; Macdonald, 2003; Park et al., 2012; Wang et al., 2011, 2013; Xu and Zhu, 2005b). Although satisfactory predictions were obtained by some, significant discrepancies were also observed, especially in the case of complex terrain, where the wind is variable, nonstationary and not homogenous. Moreover, the amount of data used for comparison is in general limited, especially under strong winds. Clearly, more comparisons, preferably from strong wind recordings, are needed for a better understanding of the limits of such analyses and the uncertainty involved, as well as the sources of uncertainty.

This paper concentrates on the strong wind characteristics and dynamic response of the Hardanger Bridge during a storm event. General information on wind conditions at the site and the bridge response were addressed in Fenerci et al. (2017), Fenerci and Øiseth (2017) and Fenerci and Øiseth (2016a,b). The wind speeds and accelerations at several locations along the bridge deck were measured by a dense sensor network. The wind turbulence statistics during the storm are presented using 10-sminute averaging intervals. Using the measured turbulence statistics, the wind field along the bridge is modeled separately for each interval, and the dynamic response is calculated accordingly. The measured and calculated dynamic responses are then compared, and the results are discussed.

Table 1
Sensor names and coordinates.

Wind sensors				Accelerometers			
Name	x (m)	y (m)	z (m)	Name	x (m)	y (m)	z (m)
A1	460	7.25	0.3	H1E/H1W	480	6.33/-6.64	−8.38
A2	280	7.25	3.2	H2W	360	−6.64	−6.41
A3	240	7.25	3.9	H3E/H3W	240	6.33/-6.64	−4.45
A4	200	7.25	4.6	H4E/H4W	120	6.33/-6.64	−2.48
A5	180	7.25	4.9	H5E/H5W	−7	6.33/-6.64	−0.4
A6	−10	−7.25	8	H6E/H6W	−120	6.33/-6.64	−2.25
A7	−180	7.25	5.2	H7E/H7W	−240	6.33/-6.64	−4.22
A8	−420	7.25	1.2	H8E	−360	6.33	−6.18
A9	−655	4.5	140	H9E/H9W	−480	6.33/-6.64	−8.15
				T1E/T1W	655	4.5/-4.5	120.5
				T2E/T2W	−655	4.5/-4.5	120.5

2. Hardanger Bridge and the monitoring system

The Hardanger Bridge (HB) is currently the longest suspension bridge in Norway with a single span of 1308 meters (Fig. 1). It is located in mountainous terrain in Norwegian fjords and is subjected to strong European windstorms. The unique wind exposure of the site and the slender deck of the bridge make it an attractive case study when investigating the wind-induced dynamic response of long-span suspension bridges in such complex terrain. For this reason, shortly after the bridge was opened to the public in 2013, it was instrumented by a state-of-the-art monitoring system to measure wind velocities and accelerations along the girder. The system is comprised of 20 accelerations and 9 anemometers, where the data is transferred on the bridge by Wi-Fi and synced by GPS time. The sensor layout is shown in Fig. 2, and the coordinates of each sensor are listed in Table 1, where the origin of the coordinate system was taken as the midspan of the bridge. Detailed information on the HB and the workings of the monitoring system can be found in Fenerci and Øiseth (2017).