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Tension during parametric excitation in submerged vertical taut tethers

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ABSTRACT

The construction of a suspension bridge with floating pylons or a submerged floating tunnel requires the installation of a mooring system. The option of taut vertical tethers, similar to those used in tension-leg platforms, has been suggested in preliminary designs. The environmental loading on the tether, mainly due to wind waves and swell, results in a parametrically excited system. Certain loading conditions develop instabilities that translate into large horizontal motion. However, the effects of parametric resonance on the tension values have rarely been investigated. This paper aims to clarify the relation between lateral displacement and tether tension and to quantify the extreme tension values in the event of parametric resonance. The presented analysis is based on a full numerical model of the tether that includes geometric and hydrodynamic nonlinear effects. This model is used to investigate a representative example that illustrates parametric resonance and multiple parametric studies to assess the effects of the excitation frequency, amplitude, initial pretension, tether length and inclination angle on the tether's response. The results reported here provide the basis for a recommendation on designing a tether under parametric resonance regarding the ultimate extreme values and fatigue life.

1. Introduction

The National Roads Authority (NRA) in Norway is planning to cross several fjords along the west coast of the country as part of the "Ferry-free E39" project [1]. These crossings are characterized by large widths (up to 5 km) and depths (up to 1 km) that require unconventional engineering solutions. The preliminary designs suggest the construction of floating suspension bridges and submerged floating tunnels, as illustrated in Fig. 1. A floating bridge is not a new idea and several examples can be found worldwide [2]. However, no precedent exists of a suspension bridge with multiple floating towers. A submerged floating tunnel is a structural concept that has been considered several times during the last century [3]; this tunnel essentially consists of a watertight buoyant tube at a certain depth underwater. To date, no such structure has ever been built. Both a long floating bridge and a submerged floating tunnel require a mooring system (Fig. 1) to position these floating structures and to resist any imposed motion due to environmental loading. Since these structures would be located near the end of the fjord next to the sea, they would be exposed to sea states with wind waves and swell. In particular, swells have a long period and can last for several hours with effects that decrease linearly with water depth. There are concerns that these environmental loads can parametrically excite the tethers of the mooring system, leading to parametric resonance or Mathieu instability.

The taut mooring systems proposed in Fig. 1 are similar to those used in Tension-Leg Platforms (TLP), which are usually made of steel tubes [4]. These tension pipes or tethers are designed to avoid slack cable configurations while also considering the peak and fatigue loading conditions [5]. As a result, these tethers have high pretension levels, zero net buoyancy and such massive dimensions that they cannot be considered to be compliant in the axial direction [4]. The environmental loads on the bridge towers or the submerged tunnel lead to varying tension levels and imposed motions on the tether that define a parametrically excited system.

A tether excited by harmonically varying imposed displacements of one of its ends is a parametrically excited system. Under certain conditions, parametric excitation leads to parametric resonance, which is an unstable situation that produces excessive lateral motion. The principal parametric resonance occurs when the frequency of the upper support motion is twice the fundamental frequency of the tether, i.e., a 2:1 frequency ratio. However, there are many more frequencies that induce instability in the system. Reasonably small amplitudes of anchorage oscillations may lead to important steady-state tether responses [6,7]. Fur-

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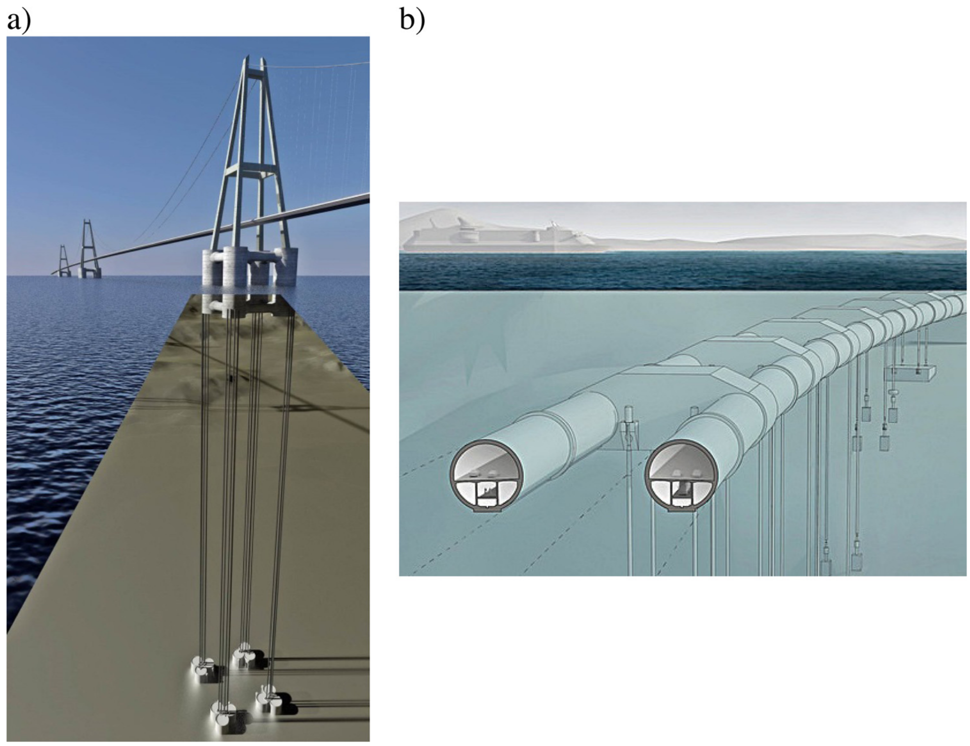

