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Aerodynamic design of the floating bridges

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1 Abstract

Modern numerical computational tools are available to evaluate bridge aerodynamics. An effective parametrization can be applied to analyze different alternatives. Steady and self-excited aerodynamics investigations were performed with the help of modern CFD tools, in order to improve the overall bridge design. Different airflow control alternatives for bridge deck aerodynamics are investigated, such as installation of wind shields, installation of guide vanes, protective traffic and wind fences. These elements influence the aerodynamic performance and can lead to a reduction of global bridge response. The early design phase is most suited for the introduction of these possibilities and optimization processes. Successful design can be achieved by utilizing different aerodynamic aspects of torsional divergence check, galloping, multimodal flutter instability and their effects on the global bridge response. Presented works are some alternatives from expert group work on the multi-pontoon floating bridge project Bjørnafjorden. Complex global bridge response consists of structural bridge dynamics, hydrodynamic interaction and wind interaction. Aerodynamic optimization can lead to better use of material in the structure. The publications is a collection of work performed on different aerodynamics tasks, offering comprehensive overview of wind design.

Keywords: Floating bridges; wind aerodynamic; aeroelasticity; CFD.

Figure 1. Bjørnafjorden floating bridge concept (Illustration. Statens Vegvesen / Vianova /Baezeni)

2 About floating bridge

The vision of the ferry free E39 project is to create a time-efficient highway, connecting the western part of Norway, from Kristiansand to Trondheim. The E39 is oriented mostly north-south, while the many fjords are oriented east-west. Currently, these fjords are crossed with ferries. By replacing the ferry-connections with fixed links the travel time is significantly reduced. Due to local topography, different technical solutions are needed for each crossing, and some of them will challenge the boundaries for current technology. The first major project of the ferry free E39, Rogfast, is already out for tender, which is a tunnel project north of Stavanger. Establishing an effective connection between the major cities of Stavanger and Bergen will have great benefit for the region and can be completed by establishing a bridge across Bjørnafjorden, depicted in Figure1. This fjord is more than 5km wide, and the seabed drops rapidly off to a depth of more than 500m. Thus, conventional tunnel or bridge concepts will be costly to adapt. The Bjørnafjorden crossing is sheltered by a group of islands, effectively blocking big waves generated offshore from entering the fjord. This opened up for exploring floating bridge options. Through a series of early phase projects, several concepts have been developed and thoroughly evaluated for this particular crossing. Thus, by weighting the technological solution, cost and risk the floating bridge concept as shown in this paper, was found to be an attractive solution. At the southern end, the bridge starts near a tunnel at elevation 66m. A navigational channel is created here by a cable-stayed bridge with a main span of nearly 400m. From there the bridge deck ramps down to about 18m above sea level, supported by pontoon at a distance of 100-125m. Mooring lines have also been considered for some concepts to provide additional system stiffness and damping. Several advanced analysis tools are utilized in the design, often with overlapping capability for verification purposes [1] [2] [3]. Time domain analysis is used in design to study interaction effects between wind and wave response. The numerical aerodynamic tools were applied and several variations of the design elements were explored, supplemented with additional wind tunnel tests.

3 Floating bridge dynamics

The lateral dynamic wind response is governed by the first five lateral modes of the bridge deck, shown in Figure 2. Multiple vertical modes govern vertical wind and wave response. Major participant to the vertical response are wave loads, with response stretching over 50 modes from 3.5s to 6.0s periods. The response is modeled by a complex fully coupled dynamic equation of motion [3]. The bridge has irregular dynamic response under wave and wind loads. The response is influenced by the structural damping hydrodynamic damping, aerodynamic damping and mooring lines damping.

