Ocean Engineering 163 (2018) 555–569

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Coupled analysis method of a mooring system and a floating crane based on flexible multibody dynamics considering contact with the seabed

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ARTICLE INFO

Keywords:
Mooring system
Flexible multibody dynamics
Seabed interaction
Non-interpenetration constraint
Floating crane

ABSTRACT

The mooring system keeps the position of a floating body in the ocean under environmental loads. Mooring analysis should be performed based on the accurate mathematical model in order to predict the behaviors of the floating body and the mooring system. For this purpose, the finite element method (FEM)-based model has been widely used in recent years to model the mooring line numerically. However, existing studies were only applicable to a single floating body, and solved the equations of motion for the floating body and the mooring lines separately. For the application to a floating crane, which consists of several bodies connected to each other, the coupling effect due to the relative motion of each body should be taken into account. Therefore, in this study, the FEM-based mooring line model applicable to a multibody system is introduced based on flexible multibody dynamics. Then, to realize the interaction between the mooring line and the seabed, the non-interpenetration and slope constraints are suggested, and the friction model including sticking are adopted. For the verification of the suggested model, comparisons with the analytic solution and the commercial software are performed. Finally, the applications for a floating crane under various environmental loads are simulated. The results show that the suggested model can be properly adapted for mooring analysis.

1. Introduction

1.1. Background

The mooring system is a system that includes the mooring line and anchor which keeps the position of the floating bodies under environmental loads. The mooring line connects a floating body to the anchor on the seabed. In the field of offshore engineering, there has been a necessity to increase the dynamic analysis in a mechanical system with a simulation tool. Above all, dynamic analysis of the mooring system is one of the active areas under investigation.

Modeling of the mooring line is very important to predict the motion response of the floating body and the dynamic loads on the mooring lines. There are two types of mooring systems depending on the method of applying a force: a taut mooring system and a catenary mooring system. In a taut mooring system, the mooring lines can be modeled as massless springs, as it keeps the position of the floating body using the tension of the mooring lines. On the other hand, the weight of the mooring lines plays an important role in a catenary mooring system. Tang et al. (2009) analyzed the catenary mooring system and divided it into three types of models, i.e., an analytic catenary model, lumped-mass model, and finite element model. The analytic catenary model (Faltinsen, 1993) is a quasi-static model which calculates the force exerted by the weight of the mooring line based on a force equilibrium equation. Therefore, dynamic effects due to inertial and drag forces cannot be considered. The lumped-mass model was first suggested by Walton and Polacheck (1959); it considers the dynamic effects as it concentrates mass and external loads to the nodes which are connected by massless springs. However, for a system with multiple mooring lines, the lumped-mass model appears inopportune for programming (Ma et al., 2015). Therefore, with these disadvantages in mind, the finite element method (FEM)- based mooring line model is adopted in this study.

Traditionally, the dynamic motion of the floating body, such as the floating crane, has been analyzed by many researchers based on the multibody dynamics. For this purpose, simulation tools are developed for dynamic analysis of the shipbuilding and offshore operation processes (Ham et al., 2015; Park et al., 2016). In these programs, modeling of the mooring line is simply suggested, using the massless spring or analytical catenary model, which is not appropriate for dynamic

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https://doi.org/10.1016/j.oceaneng.2018.06.025
Received 6 February 2018; Received in revised form 15 May 2018; Accepted 9 June 2018
0029-8018/ © 2018 Published by Elsevier Ltd.

Table 1
Comparison of this study with related works.

Related works	Mooring line model	Shape function for beam	Applicable to multibody	Stretching	Bending	Contact with seabed	Simulation cost	Integration scheme	Iteration
Tang et al. (2011)	Linear spring	–	O	O	X	X	Very low	-	No iteration
Ham et al., 2017a,b	Analytic solution		O	X	X	O	Low	Störmer-Verlet method and Midpoint rule	No iteration
Gobat and Grosenbaugh (2006)	Finite difference		X	O	O	O (Linear spring on node)	Very high	Generalized-α method	Iteration required
Kim et al. (2013)	FEM	1st order	X	O	O	O (Linear spring on node)	Very high	Generalized-α Newmark method	Iteration required
Gutiérrez-Romero et al. (2016)	FEM	1st order	X	O	X	O (Linear spring on node)	Very high	Bossak-Newmark method	Iteration required
Jeong et al. (2017)	FEM	1st order	O	O	X	O (Linear spring on node)	Very high	Newmark method	Iteration required
This study	FEM	3rd order	O	O	O	O (Non-interpenetration constraint)	High	Störmer-Verlet method and Midpoint rule	No iteration

analysis. Therefore, in this study, we suggested the FEM-based mooring line model applicable to the multibody system using the flexible, multibody dynamics. The mooring line was modeled with a group of flexible beam elements which are connected to a floating body and the seabed with ball joints.

1.2. Related works

There are various studies on the dynamic analysis of the moored floating bodies. They are compared in Table 1.

Tang et al. (2011) investigated the dynamic behavior of the dual-pontoon floating structure using a massless spring model for the mooring lines. The massless spring model is not appropriate in the case of the catenary mooring system, as it neglects the weight of the mooring line. Nevertheless, it has some advantages such as being easily adapted to a multibody system and reducing the simulation cost.

Ham et al., 2017a,b developed the safety evaluation program for the mega-floating crane based on the multibody dynamics. He adopted the massless spring model for the taut mooring line and the analytic catenary model for the catenary mooring line. Here, the contact between the mooring line and the seabed is considered for the analytic catenary model. As mentioned in 1.1, this model only considers the static load on the mooring line due to its weight.

Gobat and Grosenbaugh (2006) described the numerical features of the cable structures for the static and dynamic simulation. The discretization scheme based on finite differences is used to model the mooring line. The finite difference is distinguished from the lumped mass method by using an infinitesimally small differential element, rather than a finite discrete element.

Several studies have focused on mooring line analysis based on FEM. Gutiérrez-Romero et al. (2016) presented the non-linear dynamic FEM mooring model to analyze the response of moored floating wind turbine. The interaction with seabed is considered using a spring-damper system. Then, the suggested model is validated against several experimental results. Kim et al. (2013) analyzed the behavior of the catenary mooring line, considering elastic deformation employing FEM. Using different models for the mooring line, such as the linear spring, researchers then compared the motion of the floating body and the mooring line. However, the FEM models in most studies are not applicable to the multibody system, as the floating body was considered as a single body.

More recently, Jeong et al. (2017) suggested the FEM-based mooring line model, which applies to the multibody system. He used linear beam elements to model the mooring line, and also considered the stretching of the mooring line. To consider contact with the seabed, the linear springs are adopted that connect each node of the mooring line and the seabed. In this study, the equation of motion of the floating body and the mooring line was solved separately. Therefore, an iteration process is required to match the boundary condition between the floating body and the mooring line at every time interval, which leads to very high simulation costs.

In this study, the FEM-based mooring line was suggested for the multibody system using a 3rd-order shape function for the beam elements. Both stretching and bending of the mooring line were considered. The contact with the seabed was modeled using the constraints. Then, the equations of motion of the floating body and the mooring lines were formulated together for a fully coupled analysis.

The remainder of this paper is presented as follows. In Section 2, the theoretical background for coupled analysis using the suggested model are presented. Then, the model is verified with an analytic solution and commercial software in Section 3. Section 4 investigates the simulation results of various applications. Section 5 summarizes this study and discuss future works.

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