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Active truncation of slender marine structures: Influence of the control system on fidelity

Thomas Sauder[a,c,*], Stefano Marelli[b], Kjell Larsen[d,a], Asgeir J. Sørensen[a]

[a] Centre for Autonomous Marine Operations and Systems (NTNU AMOS), Department of Marine Technology, NTNU, 7491 Trondheim, Norway
[b] Chair of Risk, Safety and Uncertainty Quantification, Institute of Structural Engineering, ETH Zürich, Stefano-Franscini-Platz 5, CH-8093 Zürich, Switzerland
[c] SINTEF Ocean, P.O. Box 4762 Torgarden, 7465 Trondheim, Norway
[d] Statoil ASA, Arkitekt Ebbells veg 10, 7053 Ranheim, Norway

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ABSTRACT

Performing hydrodynamic model testing of ultra-deep water floating systems at a reasonable scale is challenging, due to the limited space available in existing laboratories and to the large spatial extent of the slender marine structures that connect the floater to the seabed. In this paper, we consider a method based on real-time hybrid model testing, namely the *active truncation* of the slender marine structures: while their upper part is modelled physically in an ocean basin, their lower part is simulated by an adequate numerical model. The control system connecting the two substructures inevitably introduces artefacts, such as noise, biases and time delays, whose probabilistic description is assumed to be known. We investigate specifically how these artefacts influence the fidelity of the active truncation setup, that is its capability to reproduce correctly the dynamic behaviour of the system under study. We propose a systematic numerical method to rank the artefacts according to their influence on the fidelity of the test. The method is demonstrated on the active truncation of a taut polyester mooring line.

1. Introduction

Floating structures used in the oil&gas, offshore wind or aquaculture industries require significant investments and must operate according to high safety and environmental standards. Therefore, the design of such structures is in general verified by means of hydrodynamic model testing prior to their construction. When performing such laboratory testing, the floating structure under study is constructed at reduced scale, and exposed to selected environmental conditions (wave, wind and current) that may be experienced during its design life. It is verified that the motions of the platform, the loads in the mooring and riser systems, or other quantities of interest (QoI) are acceptable under these conditions. The test campaign is in general also a final risk mitigation campaign, during which events not yet fully described by engineering numerical tools, such as green water and wave impact, could be detected and analyzed [1].

Floating structures are, however, installed at locations with increasingly large water depths. Oil exploitation takes nowadays place down to nearly 3000 m water depth [2], and deep-sea mining of minerals is considered in water depths reaching 6000 m [3]. Modelling such systems with a reasonably large scale factor in existing hydrodynamic laboratories is challenging, due to both the vertical extent of the mooring system, but also due to its horizontal footprint, that ranges from two to four times the water depth [4]. This challenge has been identified two decades ago, and has been addressed in details in [5]. The state-of-the-art approach, up to now, consists in performing *passive truncation* of the slender marine structures, as described briefly in the following. In a first stage, a truncated version of the mooring/riser system is designed such that it is *statically equivalent* to the full-depth system, and fits in the ocean basin [6]. It should be emphasized that the *dynamic* properties of the truncated system, such as the level of drag-induced damping of the horizontal motions of the floater, are generally not representative of the full-depth system, except possibly on a narrow range of sea-states. Model testing is then performed using the truncated system, and the experimental results are used to cali-

* Corresponding author at: Centre for Autonomous Marine Operations and Systems (NTNU AMOS), Department of Marine Technology, NTNU, 7491 Trondheim, Norway.
E-mail addresses: thomas.sauder@ntnu.no (T. Sauder), marelli@ibk.baug.ethz.ch (S. Marelli), klars@statoil.com (K. Larsen), asgeir.sorensen@ntnu.no (A.J. Sørensen).

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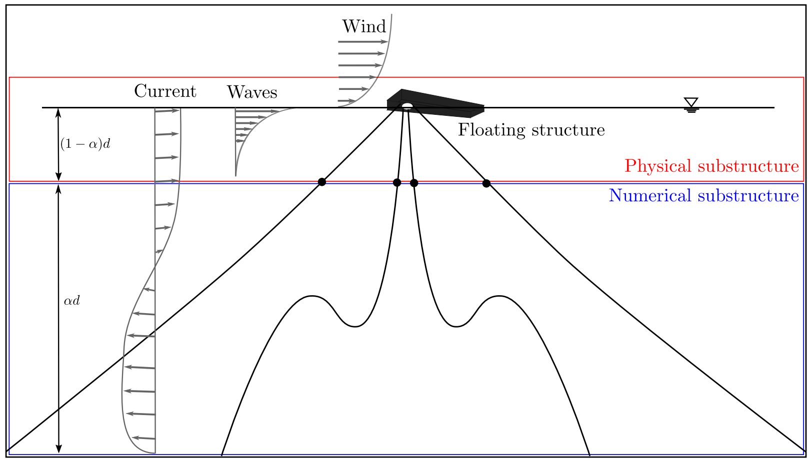

