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Prediction of long-term extreme load effects due to wind for cable-supported bridges using time-domain simulations

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ABSTRACT

Many long-span bridges that are slender and susceptible to wind-induced vibrations are currently under construction all over the world. As nonlinear structural behavior and nonlinear displacement-dependent wind loads become of higher importance, time-domain methods are commonly applied instead of frequency-domain approaches. This paper discusses how rational functions, fitted to aerodynamic derivatives, can be converted to a state-space model to transform the frequency-dependent aerodynamic forces into the time domain. A user element has been implemented in ABAQUS to include the self-excited forces in the dynamic analysis. The flutter stability limit and buffeting response of the Hardanger Bridge have been calculated in a comprehensive case study to illustrate the performance of the presented methodology. The Average Conditional Exceedance Rate method is used to estimate long-term extreme load effects. A simplified full long-term method that ignores wind velocities which contribute little to the long-term extreme values is introduced to reduce the required computational effort. The long-term predictions are also compared with results obtained using a short-term approach and it is concluded that the long-term extreme load effects are approximately 14% higher than the short-term extreme values.

1. Introduction

Flutter and dynamic behavior in strong winds are always two of the main concerns when designing long-span bridges. The self-excited forces cause flutter, while both the self-excited and the buffeting forces are important for the dynamic response of bridges in strong winds. The multi-mode frequency-domain method has been widely used to study flutter stability and dynamic response to strong winds [1–3]. The method will provide results of high accuracy if there are no strong nonlinear characteristics in the system. Modern bridge designs, however, are characterized by high flexibility and sensitivity to wind actions due to the increased span lengths. As a consequence, time-domain modelling of the self-excited forces has received much attention in recent years [3–15]. One possibility is to use quasi-steady theory by modelling the self-excited forces using coefficients from static wind tunnel tests. The coefficients in the model are frequency-independent, making the model convenient to implement in the time domain. Diana et al. [8] developed a corrected quasi-steady theory by including aerodynamic nonlinearities. The predicted quasi-steady aerodynamic forces were reasonable but not perfectly correct. The low reduced velocity range is particularly hard to capture accurately. The fluid memory effect can be taken into account not only by transfer functions in the frequency domain but also by convolution integrals in the time domain. Scanlan et al. [16,17] generalized the Wagner function that was originally developed for airplane wings and applied it for bridge decks to represent the self-excited forces. The Wagner function is also addressed as an indicial function and has been widely used by many research studies in time-domain simulation of unsteady self-excited aerodynamic forces [5,6,13,18]. The challenge is to fit the various models to the experimental data of the aerodynamic derivatives. The most common approach thus far is to approximate the aerodynamic derivatives using rational functions, which is also known as Roger's approximation [19].

Most of the studies mentioned above were limited to simple systems, such as a two-degrees-of-freedom 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. [18] and Salvatori and Spinelli [13] expressed the self-excited forces in the time domain by indicial functions. Borri et al. [18] checked the time domain load model with a three-dimensional full-bridge model in the finite element code FEMAS. Salvatori and Spinelli

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[13] developed a finite element program capable of handling simplified bridge models and found that the structural nonlinearities could limit the oscillation amplitudes in super-critical velocity range and deemphasize the presence of the critical wind velocity. Chen et al. [5,6] and Arena et al. [20] replaced the convolution integrals with a state-space model, making the numerical simulation more efficient. Chen et al. [5,6] conducted the flutter and buffeting analysis in the time domain, but in terms of generalized modal coordinates. Their studies showed that the response increased slightly when the nonlinear unsteady aerodynamic forces are considered. Arena et al. [20] analyzed the flutter and the dynamic response of long-span suspension bridge considering nonuniform span-wise wind profile and time- and space-dependent gust loading conditions, respectively. The dynamic behavior was found significantly different from that under uniform gust loading conditions. Øiseth et al. [12] also used a state-space model and introduced the state variables as additional degrees of freedom in each node of a beam element to simulate the fluid memory effect. The critical velocity and the buffeting response predicted by the model corresponded well to the frequency-domain results. It is, however, a significant drawback that it is rather complicated to introduce additional degrees of freedom into existing finite element programs.