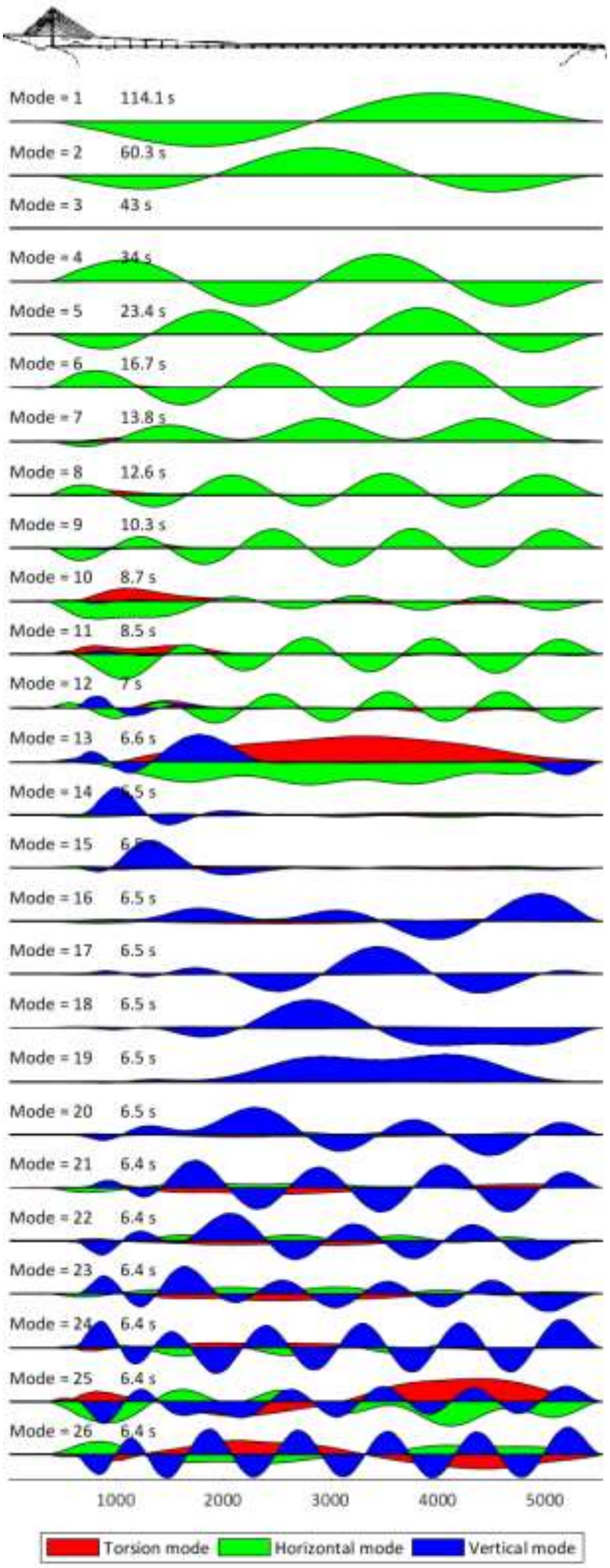

Figure 2. Eigenvalues of the end-anchored floating bridge without mooring lines.

A parameter study in the time domain is performed to assess the effect of varying aerodynamic load coefficients on the bridge response. Fully coupled wind and wave analysis were run. The main finding is that for this structure a rather large change of aerodynamic coefficients only gives a small change of design moment. An increase in the drag factor, C_D, from 0.8 to 0.9 increased the strong axis moment with about 2%. Similarly, an increase in C\`$_L$ from 3.0 to 4.0 increased the week axis moment with about 4%. Thus, there may be an economic gain to trade in some aerodynamic efficiency to get a better working structural cross section, and by this obtain an overall reduction of cost of the structure. Better deck airflow can be achieved by installation of wind shields and guide vanes.

3.1 Optimal bridge design

Numerical design optimization methodologies are widely used techniques, which can provide various design options especially at an early stage of the design process. In general, structural optimization can be classified into three main categories of size, shape and topology optimization. This technique can be applied to a cable-supported floating bridge by optimizing its aerodynamic behavior, which can provide different cross-section alternatives while other structural limit states are satisfied. Such optimization can be deterministic or probabilistic depending on whether we consider system uncertainty. Traditional deterministic optimization utilizes partial safety factors to count for overall uncertainty, while reliability-based design optimization (RBDO) searches for the best middle ground between cost and safety. Although the RBDO is computationally intensive, it has become more common due to the advances in computational technology in recent years. Attractive alternative represents a Multi-fidelity optimization commonly used in the aerospace industry. This method has emerged from the idea of alleviating the high computational cost of numerical simulations such as CFD without compromising its accuracy. It utilizes high-fidelity fine-mesh and low-fidelity coarse-mesh models and design optimization is carried out using the low-fidelity model with a corrector. This method may be applied to determine the best deck alternative analyzed by CFD simulations.

