Experiences from the Five-year Monitoring of a Long-span Pontoon Bridge - What Went Right, What Went Wrong and What's Next?

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ABSTRACT

The Bergsøysund Bridge is a 930-metre-long end-supported pontoon bridge located in Norway, and has been the target of a five-year-long, extensive monitoring program. Herein, we will describe the unique structural characteristics of the bridge. The monitoring system has been under continuous expansion and revision, and consists of sensors monitoring both the excitation and the response of the bridge. Quantification of the uncertainties of the modelling methodology for structures of this nature has been the main goal, for which purpose modal analysis has been an indispensable tool. Modal analysis has also been used to study the effects the environment has on the structure's dynamic behaviour. We discuss the limitations of the results from modal analyses. Furthermore, we rise the question of how long monitoring campaigns may continue to provide useful information of this bridge and similar civil structures.

Keywords: floating bridge, monitoring campaign, modal analysis, numerical prediction, structural health monitoring

Background

The western coast of Norway is the part of Norway that is put on postcards. Immense fjords surrounded by dramatic mountains dominates the region. The same region is also housing industry that is producing and refining more than half of the Norwegian export, such as oil, gas and fish. Ferries are currently a necessity for both private and industrial transport in the region. The combination of these two factors is what made the government initiate the funding of the massive road infrastructure project *Ferry-free Coastal Highway E39*, organized and led by the Norwegian Public Roads Administration (NPRA), with the intention of substituting all the ferries along the highway with permanent road links. However, the geography does pose a big challenge: the deep and wide fjords imply that several world records have to be broken. The research community has therefore played an important role in finding and assessing technological solutions for the fjord crossings. Floating bridges are possible options for several of the crossings.

Floating bridges take advantage of the buoyancy of the water they are resting on, making them very stiff vertically. This makes them circumvent the problem that constrains the lengths of suspension bridges – gravity. However, a floating structure is very sensitive to forces induced by water waves. For some of the crossings required in the NPRA project, side-anchoring is not feasible. With spans of 4–5 kilometres this will result in very flexible structures. To better understand how floating bridges behave, and how to model them, experience and observations of existing subjects are highly valuable. The Bergsøysund Bridge is an existing end-supported floating bridge with a floating section of 830 metres, exposed to harsh marine environment. The bridge is comprised of a horizontally arc-shaped steel truss superstructure, that is supported on seven concrete pontoons. A photograph of the bridge is shown in Figure 1. This bridge has been the target of a five-year-long, extensive monitoring program.

Figure 1: The Bergsøysund Bridge. Photograph by NTNU/K.A. Kvåle.

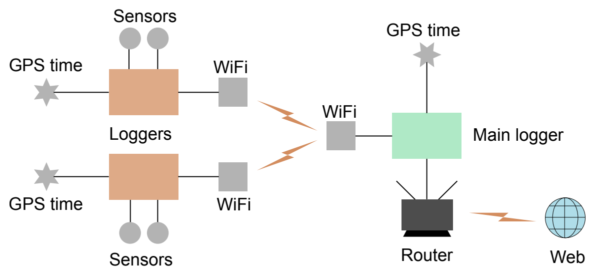

Figure 2: Data acquisition structure. Reproduced from [1], with permission from Elsevier.

Structural monitoring

The bridge has been, and is still, under extensive monitoring. Currently, six wave radars and five anemometers are measuring the environmental excitation, whilst 14 tri-axial accelerometers and one Global Navigation Satellite System (GNSS) sensor are measuring the dynamic response of the bridge. The sensor data is sent digitally to logger units that communicate with a main logger unit via Wi-Fi (Figure 2). The system ensures synchronous data by frequently obtaining common time stamps with global positioning system (GPS) units. The monitoring system is described in detail in [1]. Since the first version of the monitoring system was installed early 2013 [2], the system has been under continuous expansion and modification. The different stages of the monitoring system are indicated in Table 1.

