



# Estimation of the full-field dynamic response of a floating bridge using Kalman-type filtering algorithms



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## ABSTRACT

Numerical predictions of the dynamic response of complex structures are often uncertain due to uncertainties inherited from the assumed load effects. Inverse methods can estimate the true dynamic response of a structure through system inversion, combining measured acceleration data with a system model. This article presents a case study of full-field dynamic response estimation of a long-span floating bridge: the Bergøysund Bridge in Norway. This bridge is instrumented with a network of 14 triaxial accelerometers. The system model consists of 27 vibration modes with natural frequencies below 2 Hz, obtained from a tuned finite element model that takes the fluid-structure interaction with the surrounding water into account. Two methods, a joint input-state estimation algorithm and a dual Kalman filter, are applied to estimate the full-field response of the bridge. The results demonstrate that the displacements and the accelerations can be estimated at unmeasured locations with reasonable accuracy when the wave loads are the dominant source of excitation.

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## 1. Introduction

In many civil engineering structures, the dynamic response is an important variable for determining sufficient structural safety and design. In the design phase, the dynamic response is traditionally obtained using a numerical model of the structure and combinations of load states as dictated by design codes. However, there are uncertainties associated with the load effects and with the way the structure responds to the loads. Consequently, the numerically predicted response has inherited uncertainties, meaning that the design limit states, such as structural failure, instability, fatigue or serviceability, must also be treated as having uncertainties.

Monitoring systems installed on existing structures enable the structural behaviour to be studied under the true operating conditions. The collected data may be used for long-term statistics, model parameter identification, operational modal analysis (OMA) or structural health monitoring (SHM). A shortcoming of full-scale measurements is that only output data are typically available since inputs on structures are often impractical to measure directly on a large scale. In addition, the dynamic response can only be measured at a limited number of points because of cost limitations and/or due to practical restrictions on sensor locations.

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In recent years, researchers have explored techniques for using incomplete measurement data to estimate the response at unmeasured locations in structural or mechanical systems. One example of this approach is modal expansion techniques, which can use strain or stress predictions as an indicator of the local utilization of the structural capacity. Modal expansion algorithms have been shown to perform well on offshore wind turbines [1,2] and platforms [3,4], estimating strain histories as a tool for monitoring the fatigue service life. Another class of methods consists of filtering techniques for coupled input and state estimation, and these techniques are commonly based on Kalman-type filters. Multiple methods have been proposed in the recent literature [5–15]. Among the popular contributions are the algorithm for joint input-state estimation (JIS) [9]. This methodology has also been developed further [10] and tested in situ [11]. In the proposed dual Kalman filter (DKF) [12], the inputs and states are estimated from two Kalman filters working in conjunction. Experimental testing and verification of the DKF can be found in [13]. The assumptions and structure of the different Kalman-type filters lead to advantages and disadvantages, which means that the applicability of the different methods can vary from one case study to another. The experimental comparison in [14] focuses on the stability in the real-time application of some filter variants. Practical applications of the techniques include strain prediction for fatigue [16] and studies of ice-structure interaction [17,18]. Other Kalman filter approaches have been used to estimate the responses of tall buildings due to wind loads using acceleration data [19,20].

Although many full-scale measurement campaigns have been conducted on long-span bridges (see, e.g. [21] for a brief overview), the methodologies for full-field response estimation have seen little exploration on these types of structures. This may be explained by several reasons. First, most of the relevant methodologies have been developed quite recently, and the research field is still in active development. Second, long-span bridges typically exhibit a highly complex dynamic behaviour since many modes contribute to the total response. Finally, (non-linear) fluid-structure interaction phenomena can occur, which may be difficult to implement in a model. The implication of the complex dynamics is that accurate system models and dense sensor networks are required for many of the current prevailing methodologies to be applicable. If a system for full-field response monitoring is successfully implemented, then the reward is better control over the condition of important civil infrastructure.

This article focuses on applying filtering techniques to estimate the full-field dynamic response of very large bridges, making use of measured acceleration data together with a numerical model of the structure. We present a case study of a long-span floating bridge, the Bergsøysund Bridge, and assess how well two of the aforementioned filter algorithms, JIS and DKF, are able to reconstruct the global response. Herein, the methodology is tested in full scale on a structure that is in operation using three recorded data sets with different ambient wave and wind conditions. The presented work is a continuation of previous studies [22]; in the current paper, the studies are extended in the use of the methodology and the results are improved. The remainder of this paper is organized as follows: Section 2 presents the Bergsøysund bridge and relevant mathematical formulations for floating bridge dynamics. Section 3 is devoted to the response estimation methodology and system model. In Section 4, the dynamic response estimation from several time series are shown and the results are discussed. Conclusions are drawn in Section 5.

## 2. Floating bridges

### 2.1. The Bergsøysund bridge

The Bergsøysund Bridge (Fig. 1) is located on the midwestern Norwegian coast as a part of the E39 Coastal Highway Route. This bridge opened in 1992 and is a unique type of structure since it is one of a few long-span floating bridges with end support only. The bridge consists of a trusswork of steel tubes and is supported by seven pontoons. The pontoons are shell structures that are made from lightweight aggregate concrete. The floating span of the bridge is 840 m long, with free spans of 105 m between the pontoons. Since the bridge has no anchoring, it is susceptible to dynamic excitation, particularly



Fig. 1. Left: The Bergsøysund bridge viewed from the northeast end; right: the truss structure as viewed from below the bridge deck. Photo: K.A. kvåle.

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