Experimental evaluation of nonlinear engineering approaches to model the springing and ringing responses of Floating Offshore Wind TLPs

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Highlights

- Experimental and numerical simulations of the springing and ringing responses of a FOWT-TLP are compared for the first time
- Results reveal a significant contribution of viscous forces to the third-order high-frequency excitation and resulting resonant responses

1 Introduction

Floating offshore wind turbines on tension-leg-platforms (FOWT-TLPs) have the particularity of being stiff systems when compared to competing platform concepts. Their pre-tensioned mooring lines maintain the hull in a position of positive buoyancy and significantly restrain the motions. The advantage of such platforms is one of material cost reduction with hulls lighter than their semi-submersible or spar counterparts by a factor of four to five. Furthermore, for designs with inclined mooring lines, the limited amplitudes of movement at the nacelle elevation can remove the requirement for a dedicated turbine controller. However, the stiffness of such systems makes them prone to high-frequency (HF) response in the vertical degrees of freedom (heave, roll, pitch) due to nonlinear wave-body interaction. These nonlinear effects are referred to as springing and ringing for the steady and transient resonant responses respectively (DNV-GL 2016). These HF resonant responses are responsible for an increase in the ultimate design loads as well as an increase in the fatigue damages over the life of the turbine (Bachynski 2014). Furthermore, the natural modes of the turbine tower and of the platform in heave, roll and pitch motions lie typically in a similar frequency bandwidth, $f = 0.2 - 1.0$ Hz, and strong coupling effects between the tower fore-aft bending and the platform pitch motion have been observed. Hence, accounting for springing and ringing also has an impact on the stochastic prediction of the maximum bending moment and fatigue damages accumulated at the tower base (Bachynski 2014). Therefore, including nonlinear HF hydrodynamic forces is crucial for simulating design load cases and fatigue of FOWT-TLPs.

Engineering approaches rely on frequency domain potential flow theory to model the nonlinear diffraction-radiation effects and couple them with the drag term of the Morison equation to account for viscous forces. This methodology has the advantage of being light and applicable to aero-hydro-elastic time-domain solvers widely used for the stochastic design of FOWT systems under many sea-state realisations. Whilst second-order inertial HF loads are generally well represented in the frequency domain using quadratic transfer functions (QTFs) which can be calculated with Boundary Element Method (BEM) solvers, the choice of models is less trivial when it comes to model the third-order inertial loads. This study therefore presents the results of an experimental campaign aimed at evaluating various engineering numerical approaches to simulate the springing and ringing responses of an academic FOWT-TLP system.

2 Method

2.1 Experimental method

An experimental campaign was carried out in wave flume No 5 of the LHSV-LNHE laboratory at EDF R&D facilities in Chatou (France). An 1:83 scale model of an academic FOWT-TLP system carrying the 10MW DTU reference wind turbine is tested in unidirectional regular and irregular waves (Figure 1). The academic model consists of a tri-floater hull with a central mast carrying the turbine and three submerged side buoys connected by an assembly of bracings and anchored using three inclined mooring lines. The physical model represents the hull as a rigid body whilst the tower is pseudo-flexible. The mooring lines are represented in the physical model using steel wires with the correct linear mass distribution and a spring representative of the axial stiffness at scale. The mooring system is anchored to the sea-bed using three tension load cells which measure the vertical mooring force. The displacement at the nacelle is measured in a 2D vertical plane using a camera tracking system. Finally, a pair of Inertial Measurement Units (IMUs: 3DOF Accel. + Gyros.) installed at the nacelle and at the base of the tower serve to provide acceleration and static inclination readings.

