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Design and deployment of a monitoring system on a long-span suspension bridge

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ABSTRACT: Monitoring systems have become a standard component for many landmark bridges. This paper describes the design of a new monitoring system for the Hålogaland bridge, a suspension bridge has a main span of 1145 m located in an arctic environment in northern Norway. This bridge being a prime example of a wind-sensitive structure, the monitoring system is designed with focus on wind engineering research for long-span bridges. Previous monitoring projects on bridges of similar scale have also revealed some knowledge gaps (e.g. discrepancies in predicted and measured responses) and interesting observations (e.g. strong effects on the surrounding terrain on the wind loads). Such results should be further investigated and cross-checked for bridges in other locations.

The monitoring system is custom designed and built by researchers at NTNU, using NI CompactRIO controllers as base data acquisition units for sampling and controlling the system. The CompactRIOs are programmed using the LabVIEW software. Multiple types of sensors are employed; sonic anemometers for wind measurements, accelerometers in the bridge deck and hangers for structural responses, strain gauges, and temperature sensors. Timestamps from GPS antennas are used to sync the measured data between the different CompactRIOs. Ultimately, the acquired data is planned to be used in research on modal parameter identification under the influence on wind, identification of wind loading, modelling of spatial wind fields, serviceability limits with respect to road accidents during strong winds, in addition to new techniques on machine learning in structural health monitoring.

KEY WORDS: Structural monitoring; Suspension bridge; Wind engineering

1 INTRODUCTION

Long-span bridges are known to exhibit dynamic behavior to environmental loading such as wind. The bridge design and assessment of structural safety necessitate understanding complex aerodynamic behavior in stochastic loading conditions. Studies have shown that there still are aspects of wind fields, wind loads, and wind-induced response that are not always well predicted by current models [1] [2] [3]. In recent years and decades, technological developments have provided opportunities to obtain valuable direct and indirect data from civil engineering structures by monitoring [4] [5] [6]. For long-span bridges, full-scale monitoring can provide insight that is overlooked by theoretical models or small-scale experiments.

As pointed out in [7], although not all monitoring of bridges is performed with health assessment intentions, the term structural health monitoring (SHM) has become a common term to describe all types of measurements in civil engineering. The instrumentation of the bridge discussed in this contribution is motivated by extending wind engineering research for long-span bridges. We outline the design and main architecture of the monitoring system.

2 MONITORING PROJECT

2.1 The Hålogaland bridge

The Hålogaland bridge (shown in Figure 1) is a suspension bridge that opened in December 2018 and is located in the town of Narvik in northern Norway. The bridge has a deck made from a closed steel box girder, concrete towers, air-spun steel main cables, and locked-coil steel hangers. The main span of the bridge is 1145 m, thus the low natural frequencies of the structure mean that the wind-induced response is a critical factor in ensuring safe design and operation. As shown in the map in Figure 2, the bridge is situated almost on the north-south axis across the fjord, so it will be exposed to western winds from the North Atlantic Ocean and eastern winds from inland areas.

Figure 1. The Hålogaland bridge.

Figure 2. Left: bridge location in Norway; middle: coastal topography; right: location of bridge crossing the fjord.

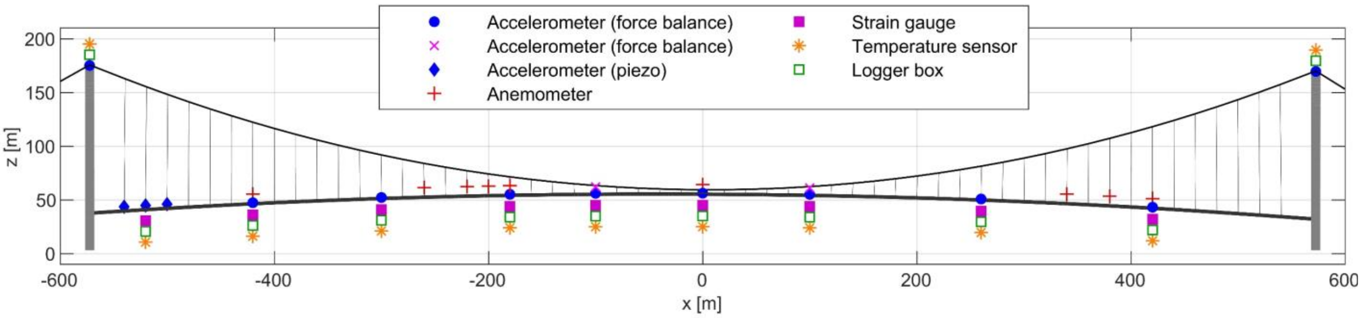

Figure 3. The positions of the sensors. The locations in the bridge deck are shown in Figure 4.

