Ocean Engineering 108 (2015) 493–503

Contents lists available at ScienceDirect

Ocean Engineering

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

Robust dynamics calculation for underwater Moving Slender Bodies via Flexible Segment Model based optimization

Xuesong Xu *, Zaojian Zou

State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, 200240 Shanghai, China

ARTICLE INFO

Article history:
Received 23 June 2014
Accepted 24 August 2015
Available online 10 September 2015

Keywords:
Dynamics calculation
Underwater slender bodies
Numerical calculation
Marine risers
Towed cables

ABSTRACT

Flexible Segment Model (FSM) based optimization method is proposed as a robust dynamics calculation method for underwater Moving Slender Bodies (MSBs). In the method, the underwater MSB is divided into a series of flexible segments, their deformations are analyzed individually, and the dynamics calculation is accomplished by the optimization of a mechanical equilibrium function in a simple form. Because the whole deformation of a MSB is decomposed into small 'curve' deformations of all segments, the dynamics calculation needs a relatively small number of segments for accuracy. The comparison with experimental results shows that the numerical results by FSM based optimization method have good accuracy. Moreover, the tests of sensitivity and error tolerance show the numerical calculation by FSM based optimization method has high stability.

1. Introduction

MSBs often occur in the ocean engineering: marine cables in the towed system, umbilicals of forwarding ROVs, free hanging risers in re-entry operation, underwater waving slender structures, and so on. Due to their flexibility, they may undergo large deformations. Under bad sea condition or high stress, they are vulnerable and easy to be destroyed. To predict their underwater configuration and tension, it is necessary to make dynamics calculation.

In the past decades, there came up a lot of dynamics calculation methods for underwater cables or risers. Cables are of high flexibility, so they may take on large bending deformation anywhere. Howell (1992) investigated the dynamics of low-tension cables. He formulated 3D nonlinear motion equations for a submerged cable, all forces and moments were equated for an incremental cable segment, and temporal finite differences is used to get the numerical solution. Park et al. (2003) also provided a discrete method of dynamics calculation for towed low-tension cables. In his method, the cable was actually discretized into a number of elements, the nonlinear governing equations were derived from force and moment balance analysis on these elements, and an implicit finite difference algorithm was employed to solve 3D-cable equations. Grosenbaugh (2007) examined the dynamic behavior of a towed cable system during ship turning manoeuvers. The governing equations included the effects of geometric and material nonlinearities and bending and torsional stiffness for seamless modeling of slack cables (Gobat and Grosenbaugh, 2006). The equations were solved using an implicit finite difference scheme.

Although marine risers are of low flexibility compared with cables, they may take on large deflections in deepwater cases. Raman-nair and Baddour (2003) formulated the equations of 3D dynamics of a marine riser undergoing elastic deformations using Kane's formalism. The riser was modeled using lumped masses connected by extensional and rotational springs. Hong (2004) provided a dynamics calculation method based on numerical approximation of model functions, in which complex integral and differential governing equations of motion were derived from Hamilton's Principle, and the numerical solution of the equations was approximately got by model functions. Chatjigeorgiou (2008) proposed a finite differences solution method for the numerical treatment of the dynamic equilibrium problem of 2D catenary risers, and the method was based on the so-called Box approximation. Chen et al. (2009) listed dynamics equation based on Euler–Bernoulli beam theory, extracted natural frequencies and mode shapes of marine risers by the method of differential transformation and re-examined the natural frequencies of marine risers by the method of variational iteration (Chen et al. 2015). Sun et al. (2011) analyzed nonlinear dynamics of cable towed body system using a new nodal position finite element method, which calculated the position of the cable directly instead of the displacement by the finite element method, and eliminated the need of decoupling the rigid-body motion from the total motion.

In dynamics calculation, the slender body is often discretized into a lot of elements. In most of the cases, the elements are straight, but the straight elements are not propitious to accurately

* Corresponding author: Tel.: +86 21 34207293; fax: +86 21 34207991.
E-mail address: xsxu@sjtu.edu.cn (X. Xu).

http://dx.doi.org/10.1016/j.oceaneng.2015.08.036
0029-8018/

fit the configuration of slender bodies. Zhu and Meguid (2006) introduced a new curved beam element to analyze low-tension cables. His numerical results demonstrated superior accuracy and high convergence rate of the developed curved beam element.

Xu et al. (2013) also proposed a Flexible Segment Model (FSM) for underwater MSBs. In FSM, a slender body was discretized into a series of flexible curved segments. For each flexible segment, its deflecting feature and external forces were analyzed independently. The deformation of the whole slender body was decomposed into micro-deformations of all flexible segments. And the complex governing equations were listed according to the moment equilibrium on these segments. A linearization method was provided to get the numerical solution to the governing equations. But the segment length and the time interval would influence the stability of numerical calculation. If the segment length was too small or the time interval was too large, the numerical calculation might come up with the divergent results. The reason of divergence in that case was that the errors in the linearization iterations could be magnified gradually.

To improve the applicability and stability of FSM based linearization method, this paper presents a robust dynamics calculation method for underwater MSBs via FSM based optimization. In this method, dynamics calculation is accomplished by minimizing the mechanical equilibrium function instead of solving the governing equations. The stability of FSM based optimization method is very high, so we call it "robust".

The remaining sections is organized as follows: Section 2 introduces FSM and deformation analysis of the MSB; Section 3 lists the equations of mechanical equilibrium based on the deformation analysis; Section 4 presents the numerical calculation of the FSM based optimization method; Section 5 presents the comparison between the experimental and numerical results, and tests the stability and sensitivity, error tolerance of numerical calculation of FSM based optimization method. Section 6 sums up the paper.