It is the extreme deflections and load effects that are relevant for design. Long-term analysis is the most accurate approach to obtain the N-year load effects for ultimate limit state (ULS) design checks. Nevertheless, short-term analyses are still widely used because the long-term approach normally requires massive computational effort, especially when it is necessary to consider the variability of, for instance, the mean wind velocity, wind direction, turbulence intensities and integral length scales by means of a joint probability distribution. In short-term analysis, the N-year load effects are approximated by the extreme values for a short-term environmental condition with a selected return period and duration, for instance, 100 years and 10 min. The design load effect obtained from the short-term analysis needs to be multiplied by a factor to take into account the fact that less severe conditions that occur more frequently and more severe conditions that occur less frequently will also contribute to the long-term extreme value distribution. This approach generally needs to be verified by a full long-term analysis. Many studies of short- and long-term extreme load effects for marine structures have been conducted over the years [21–24].

The Gumbel method [25,26] and the Weibull tail method [21,27] are widely used for short-term extreme value analysis. In the Gumbel method, the single largest maximum value is extracted from each simulation, and the sample of the independent maxima from an ensemble of simulations is assumed to follow the Gumbel distribution. In the Weibull tail method, all peaks above a selected threshold are extracted, and the tail regime is fitted to a Weibull distribution. The empirically selected threshold is very important for the predicted results, which can be a disadvantage. Naess and Gaidai [28] developed an Average Conditional Exceedance Rate (ACER) method to estimate the extreme values from sampled short-term time series, which can account for the dependence of the neighboring up-crossings. This method has been widely used for many applications [23,24,29]. Saha compared the predicted short-term extreme response of an offshore wind turbine subjected to wind and wave loading with applications of the up-crossing rate method, Gumbel method and Weibull tail method. The up-crossing rate method performed better in his case.

For estimation of long-term extreme value distributions, the full long-term method, which is the convolution of short-term distributions for all environmental conditions, is the most accurate but requires massive computational effort. More efficient approximate methods have been introduced over the years. For areas governed by occurrences of some extreme storms, the "peaks over threshold" approach is recommended [30,31]. It is more effective than the classical approach because it only considers the exceedance probabilities from a limited number of environment events, e.g., severe storms or hurricanes. The environmental contour method is discussed in [32,33], in which only one single short-term environmental condition with the desired return period is required to obtain the extreme value distribution. This method is widely used in offshore engineering. Li et al. [34] introduced a modified environmental contour method in bottom-fixed offshore wind turbines to take into account the non-monotonic behavior of the response under wind loads. He also applied a simplified full long-term method, which considers only the environmental conditions that give significant contributions to the long-term extreme values.

Although many studies of long-term extreme value analysis have been carried out for marine structures, very few studies of wind-induced load effects for civil engineering structures seem to exist. Some studies have been conducted for high-rise buildings [35,36], but the authors have not found any contributions related to long-term analysis of cable-supported bridges. Both time- and frequency-domain methods can be applied to carry out the long-term extreme value analysis. The analysis will be carried out in the time domain in this paper because it is convenient to include non-liner behavior in the analysis. A full long-term method is very computationally demanding, making efficient simulations essential. The self-excited forces are therefore modelled by applying a state-space model. The state variables are solved directly at the element level and considered in the analysis by developing a finite element, making it unnecessary to include them in the global system matrices. A full long-term analysis of important load effects has been studied in detail, and a possible approximation considering only mean wind velocities that contribute significantly to the long-term extreme value distributions has been investigated. A short-term analysis has also been carried out to investigate how short-term extremes can be used to approximate the long-term extreme values.

2. Wind-induced dynamic response

The equation of motion for a cable-supported bridge subjected to wind loading is

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{F}_{wind}(t). \tag{1}$$

Here, $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ symbolize the still-air mass, damping and stiffness matrix, respectively; $\mathbf{u}$ represents the degrees of freedom of the finite element model. $\mathbf{F}_{wind}$ represents the wind actions that consist of a time invariant part due to the mean wind velocity, and a dynamic part due to turbulence in the wind field, vortex shedding and self-excited forces generated by the motion of the structure. Since vortex shedding induced vibrations typically occur at very low mean wind velocities and will usually not give a significant contribution to the long-term extreme value distribution of the load effects, this paper will focus on modelling of wind loading due to the mean wind velocity, turbulence and the motion of the structure. A special attention is put into how one can model the self-excited forces in an efficient manner to reduce the required computational effort.

2.1. Efficient modelling of self-excited forces

2.1.1. Simulation of self-excited wind force in the time domain

The self-excited forces acting on a bridge deck section are commonly represented by the aerodynamic derivatives developed by Scanlan and Tomo [16]. The self-excited forces $\mathbf{q}$ for a bridge deck in a single-frequency harmonic motion can be expressed as follows