2.2 *Motivation and objectives*

The project aims to improve the understanding of the dynamic behavior of long-span bridges subjected to wind loading. This research is a continuation of studies on similar types of bridges in the western part of Norway [8] [9]. There still are knowledge gaps that needs to be investigated to increase confidence in wind-resistant design of slender bridges. Some of the research questions of interest are given below:

- Is the large spatial wind field in agreement with currently applied prediction models in wind engineering?
- Does the bridge aerodynamic behavior correspond according to the predictions from wind tunnel tests?
- How is the identification of modal parameters influenced by the wind and environmental factors?
- Can the wind loads be inversely identified from measured response data?
- What should be the guidelines on serviceability limits (closing of the bridge) to avoid vehicle accidents during strong winds?
- What is the effectiveness of Stockbridge dampers on cables to mitigate vortex-induced vibrations?

3 MONITORING SYSTEM

The main hardware and sensors are summarized in Table 1. In the following, the main variables of interest in the monitoring are discussed.

As the system is not yet installed on-site, all discussions on sensor types and locations herein refer to the planned system configuration; however, few deviations from the presented plan are expected.

Table 1. Overview of hardware and sensors

Type	Specification	Count	Location(s)
Controller	NI9045 CompactRIO	11	Bridge deck, tower
GPS antenna	Trimble Bullet Antenna	11	Hanger, tower
Accelerometer	GeoSIG AC-73 Triaxial Force Balance	22	Bridge deck, hanger, tower
Accelerometer	Dytran 3063B, Triaxial IEPE	3	Hanger
Strain gauge	Poisson half-bridge	36	Bridge deck
Anemometer	Gill Windmaster Pro 3D	10	Hanger
Temperature meter	RTD Pt 100	20	Bridge deck, tower

3.1 Structural response measurements

In total, 22 tri-axial force balance-type accelerometers are available for installation. As shown in the planned sensor layout in Figure 3, the accelerometers are located in the towers and the bridge span. The accelerometer locations have previously been optimized by the principle of maximum entropy [10] [11]. Except for the towers, the accelerometers are allocated in pairs inside the bridge deck or on the hangers close to the main cable (Figure 4).

A challenge encountered in the optimal sensor placement for such bridges is the multimodal behavior necessitating a large number of sensors. Many low-frequent modes will be excited by the wind; below 0.6 Hz already 18 modes are found in the finite element model of this bridge [10].

Strain measurements are also planned at the same coordinates as the accelerometers. Four strain gauges are distributed inside the bridge deck (Figure 4). Each strain gauge is arranged in the Poisson half-bridge configuration.

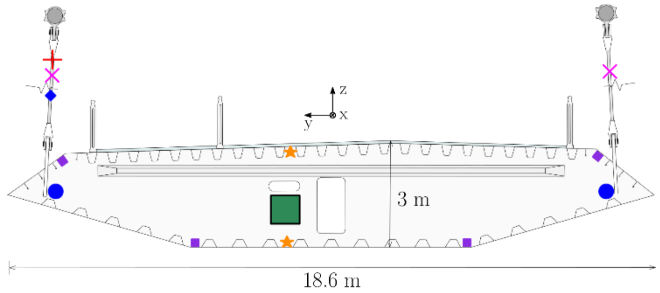

Figure 4. Positions of sensors in a generic section of the bridge deck. Blue circle: accelerometer inside bridge deck; pink cross: accelerometer on hanger; blue diamond: piezo accelerometer on hanger, purple square: strain gauge; orange star: temperature sensor, red cross: anemometer.

3.2 Wind measurements

10 sonic anemometers of the type Gill Windmaster Pro are available in this project. These sensors have excellent performance for turbulent wind measurements in three directions.

For large spatial structures with a limited amount of wind measurements, there is a trade-off between the two objectives: *i)* capturing the distributed wind field and possible inhomogeneities by spreading out the anemometers in the entire length of the structure, and *ii)* accurately estimating the spatial coherence of the wind field, which approximately vanishes as $\exp\left(-K\frac{f\Delta x}{\bar{U}}\right)$ (where $\bar{U}$ is the mean wind velocity, f is the frequency, and $K \approx 5 - 15$ is a decay constant) [12], thus necessitating clustering the anemometers with a maximum inter-distance (Δx) well below 100 m. In this project, both these objectives are considered, leading to the chosen anemometer locations shown in Figure 3; 5 are clustered 200 m south of the midspan, 3 are clustered 400 m north of the midspan, and additional 2 single anemometers are located at the midspan and 400 m south of the midspan. The hangers are equidistantly spaced with 20 m, which is sufficiently small to meaningfully estimate coherence parameters.