The monitoring system was installed to address the main objective of studying and quantifying the accuracy of the numerical methodology for response predictions of floating bridges. This encompasses both the structural part of the model and the excitation model. This may furthermore be subdivided in the following sub-tasks: (i) evaluation of accuracy of structural model and excitation model, with reference to measurements; (ii) model updating [3]; (iii) system identification, both as a part of the first objective and by itself to study the behaviour of the structure [4]; and (iv) force identification [5].

What went right?

The system has provided data with quality sufficient for its purpose. State-of-the-art wind and wave sensors have been used to ensure the highest quality possible, with sampling rates high enough to provide useful information from a dynamic perspective. Digital sensors ensure the no measurement noise accumulate in the wiring. By transferring data wirelessly from the logger units to the main logger, problems concerning voltage drops for sensor power and extensive cable lengths have been avoided.

Table 1: Stages of system set-up.

Set-up no.	Start-up time	Description	Purpose with revision
1	Early 2013	Eight accelerometers [2]	-
2	December 2014	10 accelerometers	Better spatial description of vibrations.
3	March 2015	14 accelerometers, one temporary anemometer and six wave radars	Better spatial description of vibrations, all pontoon accelerations are measured (good mode shapes). Measurement of excitation.
4	September 2015	14 accelerometers, six wave radars [1], five anemometers and one GNSS sensor	Check accuracy of GNSS sensor and verify displacements from integrated accelerations. Better representation of excitation situation.
5	May 2017	As above, but with rearranged wave radars [6]	Enable a better characterization of the wave field from measurements.

The GPS time stamping have provided data with no noticeable time lags. Down-time of the network or electricity grid did not affect the data collection, as the system was logging data autonomously upon triggering and all units were equipped with backup batteries for robustness. This has ensured that the system has been operable when the power is down and the weather is potentially at its harshest.

What went wrong?
As mentioned above, the different stages of the monitoring system are shown in Table 1. Mid-campaign changes are not ideal regarding long-term consistency, as you end up with recordings of different data structures to handle, but nonetheless it has been an unavoidable consequence of economic and practical concerns. Some of the changes have been made because different sensor networks have served different purposes, scientifically. The most obvious example concerns the two goals of the wave radars: (i) characterize the homogeneity of the wave field across the strait and (ii) characterize both the frequency- and direction-dependency of the local wave field. These two applications required entirely different setups, and it was not economically feasible or reasonable to acquire more sensors to cover both needs simultaneously. To handle changing sensor networks, generic metadata files for all time periods of the different stages was used. These files defined all necessary properties to enable global analyses of the data, for instance Cartesian coordinates and transformation matrices describing the local coordinate system of all the sensors. The close-to inevitable down-time of sensors must also be handled with care when analysing data bulk-wise. Stability issues with consumer-level network modems resulted in the need of digital electric timers to reboot the modem regularly.

What's next?
For the applications mentioned above, the monitoring system has provided high-quality data that combined with state-of-the-art numerical methods has yielded good results. After five years of monitoring, we are, however, left with the question: what's next? How can we take advantage of new data from the monitoring system? What will more recordings provide, that the data already available does not? Structural health monitoring (SHM) is a topic that deservedly has received a lot of research attention. Vibration-based SHM is normally based on the modal parameters. During the first years of the operation of a structure, it is expected to experience some settling of the structural properties, leading to changes in its dynamic behaviour and thus modal parameters. After some time, however, the structure will probably attain some sort of converged state. It is only at the end of life that significant changes are expected to arise again. Observable changes in modal parameters might require drastic changes of the structure during its mid-life period.

Modal decomposition has historically been needed to reduce the number of degrees of freedom in a system, to make it manageable. In recent years, following the revolution of computational power, the time-saving factor is not as crucial. Rather, modal decomposition serves as a tool to synthesize and analyse complicated mechanical systems. Measurement-based modal analysis has served as an indispensable tool this far in the monitoring campaign, to assess the dynamic behaviour and to compare it with numerical predictions. Still, we feel that modal analysis, or more specifically, the interpretation of the behaviour by its fundamental vibration modes, is not yet fully utilized in this case.

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