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Dynamics of offshore risers using a geometrically-exact beam model with hydrodynamic loads and contact with the seabed

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ABSTRACT

In the context of challenging scenarios for offshore oil exploitation, robust numerical models are necessary to predict the risers' mechanical behavior. This work presents a model to simulate offshore risers' dynamics using the geometrically-exact approach for beams. Expressions are derived for the hydrodynamic loads due to riser-seawater flow interaction, adopting the Morison's equation and considering large displacements and finite rotations, including the added mass and drag contributions. The consistent linearization of the weak form of such effects was obtained, permitting the use of Newton-Raphson method to solve risers' dynamics using an implicit time-integration scheme. The riser-seabed interaction is also considered with a model that accounts for the possibility of rolling on the seabed. A catenary riser dynamics and a vertical riser experiencing parametric resonance due to heave-imposed motion were simulated. The model showed promising behavior to deal with large nonlinearities.

1. Introduction

The offshore oil exploitation involves usage of many structural solutions. These have to be designed to keep their functions under challenging environmental scenarios, such as very-deep water, severe sea waves, ice and others. Particularly, the present work focuses in risers' analysis, which can be structurally-viewed as very slender beams, connecting the floating unit to the seabed. Fig. 1 shows two examples of riser configurations: a vertical riser, which presents a steep connection with the seabed, and a catenary riser that presents a smooth connection between the riser and the seabed. The riser touches the ground laterally, establishing a contact region which starts at the touchdown point (TDP) – see Fig. 1(b). There are other possible riser configurations that are not the main concern of the present work (see e.g. [1] for examples).

When looking at the details of the cross section of risers, one can find many different geometries and materials, depending on the required operational function. When referring to pipes, one can elect basically two different possibilities: the rigid pipes (steel pipes), or the flexible pipes (composed by many layers) – see [2,3] for more details. Furthermore, there are umbilical cables, which may also be installed in catenary configuration and can be viewed as riser structures used to transmit power and commands. Additionally, there are other elements in an offshore plant that may be globally modeled as long beams, such as hoses and mooring lines. The beam cross-section equivalent properties to be used, however, is another concern that is usually solved in a local modeling, which depends on the kind of structure to be represented. Here it is possible to list some classical and recent works that present analytical and numerical methodologies to establish equivalent cross sectional stiffness data of flexible pipes and umbilical cables.[1] As examples, one may see [3], where a comparison of different models was made to represent the internal mechanics of a flexible pipe, [4], where an analytical model was developed to account for tension/torsion behavior, [5] and [6], where the bending behavior was addressed, [7], which presents numerical models to account for bending behavior and explores the limitations of analytical approaches, [8], where a linear operator was developed to relate generalized stresses and strains in a flexible pipe, and [9], that presents a finite element model to account for internal mechanics of umbilical cables. The present work focus is in riser's global modeling. Then, the properties of the equivalent beam cross section will be treated as an input to be taken from experiments or other analytical/numerical models.

The ocean environment induces several loading in offshore structures. One can organize them in two main categories: static

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[1] The stiffness data may depend on loading magnitude. This can be seen in referenced works by curves, e.g.: bending moment vs. curvature and torsion moment vs. axial rotation, which are may be nonlinear. For flexible pipes and umbilical cables, this can be a result of sliding between layers. When inputting such data in a global beam model, one can face this behavior as an equivalent physical nonlinearity.

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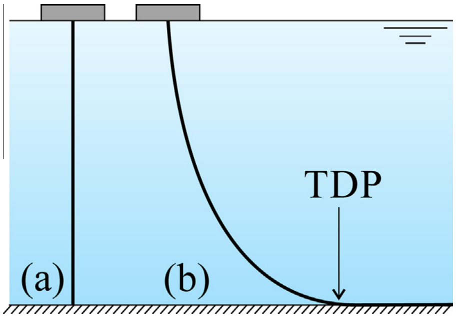

Fig. 1. Offshore riser examples: (a) Vertical riser and (b) Catenary riser.

and dynamic. This is done according to the time-scale associated with each load variation and the structure natural periods in which one is interested. Typically, for riser structures, one can elect as static loading: the structure self-weight, the buoyancy (due to external/internal fluid pressures) and the sea current drag (assuming a constant relative far-field velocity between the fluid and the structure).

