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Time domain simulations of wind- and wave-induced load effects on a three-span suspension bridge with two floating pylons[☆]

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ABSTRACT

The construction of a three-span suspension bridge with two floating pylons is currently being considered for crossing the 5-km-wide and 550-m-deep Bjørnafjorden in Norway. The bridge design represents a novel concept that requires a detailed dynamic analysis to improve the current understanding of its dynamic behavior. Geometric nonlinearities in the cables and mooring system and nonlinearities in the load models are of particular interest; in addition, the relative influence of the buffeting wind forces and the first- and second-order wave excitation forces were carefully studied. The response predictions were obtained using state-of-the-art time domain methods.

1. Introduction

The Norwegian Public Roads Administration is administering a project—Ferry free coastal route E39—which aims to eliminate all ferries along the coastal highway E39 in Norway. One of the straits, Bjørnafjorden, is up to 5 km wide and 0.5 km deep, calling for a significant extension of current bridge technology. A three-span suspension bridge with two floating pylons, a combination of offshore and bridge technology, is a new concept for crossing wide and deep fjords [1,2]. The bridge represents an entirely new design, requiring a detailed analysis of its dynamic behavior. Time domain methods are commonly applied when nonlinearities must be considered, as it is challenging to include such nonlinearities in a frequency domain analysis. Thus, assessing the influence of nonlinearities in the model is of particular interest to determine whether the calculations must be performed in the time domain or if the faster frequency domain methods are sufficient.

Modeling the motion-induced forces is a major challenge in the time domain simulations of the dynamic response, as they are dependent on the motion history. It is convenient to model the self-excited force in the time domain based on quasi-steady theory [3] and use coefficients from static wind tunnel experiments because the coefficients in quasi-steady theory are not dependent on the frequency; however, it can be challenging to accurately model the self-excited forces using quasi-steady theory, which has resulted in a number of suggestions for improvements [4,5]. The fluid memory effect can be considered by transfer functions in the frequency domain or by convolution integrals in the time domain. The self-excited forces for bridge decks are commonly modeled in the frequency domain using flutter derivatives, as proposed by Scanlan and coworkers [6]. The flutter derivatives represent an empirical generalization of the analytical expressions of the self-excited forces for airfoils (i.e., Theodorsen's function) [7]. The Wagner function [8,9] is the time domain counterpart to Theodorsen's function, and this work has also been generalized for bridge applications. Time

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domain simulations of self-excited forces for bridge applications commonly start with an empirical expression for the transfer function in the frequency domain or the indicial functions in the time domain. The challenge is to fit the various models to the experimental data of the aerodynamic derivatives. The most common approach is perhaps the use of rational functions, also known as Roger's approximation [10]. The majority of the aforementioned studies were either limited by simplified systems using still-air modes as generalized coordinates or detailed studies of the performance of the methodology considering a bridge deck section model. In bridge design, it is necessary to include self-excited forces in a finite element analysis of the entire bridge. Borri et al. [11] expressed the self-excited forces in the time domain by indicial functions and implemented the methodology in the finite element code FEMAS. Salvatori and Spinelli [12] also simulated the self-excited forces by convolution integrals using indicial functions, developed a finite element program capable of handling simplified bridge models, and analyzed the effects of structural nonlinearities and wind coherence. Chen et al. [13,14] used a state-space model to simulate the fluid memory effect, which can be more computationally efficient than solving the convolution integrals. Additionally, nonlinear effects were carefully studied in a flutter and buffeting analysis in the time domain. Øiseth et al. [15] also applied a state-space model of a simple beam with properties similar to a long-span bridge, and state variables were included as additional degrees of freedom in each node of a beam element.

The hydrodynamic radiation forces are similar to the aerodynamic self-excited forces in that they also depend on the motion history. The most convenient approach is to replace the frequency-dependent added mass and damping by constant coefficients, which are chosen at a dominating frequency, for instance, the peak frequency of the wave or the natural frequency of the structural system. However, this simple method cannot provide accurate results in the analysis of the structures' transient response under a single frequency excitation or the steady-state response under multiple frequency excitations [16]. Cummins' equation is widely used for time domain simulations of structures interacting with water to consider the frequency-dependent characteristics [17]. This equation is a vector integro-differential equation that involves convolution terms that account for the fluid memory effect and has been applied by many researchers [18,19]. However, it is time consuming to solve the convolution integrals during a dynamic analysis [15,20], and replacing the convolution integral with a state-space model is an attractive alternative. Taghipour et al. [20] verified that the same accuracy as obtained by solving Cummins equation directly can be obtained by replacing the convolution integral with a state-space model, and the calculations are approximately eight times faster. They also validated the methodology by comparing their results to experimental data for a flexible barge [21]. The state-space modal has also been used by many researchers in different areas [22,23].

As outlined above, state space models are commonly used in the modeling of both hydrodynamic and aerodynamic self-excited forces. However, there are few studies on the performance of the methodology for modeling the dynamic behavior of structures subjected to both wind and wave actions. Thus, this paper provides a brief introduction to the state space modeling of self-excited aerodynamic and radiation forces; a description of the inclusion of state space models in a finite element model of a three-span suspension bridge with two floating pylons is provided. Studies on the dynamic behavior of the bridge consider first- and second-order wave excitations as well as the mean wind and linear and nonlinear buffeting forces. The influence of the nonlinear effects on the models is also carefully studied in order to present some general trends of what is important to include in the modeling of this novel bridge concept.

2. Dynamic response of a suspension bridge with floating pylons

Fig. 1 shows a three-span suspension bridge with two floating pylons crossing Bjørnafjorden in Norway. The main cables are supported by two fixed pylons at each end of the bridge and two floating pylons in the middle of the bridge. The bottom part of the floating pylon is similar to tension leg platforms moored by four groups of tethers, providing a high stiffness in heave, pitch and roll. The water depth is 550 m and 450 m at the left and right floating pylons, respectively. To assess the dynamic behavior of the bridge, it is necessary to consider wind loading on the girder and pylons as well as wave loads on the floating pylons. The equation of motion can be written as

$$\mathbf{M}_s\ddot{\mathbf{u}}(t) + \mathbf{C}_s\dot{\mathbf{u}}(t) + (\mathbf{K}_s + \mathbf{K}_h)\mathbf{u}(t) = \underbrace{\mathbf{F}_{mean} + \mathbf{F}_{Buff}(t) + \mathbf{F}_{se}(t)}_{\mathbf{F}_{Aero}} + \underbrace{\mathbf{F}_{WA}^{(1)}(t) + \mathbf{F}_{WA}^{(2\pm)}(t) - \mathbf{F}_{Rad}(t)}_{\mathbf{F}_{Hydro}} \tag{1}$$

here, $\mathbf{M}_s$, $\mathbf{C}_s$ and $\mathbf{K}_s$ symbolize the still-air mass, damping and stiffness matrix, respectively, and $\mathbf{u}$ represents the degrees of freedom

Fig. 1. Three-span suspension bridge with two floating pylons. Illustrated by Arne Jørgen Myhre, Statens vegvesen.