Fig. 1. Model testing of an offshore structure with taut mooring and a flexible riser system in water depth d. Illustration of active truncation with truncation ratio $\alpha = 0.8$.

brate a numerical hydrodynamic model *of the floater* connected to the truncated system. The truncated system is finally replaced by the full-depth one in the *numerical* analysis, and the QoI, such as extreme motions and mooring line tensions, are evaluated numerically. In spite of recent improvements in the truncation procedures, which have been reviewed for example in [7,8], passive truncation still requires to calibrate a numerical model of the floater, which is time consuming and induces additional uncertainties. Furthermore, since the truncated system used in the model tests is only statically equivalent to the full-depth system, it can be argued that some highly nonlinear effects driven by the floater's dynamics (such as the occurrence of negative air gap or green water on deck) could remain undetected.

In the present paper, we consider an alternative solution denoted *active truncation*. It is based on the ReaTHM® testing[1] paradigm, already applied to solve issues related to model testing of floating wind turbines [9], and with applications beyond the field of marine technology [10,11]. When performing active truncation, the floating structure and the upper part of the slender structure system are modelled *physically* in the ocean basin, while its lower part, which does not fit in the basin, is *simulated* on a computer. This is illustrated in Fig. 1. At the *truncation point*, the numerical and the physical *substructures* interact through a *control system*, including sensors and actuators. Therefore, active truncation intrinsically represents the full-scale system, and allows to obtain the QoI directly after the test, without the need for numerical extrapolation. Note that a strict pre-requisite to perform active truncation is the *validity of the numerical model describing the truncated portion of the slender marine structure.* In most cases, state-of-the-art programs based on the nonlinear Finite Element (FE) method can describe the low-frequency and wave-frequency dynamics of slender marine structures in a satisfactory manner, as for example illustrated in [12,Figure 2]. However, some phenomena, such as complex soil-structure interaction or Vortex-Induced Vibrations (VIV) can still not be simulated with a sufficiently high level of confidence, at least not in real-time. This means that, as of today, if these phenomena are very subject or play a significant role in the empirical study, ReaTHM testing cannot be applied.

The uncertainties that affect purely empirical and numerical approaches have been extensively studied in the past [13,14]. However, when performing active truncation (and ReaTHM testing in general), a new source of uncertainty should be considered, namely the one originating from an imperfect *coupling* between the substructures. Indeed, various types of *artefacts*, such as noise, biases and time delays, are inevitably introduced by the presence of the control system [15]. Such artefacts, could jeopardize the *fidelity* of the setup, in the sense that they could make the system's dynamical properties deviate significantly from those of the real system under study. In the worst case, this could happen without the operator of the test, or the final user of the empirical data, being aware of it. In this paper, we will neglect the uncertainties related to the physical and numerical substructures, to isolate and focus on those related to the control system.

This paper proposes a quantitative definition of fidelity, and presents a method to evaluate it for an active truncation setup. We then show how to systematically *identify the control system-induced artefacts that jeopardize the most the fidelity* (sensitivity study). This latter aspect is believed to be a significant scientific contribution, in addition to be of great operational relevance when such testing methods are to be applied in practice.

The paper is organized as follows. In Section 2, a general method for the analysis of fidelity is outlined, and we show how it can be applied to the active truncation of slender marine structures. This method requires the capability of simulating an active truncated setup, including artefacts, which is the object of Section 3. In Section 4, the method is demonstrated on the truncation of a taut polyester mooring line, which is a widely used component for the positioning of offshore structures in deep water.

2. Fidelity analysis and its application to active truncation

In this section, we first introduce some concepts and terminology which will be used throughout the paper. We then define a quantitative measure of fidelity, and outline a general method to evaluate it and study its sensitivity to artefacts. We finally show how it can be applied to address the active truncation problem.

2.1. Background and terminology

The *real system* (Fig. 2a) is the subject of the study, whose performance under given load conditions should be documented. It is for example the marine system (floater, mooring and riser) represented in Fig. 1. For analysis purposes, it is assumed that the real system can be fully represented by an *emulated system* (Fig. 2b). The emulated system consists of a numerical model capable of simulating the behaviour of the real system in a wide range of operational conditions, including extreme environmental conditions. For slender marine structures, the requirements and nature of this model

[1] ReaTHM® testing stands for "Real-Time Hybrid Model testing", and is a registered trademark of SINTEF Ocean AS.