3.3 Vortex-induced vibrations of hangers

Already since the construction of the bridge, strong vibration of the hangers was reported, presumably due to vortex shedding. At the request of the bridge owner, the hangers have now been equipped with Stockbridge dampers as shown in Figure 5. Three of the longest hangers are planned to be instrumented with piezoelectric accelerometers to measure the vortex-induced vibrations. As a part of the research project, we also aim to remove the dampers for a time window to evaluate the effectiveness of this vibration mitigation strategy.

Figure 5. Stockbridge damper mounted on hanger.

3.4 Temperature measurements

Temperature meters are to be installed on the floor and ceiling inside the bridge deck (Figure 4) at 9 locations along the span. Additional sensors for measuring the ambient air temperature are located at the top of the towers. The influence of environmental effects on the dynamic behavior (particularly modal properties) is frequently observed in SHM data from bridges [13] [14] [15].

The arctic climate in this area naturally leads to low temperatures. However, the range of the temperature variation, which could dictate the range of e.g. frequency variation, is not necessarily unusually large; for an average year the coldest and warmest months have mean temperatures of -3 °C and 14 °C, respectively.

3.5 System hardware and software

The monitoring system is custom designed and built at NTNU, Norway. As shown in Figure 3, the system has 11 local nodes with a logger box; 2 in the towers and the remaining 9 in the bridge span. All the sensors (located both outside and inside the bridge deck) are wired to the closest logger box.

The generic logger box is shown in Figure 6; each contains a main hardware unit for data acquisition, namely a NI CompactRIO controller that is programmed by the LabVIEW software. In this custom software program, the measurement data is sampled, filtered, and stamped with accurate time obtained from the Trimble Bullet GPS antenna before it is saved locally on hard drives. The CompactRIOs will also be connected to internet so that the data can be pushed to a server with regular intervals. The online connection is also important for control and robustness of the system.

The system relies on ordinary AC power to operate. In case of a power outage, a backup source is available by means of an uninterruptible power supply that can run the system for approximately 3 hours.

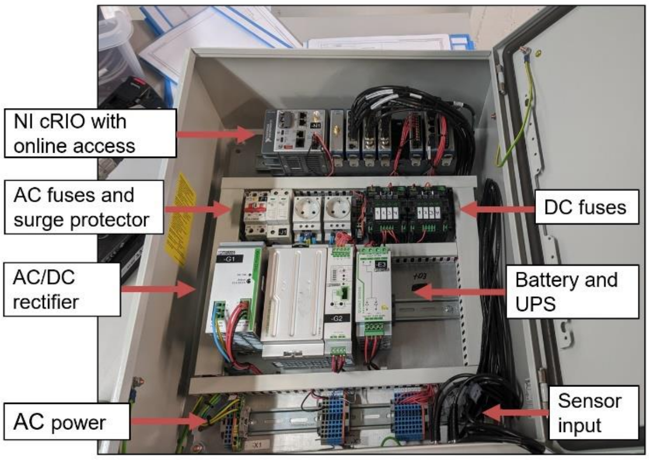

Figure 6. Logger box hardware.

3.6 Early damage and repair

In January 2019, within the first month after the opening of the bridge, it was discovered a complete fracture in an anchor bolt of the main cable located in the splay chamber. These bolts are made from a high-strength steel alloy that is prone to brittle failure. The investigation showed that this failure probably was caused by material degradation since the bolts were exposed to natural environments (such as rain) for two years during construction. Although no further damage has been observed since the first failure, the bridge owner has decided that all 344 bolts should be replaced as a cautionary measure. This replacement is scheduled to finish before September 2022, during which the monitoring system is planned to operate. The bridge will also remain in operation during the replacement. Note that the monitoring system was not designed for damage detection purposes, nor is any sensor located in the vicinity of the splay chambers. It is known that small changes in the component level hardly changes the modal properties at the global level for very large structures [16]. For this reason, it is far from certain that the effects of this damage (or the replacement) can be distinguished from the vibration data.

4 CONCLUSIONS

In this paper, it was described the main design and architecture of a SHM system which is planned to be installed on a long-span suspension bridge in northern Norway. The system consists of structural response measurements using force balance and piezo accelerometers, and strain gauges. Environmental data in the form of wind velocities and temperatures are also measured at a number of locations.

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