4 Aerodynamic design

Computational Fluid Dynamic (CFD) simulations have wide industrial application, with the possibility of describing a wide range of fluid flow mechanics. The Discrete Vortex Method (DVM) was applied to describe the incompressible airflow described by the Naiver-Stokes equations. There are exist several modeling alternatives, commonly grouped in the accuracy and complexity of turbulent models such as; LED, DES, RANS and other models. Different discretization schemes are suitable to represent fluid flow, grouped into Finite Volume, Boundary Elements, Discrete Vortex Method, numerically discretizing the space and time. Various possible solutions can provide different results, depending on the industrial application requirements. Several commercial solutions were tested for bridge wind engineering applications. CFD simulations are accompanied by high computational cost, where the different tools have various accuracy/performance ratios. Leaving engineers with the task to identify the most suitable tool for the aerodynamic design, selection of proper space and time discretization, selection of turbulence model, numerical method, input parameters, etc. Airflow simulations can represent a complex numerical task, therefore it is commonly left to the specialist or CFD trained engineers. Here the focus was cross-sectional aerodynamic performance under high wind speeds regime of Reynolds number Re=10e5. Adding rails and fences on the deck has an important contribution for safe bridge design. Here Discrete Vortex Method simulations are applied to model deck airflow. This method has been compared with the wind tunnel experiment [5]. After calibration, several deck shapes depicted in Figure 3 above were investigated. Here different aspects of aerodynamic cross-section were investigated, such as quasi-steady state coefficients, flutter derivatives and vortex shedding forces. These data were used in the aerodynamic design for galloping criterium $(C`_L + C_D) > 0$ and torsional instability investigations. Round wind shield concept showed potential galloping instability, therefore it was not used as an alternative. Further adding wind shields and adding guide vanes has a positive aerodynamic damping contribution.

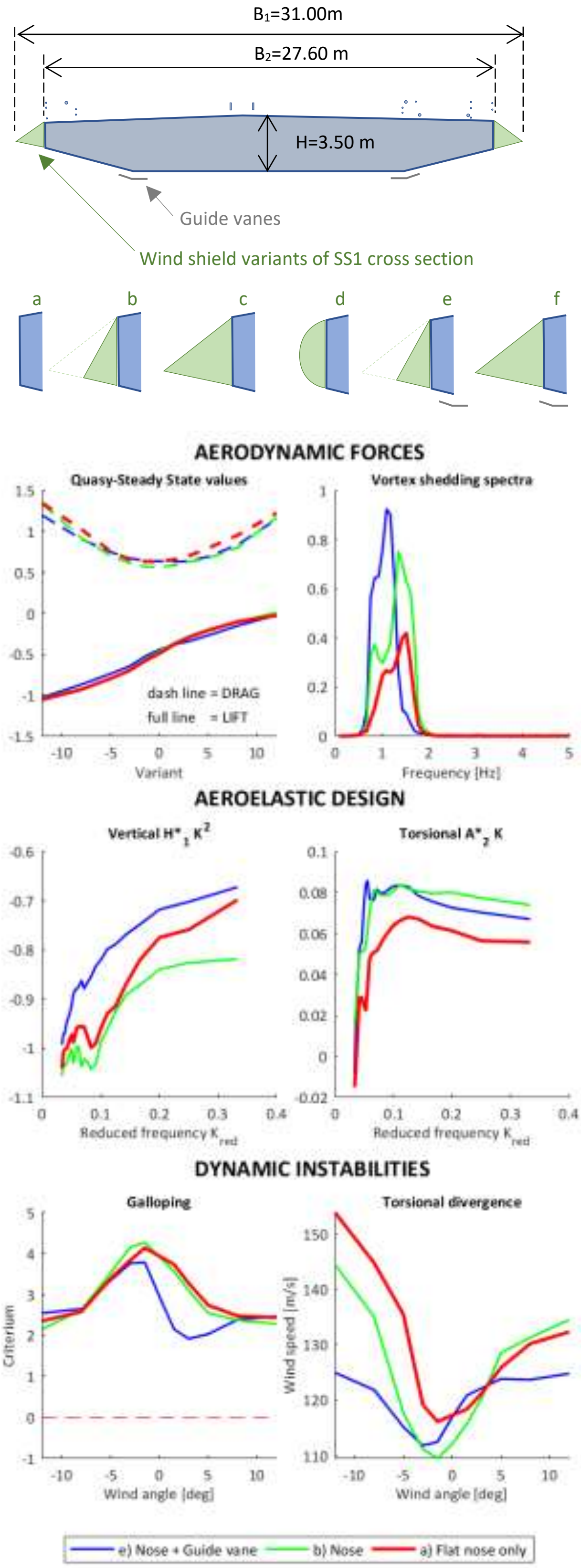

Figure 3: Aerodynamic performance by adding wind shields and guide vanes.

