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Coupled aerodynamic and hydrodynamic response of a long span bridge suspended from floating towers

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A R T I C L E I N F O

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A B S T R A C T

The present study introduces a fully coupled time-domain analysis of a multi-span suspension bridge supported by two floating towers, considered for crossing the wide and deep fjords along the west coast of Norway. The time-domain analysis is performed with a finite element model considering simultaneously the turbulent wind, irregular inhomogeneous ocean waves and sheared ocean current. The numerical results suggest that under extreme conditions with a return period of 100 years, the bridge horizontal response is dominant and governed by the low-frequency modes. For the vertical and torsional responses, the largest contributions are due to the respective motion components of the low-frequency horizontal motion-dominated modes. The investigation into the significance of the aerodynamic and hydrodynamic load reveals that in the case studied, over 80% of the bridge girder response is due to the aerodynamic excitation. The hydrodynamic loads acting on the floating towers are small due to a relatively small significant wave height in the fjord and the counteracting aerodynamic damping effect. By considering the inhomogeneity of the waves, i.e. different conditions at the two floating supports, the contribution of the aerodynamic action to the lateral, vertical and torsional dynamic responses increases by 6%, 7% and 9% respectively.

1. Introduction

The Norwegian Public Road Administration (NPRA) is considering suspension bridges on floating foundations as one of the feasible concepts to cross the deep (0.5–1.2 km) and wide fjords (up to 5 km) in Western Norway (Samferdselsdepartement, 2017). Such bridges will have eigen-frequencies as low as 0.01 Hz and will thus be extremely sensitive to wind loading. In addition, the floating tower supports will be excited by the hydrodynamic loading, so that the floating bridge structural analysis becomes a fully coupled aero-hydrodynamic problem.

The buffeting theory introduced more than 50 years ago by Davenport (1961) and further developed by e.g. Scanlan (1978) is a standard approach to evaluate the bridge dynamic response due to wind turbulence, which is one of the governing design factors for a long-span bridge in the ultimate limit state (ULS). The estimation of the buffeting response has been extensively studied in both the frequency-domain (Bietry et al., 1995; Lin and Yang, 1983; Macdonald, 2003; Xu and Zhu, 2005), and the time-domain (Aas-Jakobsen and Strømmen, 2001; Borri et al., 1995; Chen et al., 2000; Costa et al., 2007; Diana et al., 2008; Svensson and Kovacs, 1992; Wang et al., 2010). The estimated buffeting response has further been attempted to be validated through full-scale measurements (Bietry et al., 1995; Cheynet et al., 2016; Fenerci and Øiseth, 2017; Macdonald, 2003; Wang et al., 2010; Xu and Zhu, 2005). The global hydrodynamic analysis of a single offshore structural system like a tension-leg platform (TLP), comprising slender structural elements like tethers and risers, is a relatively standard procedure according to design guidelines (DNV, 2010, 2011), which has been investigated extensively in frequency-domain and time-domain numerical simulations (Bachynski, 2014; Kim et al., 2001; Masciola, 2011). Additionally, there are topics like higher-order wave forces (e.g. springing and ringing loads), which are challenging to predict accurately in numerical simulations due to their strongly non-linear nature (Faltinsen et al., 1995; Gurley and Kareem, 1998; Marino et al., 2015; Paulsen et al., 2014). These higher-frequency loads are however essential for predicting fatigue life of TLP tendons and risers (Bachynski and Moan, 2014; Petrauskas and Liu, 1987). There are also other load components, like the low-frequency drift damping of the TLP hull and the viscous damping of the slender structures, which should preferably be validated or determined through experiments (DNV, 2010).

For a floating bridge concept devised to cross deep and wide fjords, a

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recent design basis report (Borge et al., 2015) describes the co-existence of the wind, the wind-generated waves, swells and ocean current in one of the Norwegian fjords. Because of the local fjord topography, both wind-generated waves and swells, have a significant wave height and period that varies across the fjord, the wave conditions are defined as inhomogeneous. For the case of the Sulafjord studied in this paper, the islands outside the fjord provide wave sheltering effects. Accordingly, the significant wave height will be much larger at the northeast side of the fjord than at the southwest. The inhomogeneity of the waves should thus be considered when assessing the wave load effects. It is also important to account for the combined simultaneous aerodynamic and hydrodynamic actions, to properly include the structural motion-dependent loads. The motion-dependent loads comprise the self-excited aerodynamic forces on the bridge superstructure and the motion-induced hydrodynamic forces on the floater and the slender structural elements connecting the floater to the seabed. Due to the complexity and novelty of such a megastructure, there is a limited literature available on the coupled analysis considering large volume floater hydrodynamics, slender structure hydrodynamics and bridge aerodynamics. Nesteby et al. (2015) performed a feasibility study on the concept of a multi-span floating suspension bridge for the Sulafjord, in which the bridge response under separated aerodynamic and hydrodynamic actions was calculated by using two different software packages. The simple transfer functions between the wind/wave excitation and the bridge response were constructed to address the combined load effect. However, the coupling effect of the aerodynamic and hydrodynamic loads is neglected. Lie et al. (2016) used the software package SIMO/Riflex/SIMA for preliminary feasibility studies on different floating bridge concepts, where the wind action is simplified as a static load and only the homogeneous wave condition can be specified in SIMO. Wei et al. (2017) proposed a frequency domain hydroelasticity method in which the continuous floating structure was discretized into rigid modules connected by elastic beams, and inhomogeneous wave conditions at different module were applied individually. The results indicate that the inhomogeneity of the regular waves may induce larger maximum vertical bending moment to the structure compared to a homogeneous wave field along the structure.