2. Flexible Segment Model (FSM)

The MSB can take on any shape, but to simplify the problem, it is assumed to be in long cylinder shape if with no external load. In case of being towed or moved by mother vessel, they may undergo a large deformation. As shown in Fig.1(a), the MSB towed by the mother vessel has a large bending deformation. In a common case, a bottom object is attached to the lower end of the slender body. FSM is proposed by Xu et al. 2013, as shown in Fig. 1(b) and (c). In Fig. 1(b), the slender body is discretized into n flexible segments, marked as S_1, S_2, …, S_n. At the ends of these flexible segments, there are $n+1$ nodes N_1, …, N_n, N_{n+1}. N_1 is the upper end, connected with the mother vessel. N_{n+1} is the lower end, connected with the bottom object. To illustrate the deformation of the slender body, the segment S_i is magnified, although the real deformation of each segment is very small. For S_i, both ends are N_i and N_{i+1}, the midpoint is C_i, as shown in Fig. 1(c).

Although the same FSM is adopted here, the dynamics calculation method of this paper is quite different from Xu's method in 2013, in which the underlying concept is "linearization". However in the method of this paper, we emphasize the concept of "optimization". Due to the difference of underline concepts, the fundamental equations of both methods are in different form. So Sections 2 and 3 will list the fundamental equations necessary for FSM based optimization method.

2.1. Coordinate systems

The global and local coordinate systems are shown in Fig. 1(b) and (c). The global fixed coordinate system XYZ is set as X and Y axes parallel to the horizontal plane, Z axis pointing to the sea floor, and its origin at the initial position of the upper end of slender body. If the upper end is moving, it will leave the origin.

At each node N_i, there is a local moving coordinate system $b_in_it_i$. It is set as axis t_i axial, axes b_i and n_i perpendicular to t_i, and the origin at N_i. In the same way, at the midpoint C_i, there is a local coordinate system $b_{c,i}n_{c,i}t_{c,i}$.

Assume the rotational transform from $b_in_it_i$ to $b_{i+1}n_{i+1}t_{i+1}$ is carried out as the following steps: (1) rotate $\theta_{n,i}$ around axis n_i; (2) then rotate $\theta_{b,i}$ around axis b_i.

The rotational transform can be denoted by

$$\begin{bmatrix}\hat{\mathbf{b}}_{i+1} & \hat{\mathbf{n}}_{i+1} & \hat{\mathbf{t}}_{i+1}\end{bmatrix} = \begin{bmatrix}\cos\theta_{n,i} & 0 & \sin\theta_{n,i}\\ \sin\theta_{b,i}\sin\theta_{n,i} & \cos\theta_{b,i} & -\sin\theta_{b,i}\cos\theta_{n,i}\\ -\cos\theta_{b,i}\sin\theta_{n,i} & \sin\theta_{b,i} & \cos\theta_{b,i}\cos\theta_{n,i}\end{bmatrix} \times\begin{bmatrix}\hat{\mathbf{b}}_i & \hat{\mathbf{n}}_i & \hat{\mathbf{t}}_i\end{bmatrix} \quad (1)$$

where $\hat{\mathbf{b}}_i$, $\hat{\mathbf{n}}_i$ and $\hat{\mathbf{t}}_i$ are unit vectors of axes b_i, n_i and t_i, $\hat{\mathbf{b}}_{i+1}$, $\hat{\mathbf{n}}_{i+1}$ and $\hat{\mathbf{t}}_{i+1}$ are unit vectors of axes b_{i+1}, n_{i+1} and t_{i+1}.

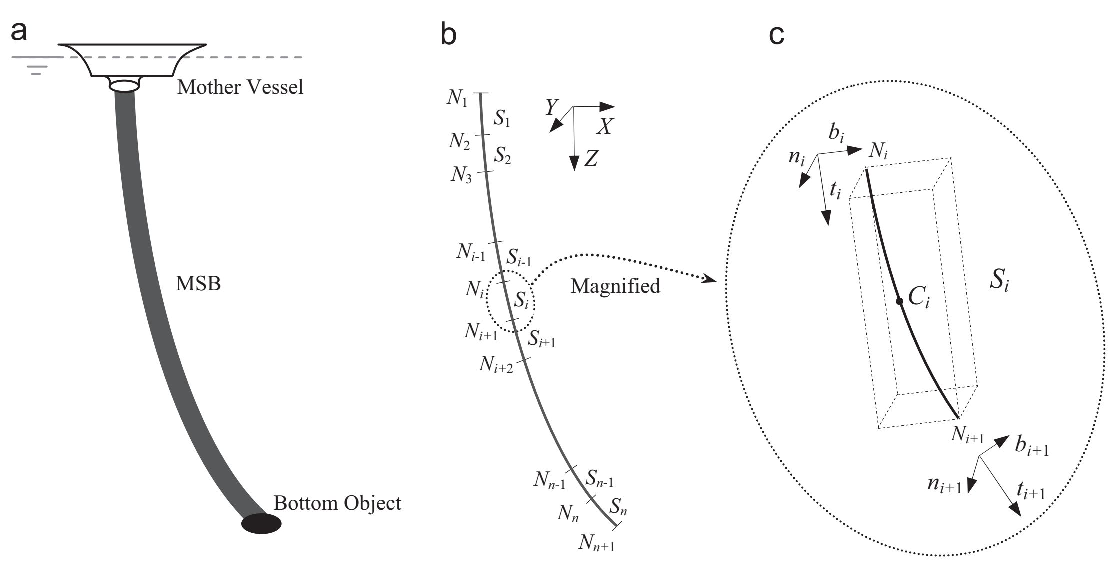

Fig. 1. FSM: (a) a MSB with large deformation, (b) FSM for the MSB, and (c) magnified deformation of S_i.