Regarding dynamic loading, among others, one can mention the many sources of hydrodynamic actions. One possible cause is related to the sea waves, which affect the water velocity and the hydrodynamic loads in the risers (see [1,11]). Usually this effect is more pronounced close to the surface. Another important dynamic action is the induced movement at the riser top connection, which comes from the floating unit movement, and may lead to time-varying hydrodynamic forces along the whole riser extension. The riser top connection, then, is subjected to a time-dependent prescribed motion due to the vessel dynamic behavior. This leads to a time-dependent relative velocity between the riser and the seawater, which creates hydrodynamic damping effects. Furthermore, as mentioned and shown in Fig. 1(b), some riser configurations may present nonlinear boundary conditions (contact) that may change during time. The touchdown point and the riser region laid on seabed may change due to dynamic actions. All the mentioned effects implies that the riser dynamics is essentially nonlinear. In this context, the riser-seabed interaction has been addressed in some interesting works, as in [11], where 3D experiments were performed to study the steel catenary risers (SCR) interaction with the soil, in order to calibrate interaction models. In [12] a study of the influence of the riser-soil interaction in SCR dynamics was addressed. Furthermore, in [13,14] one finds studies on the nonlinear seabed-riser interaction applied to models to simulate SCR dynamics.

Looking at the entire offshore plant system composed by the mooring lines, pipes, umbilical cables and the vessel, one finds a very complex fluid-structure-seabed coupled problem.[2] For the present work focus, only the riser analysis is presented, facing the floating unit movements as input data that are independent of risers' movements. The full coupling simulation of the whole system is the aim of future works. It has to include a model to predict the dynamics of the floating unit, coupled with the model of submerged structures.

In the engineering point of view, the riser analysis must be carried out considering dynamic effects. This permits the evaluation of alternating stresses along the riser structure, which leads to evaluating the fatigue life. Such kind of study is currently done by the offshore industry, which makes use of available numerical simulators. With larger depth oil exploitation, new engineering solutions are being developed. Then, the dynamic analysis may depend on a robust numerical solver. For example, situations of riser dynamic compression are common in practice, which may lead to the needing of a geometrically nonlinear model able to predict post-buckling configurations.[3] Moreover, the riser-seabed interaction is a very complex problem that involves soil mechanics coupled with a nonlinear structural behavior. These are currently research areas that need better computational models, able to predict more accurately their physical interaction. The main motivation of the present paper is: to create robust numerical dynamic models able to analyze risers, by using the geometrically-exact beam theory together with contact models. The begin of such development was presented in [2] (static model), which was used to study riser's stability under torsion in [19–21]. A preliminary dynamic model was employed with no hydrodynamic damping forces. The contact models from [22] were used to study the riser sliding and rolling/sliding on the seabed in [23], assuming statics. The present paper main contribution is the development of effects of the hydrodynamic forces using the geometrically-exact assumption, including added mass and drag effects, and inertial effects, which are developed in a complete form using the Rodrigues rotation parameters. When compared to the existing models to solve risers, the main new contribution of this work, by author's knowledge, is the consistent linearization of the weak form contribution due to anisotropic added mass and drag effects, using the Morison's equation, considering the updated Lagrangian kinematics with Rodrigues rotation parameters. It permits usage of the Newton-Raphson method to solve riser dynamics using an implicit time-integration model, in an efficient way. This was done adopting a special version of the Newmark method to integrate rotations, proposed in [24,25]. The numerical examples show the applicability of the model, which can capture important phenomena, such as the riser dynamic interaction with the seabed and parametric resonances.

The paper is divided in the following sections: an introduction, a model overview, the structural beam model description, the development of inertial contributions, the hydrodynamic forces contributions, the contact contributions and, finally, the numerical examples. In the end, the concluding remarks and references are presented. The presentation of the equations describing the models was done assuming the nomenclature: bold lowercase letters are used to represent vectors and column matrices (e.g. $\mathbf{u}$, $\boldsymbol{\beta}$) and bold uppercase letters are used to represent second order tensors and matrices with more than one column (e.g. $\mathbf{A}$, $\boldsymbol{\Gamma}$).

2. Model overview

This work employs the geometrically-exact beam model to represent the riser structure (see e.g.: [26–28]). The environmental loads that were considered in the model are: the riser self-weight, the buoyancy and the sea current hydrodynamic forces. In [2] the reader will find the complete development of the riser static loadings. Each mentioned action is discussed next.

The buoyancy (from the hydrostatic pressure load) is considered by the effective weight approach (see e.g. [29]), which is a well-employed modeling technique for riser structures. Basically, the riser is considered to be fully immersed in the sea water and the combined effect of the structure self-weight, buoyancy, and internal fluid pressure, is a resulting force named "effective weight". This is a possibility to modeling the hydrostatic effects by a simple approach. Since using that, however, after solving

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[2] For shallow water, non-floating units may be used, which also present interaction with the seabed. In such cases the platform foundation may play a role in dynamics of the system in critical situations (see e.g.: [15]).

[3] The dynamic compression of risers may occur due to the movement of the floating unit. A compression mechanical wave may achieve some regions of the riser, possibly leading to local buckling. Refs. [16–18] dealt with that for prediction of the critical compression. Since the dynamic compression may occur close to the touchdown point, the contact between riser and seabed may affect such behavior. This study is aim of future work using the here developed model.