This paper focuses on the overall bridge response under extreme environmental conditions, as well as the contributions from different excitation sources, to reveal the dominant design action for a floating bridge of this type. For this purpose, a fully coupled aero-hydrodynamic numerical tool is developed. A finite element model is integrated with a load model considering the simultaneous excitation from turbulent wind, inhomogeneous irregular ocean waves and the sheared ocean current.

2. The floating bridge concept and environmental conditions

2.1. The Sulafjord site

The case studied concerns a bridge across the Sulafjord, between the islands of Hareidlandet and Sula in Møre and Romsdal County. As illustrated by the elevation map in Fig. 1, which has been digitally evaluated based on the Shuttle Radar Topography Mission (SRTM) database (Farr et al., 2007), there are mountains on both sides of the fjord, with altitudes up to 700 m. At the northwest side of the fjord, the Godøya island, with an altitude of 400 m, is sheltering the fjord to some extent from the open ocean. To the southeast, there is a mountainous area with altitudes above 1000 m. One of the proposed concepts for the fjord crossing is a multi-span bridge suspended from two fixed towers and two towers on the floating foundations (Nesteby et al., 2015). The blue line segment across the Sulafjord in Fig. 1 shows the proposed location of floating bridge, where the fjord is around 4.5 km wide and 450 m deep.

2.2. Floating bridge structural properties

Fig. 2 presents the finite element (FE) model of the floating bridge, which gives an overview of the bridge design and structural components. The bridge consists of three main spans and two side spans suspended

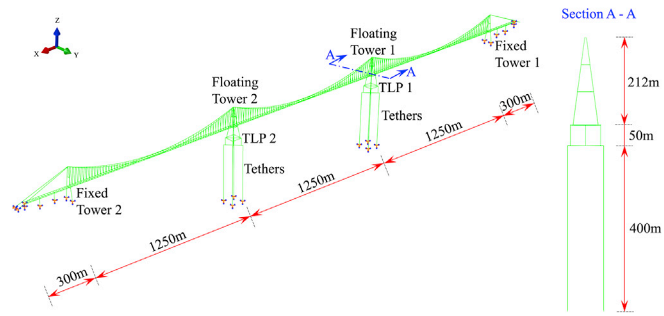

Fig. 2. The Sulafjord floating bridge model, as plotted in Abaqus (ABAQUS, 2011).

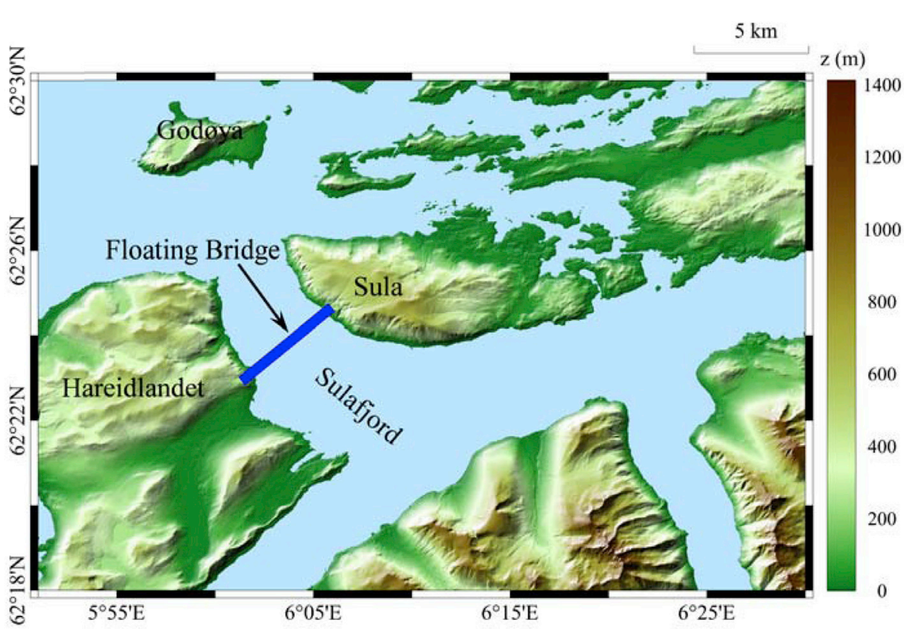

Fig. 1. Elevation map of the Sulafjord site on the west coast of Norway including the bridge location.