4.1 Verification of aeroelastic stability

Flutter is aerodynamic instability of bridge, occurring when aeroelastic forces of torsional motion coincide with a vertical motion. This creates a resonance condition commonly modeled by negative aeroelastic damping and is counterbalanced by the structure inherent damping. The tendency for torsion and vertical modes of bridge decks to couple into flutter depends on the eigenfrequency ratio and the degree of similarity of these mode shapes. A minimum critical wind speed for the onset of flutter results when the ratio of torsion / vertical eigenfrequencies approaches unity 1, where torsion and vertical eigenmode shapes are almost identical. The critical flutter wind speed increases with increasing frequency ratio and with increasing dissimilarity between torsion and vertical mode shapes. Floating bridges have several vertical modes below the first lowest torsion mode, these can potentially lead to aeroelastic interaction. Several vertical modes can combine and coupled with the torsion mode shape, thus resulting in lower flutter critical wind speed.

The modal analysis of the Bjørnafjord floating bridge reveals 9 very closely spaced vertical modes having eigenfrequencies in the range from 6.4 s – 6.5s, they are just below the first torsion mode at the period of 6.5s. With all torsion / vertical frequency ratios being very close to unity, here flutter at low wind speeds is a potential risk. However, the vertical mode shapes are very different from the torsional mode, points towards high critical wind speeds. The focus of this study was the investigation of possible aerodynamic coupling among close vertical modes, creating a compound vertical mode, which has a direct similarity to the torsion mode. This could lead to flutter at wind speeds below the minimum requirement of 82 m/s set out in the design basis.

A multi-mode (10 modes) flutter analysis was carried out following the principles outlined in [6]. This analysis combines eigenfrequencies, mode shapes presented in Figure 2, modal inertia properties and flutter coefficients for the girder cross section. Modeling apparent aerodynamic damping g as a function of increasing wind speed, shown in Figure 4. The factor g is a negative number at wind speeds where the apparent aerodynamic damping adds to the structural damping of the structure, i.e. the wind loading increases the aerodynamic stability. The onset of flutter is predicted at the wind speed for which the apparent aerodynamic damping balances twice the structural damping i.e. $g + 2\zeta = 0$.

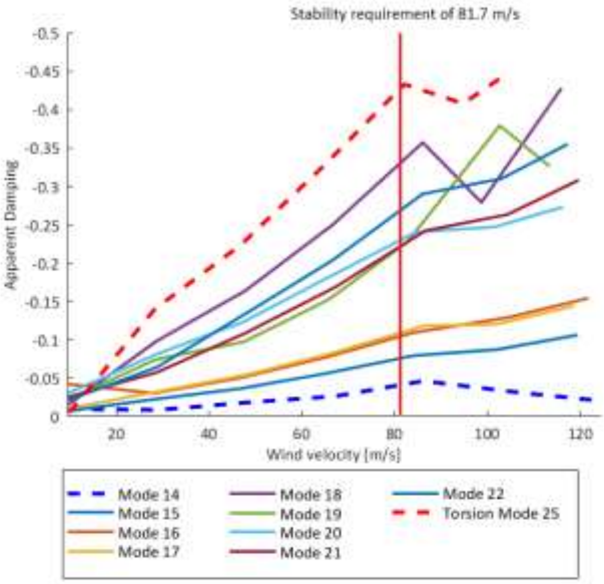

Figure 4: Modal damping for different wind speeds from multimodal aeroelastic stability analysis.

It is noted that the apparent aerodynamic damping remains negative for all modes up to wind speeds of 120 m/s. Thus, the Bjørnafjorden bridge fulfills the requirement of aerodynamic stability [7].

5 Conclusion

This design of fjord crossing represents an innovative structure, where several numerical tools can be successfully utilized. Preliminary calculations show that a cross section with better structural properties and less optimum aerodynamic properties can fulfill the stability criteria. Thus, utilizing the material in the structure more effectively, which again may lead to a more cost-efficient concept.

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