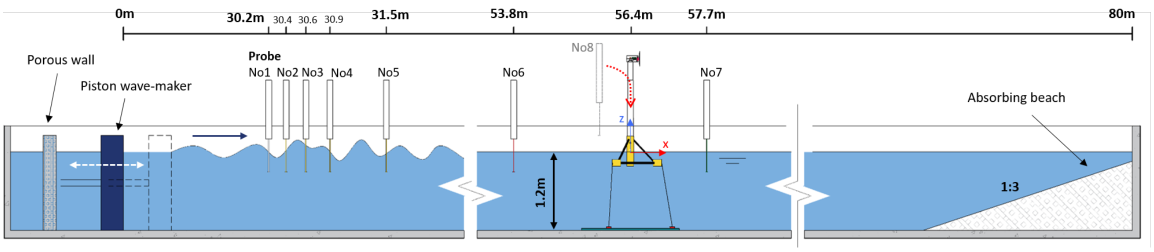


Figure 1: Sketch of the experimental set-up in the wave flume

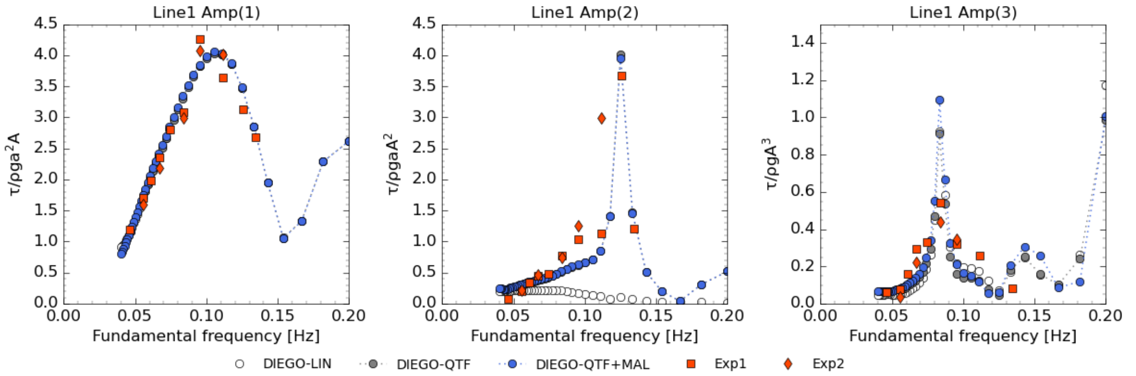
2.2 Numerical method

The numerical models used in this comparative assessment are based on so-called engineering approaches which rely on frequency domain potential flow solution and/or the Morison equation. In this work, the linear transfer functions (LIN) and QTFs are obtained with BEM solvers. On the other hand, the third-order inertial force can only be approximated based on approximate solutions of the potential flow theory. Two methods have been tested. The first approach consists in applying the semi-analytical third-order diffraction solution from Malenica & Molin (1995) (MAL) which is only valid for a fixed vertical cylinder in monochromatic waves. The second one is to use the slender body approximation proposed by Faltinsen et al. (1995), Kristiansen & Faltinsen (2017) (FNV) which can also be applied in irregular wave cases on a vertical cylinder. The third-order force is applied solely on the central mast of the academic TLP since it is the main surface piercing vertical element of the hull.

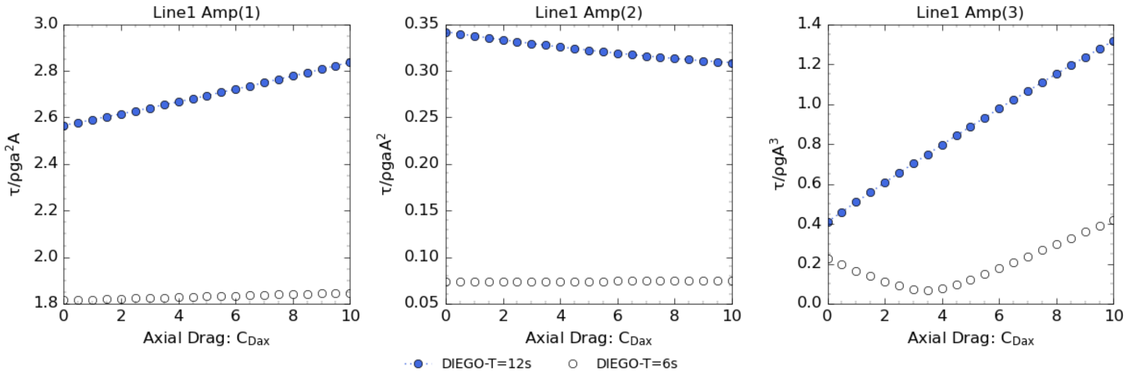
3 Wave cases

3.1 Regular wave cases

Regular wave cases were first investigated to analyse the steady resonance, or springing, of the TLP system due to the nonlinear wave forces. Using regular waves enables to extract the HF harmonics of the motions and line tension responses under various fundamental wave frequencies.



(a)



(b)

Figure 2: (a) Comparison of EDF-TLP line tension harmonics transfer functions and (b) sensitivity of the springing responses amplitudes to the axial drag coefficient for the upstream Line No1- Potential flow models in regular waves, kA=0.10

To illustrate the results of this campaign, Figure 2a displays, from left to right, the normalised line tension amplitudes of the first (fundamental), second and third harmonics as a function of the fundamental frequency of the regular wave train. Figure 2b displays the same amplitudes as a function of the axial drag coefficient used in the numerical model on the vertical cylinders (central mast and side buoys) for a selection of two wave frequencies which generate springing represented by two curves. The results in Figure 2a show that, whilst a linear potential flow model coupled with Morison drag (grey curve) does not capture the second-order springing response at all, it clearly manages to capture the third-order springing predicted experimentally. The additions of third-order inertial models (blue curve) appear to have a small impact on capturing that response. This suggests that, in the case of a TLP with large submerged elements, vertical drag forces can dominate the third-order springing response. This hypothesis is further confirmed by a sensitivity analysis to the axial drag coefficient at the springing frequency shown in Figure 2b which shows that increasing the vertical drag increases the amplitude of the third-order springing response instead of damping it. The significance of drag on the third-order excitation forces was already suggested by a CFD analysis on the hull of this TLP floater in fixed conditions (Rongé et al. 2023).