Fig. 1. a) Floating cable-stayed bridge (Source: The Norwegian Public Roads Administration; https://flic.kr/p/pcgEt3); b) Submerged floating tunnel (Source: Snøhetta; https://flic.kr/p/yGeftB).

thermore, the greater the amplitude of the support motion is, the more frequencies there are that lead to unstable motion. Parametric excitation has been extensively studied in the field of differential equations and dynamic systems [8] and is generally described by the nonlinear Mathieu equation, where the excitation appears as time-varying coefficients. In bridge engineering, this phenomenon has been theoretically studied [6], investigated in laboratory experiments [7] and examined in cable-stayed bridges [9] where girder or mast oscillations have parametrically excited the stay cables.

The response of a submerged tether differs significantly to that of a dry tether because of the influence of hydrodynamic drag, which is the most important nonlinear contribution [10] and acts as an additional line damping component. Moreover, it has been shown [11,12] that the out-of-plane motion can be neglected when calculating the response of submerged slender structures. For a tether in an unstable condition, the quadratic fluid damping force limits the amplitude of the lateral motion [13]. An example of instability analysis for TLP tethers is given in [14]. Reference [15] derives an approximate analytical expression of tether displacements including hydrodynamic effects for principal parametric resonance. Additional literature reviews of the instabilities of risers and immersed slender structures can be found in [16,17].

The majority of the publications that have studied the parametric excitation of cables (either dry or submerged) mainly focus on lateral motion. As indicated in [18], tension has been overlooked in many studies. However, displacement is not the most important load effect. In fact, tension and stress values are of greater relevance when designing a taut mooring line. Some publications have specifically investigated tension to some extent. For example, reference [6] numerically shows how tension values develop on a dry cable during parametric excitation. In addition, [19] studies numerically tension using an experimentally validated model, while [18] shows that to achieve correct tension values, the model must account for spatiotemporal variations of tension along the cable. Moreover, [20] shows that the difference in magnitude (in spatial distribution) between the maximum and minimum tensions increases for a cable with significant sag. Furthermore, [21] concludes that the increase in pretension is ultimately equivalent to the increase in damping. In addition, [22] includes tension in the numerical analysis and states the need for understanding the impacts of parametric excitation. In [12], the dynamic tension values are measured for a submerged cable with sag in a scaled laboratory experiment, and recommendations are provided for the scaling and the support's boundary conditions. Other examples in the literature study the cable tension, but they do not consider the particular case of parametric excitation. For instance, [23] derives an approximate analytical expression of dynamic cable tension, and [24] obtains an analytical approximation of the probability distribution of the dynamic tension envelope for a random sea state. Therefore, even though some investigations have considered tether tension, additional studies are needed to characterize parametrically excited taut mooring systems.

Correct tether design should include the fatigue limit state [25] to avoid failure due to crack growth initiated from a welded joint in the tether. Detailed fatigue design recommendations can be found in [26]. The magnitude of the stress cycle and the number of load cycles are the key parameters that determine the accumulated fatigue damage of the studied member. However, based on the studies published to date, it is not possible to assess correctly the stress values of a taut mooring line with parametric resonance or its effects on the tether's fatigue life. The total stress in a tether is the combined result of several load effects, namely the axial load, bending moments and hydrostatic pressures. In most parts of the tether's length, the main contributor to the stress is the total (static + dynamic) tension, whereas bending moment has only a marginal effect [25]. On the other hand, bending moments can be very important near the tether ends. It is important to note, that this study does not evaluate all the aspects required for the design of a tether. The scope of this study is limited to the study of tension.