3.2 Irregular wave cases

Simulations in irregular sea-states were also carried out with wave only and wind-wave storm conditions. Scalograms obtained via wavelet transform of a selected ringing event measured experimentally and simulated numerically for a 1h sea state realisation, with $H_s = 9.2$ m, $T_p = 12$ s (at 10MW scale) are provided in Figure 3. The time-frequency amplitude of Line tension for the downstream line (Line No1) are given for the experimental measurement and engineering approaches with increasing order of non-linearity. The results show that the transient ringing response is captured even by the linear model whilst the steady springing response appears only when including QTFs. This illustrates again that viscous forces have a significant impact on the ringing response for this TLP system. Whilst the inclusion of the third-order inertial loads do lead to increased resonance, correct modelling of the vertical viscous forces is most likely as important if not more critical. An increased interest for viscous forces impact on the ringing response of TLP system is therefore recommended.

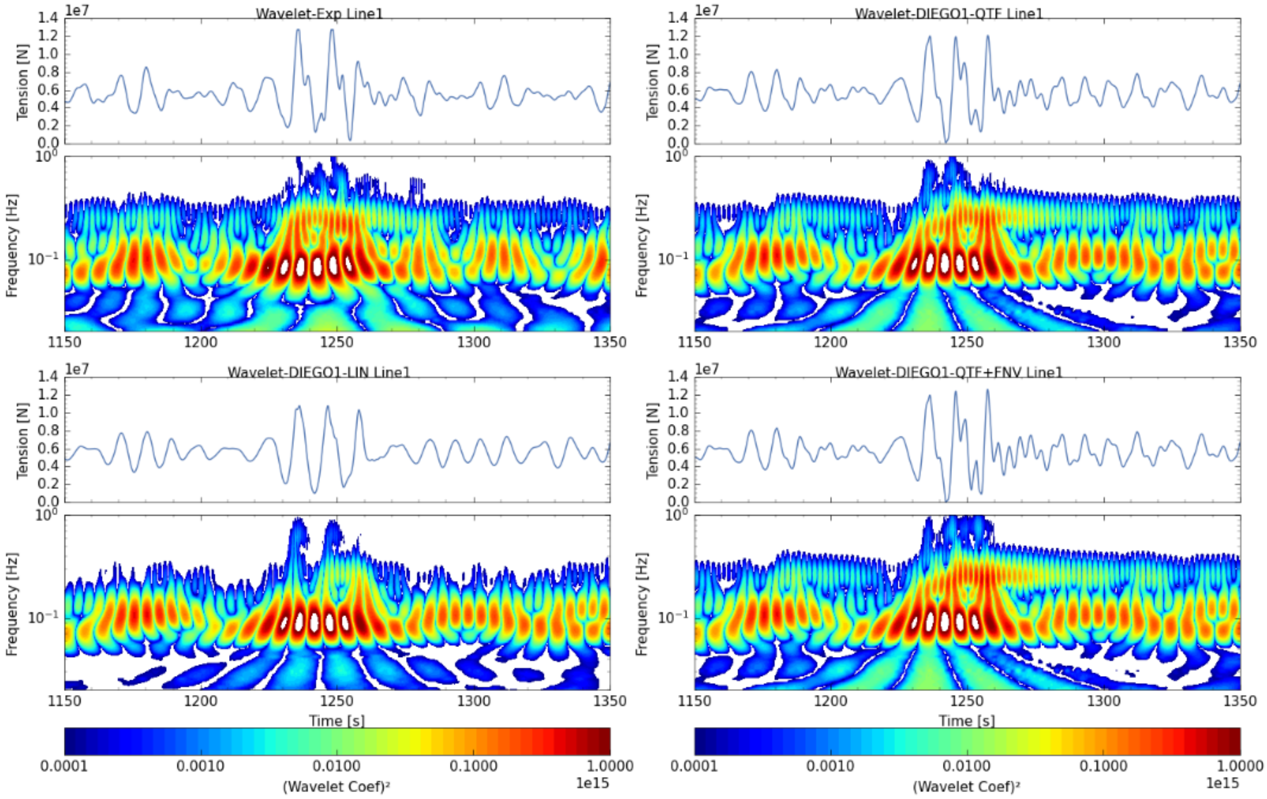


Figure 3: Scalograms of the vertical line tension time-frequency amplitudes of Line No1 for a selected ringing event in irregular wave case EC2a: $H_s = 9.2$ m, $T_p = 12$ s and $\gamma = 3.0$

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