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Numerical modelling of seabed impact effects on chain and small diameter mooring cables

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ABSTRACT

Catenary mooring lines experience liftoff from and grounding on the seabed when undergoing large dynamic motions. Numerical line mooring models account for this interaction using various seabed models and it is known that the action of liftoff and grounding may lead to large dynamic tension fluctuations. These fluctuations may be spurious due to the inability of discretised mooring models to adequately account for the effect of the seabed on the mooring line. In this work, the root cause and conditions that lead to the production of the large dynamic tension fluctuations is determined. The effect of line discretisation and seabed model on the tension fluctuations is investigated using the widely used spring-mattress approach and a modified seabed reaction force model. An in-house mooring code was developed to perform these investigations. For code validation and benchmarking, and to illustrate the existence of the tension fluctuations problem due to nodal grounding in existing mooring line simulation codes, comparisons are made to a commercial software.

1. Introduction

Catenary mooring lines provide the restoring force necessary for stationkeeping of floating structures primarily by varying its suspended weight in response to the tension applied at the fairlead connection to the floating platform. The seabed has a significant effect on mooring line motions and loads and consequently the dynamics of the connected floating structure as well.

One description of the seabed forces is the spring-mattress model, or variously referred to as the elastic seabed model, such as that proposed by Webster [1]. Similar variations of this approach are used in Refs. [2–5] and is implemented in commercial codes such as Orcaflex [6] and aNyMOOR [7]. The main advantage of this approach is that the entire line length remains active over a simulation. Hence, the effect of the grounded section on the suspended part, and vice versa, is fully accounted for. In contrast to the spring-mattress model, in which the dynamics of the grounded section are calculated, Chatjigeorgiou and Mavrakos [8] proposed a model which calculates the touchdown point from a quasi-static solution, and truncating it from the touchdown point onwards. Consequently, the effects of the line liftoff and touchdown forces are neglected. Thomas [9] proposed a seabed model in which the mass of the first two suspended nodes adjacent to the seabed are gradually reduced as they approach the sea-bed. The motivation for the development of this model was to eradicate the fluctuations in line tension associated with nodal grounding. However, a limitation of the method is that the mass modifier coefficients used to perform the nodal mass reduction have to be determined, by trial and error, for individual grounding nodes and recalibrated for each specific fairlead excitation time history.

Wang et al. [10] used the lumped mass approach to model a mooring line in conjunction with a seabed model based on rigid body collision analysis. It was noted by the authors that, upon line impact with the seabed, there were fluctuations in the fairlead tension which they attributed to the spatially discrete nature of the line structural model. Triantafyllou et al. [11] showed analytically that tension shocks may occur during both the loading and unloading phases of a dynamic mooring cable motion period and derived a condition for its occurrence. Gobat and Grosenbaugh [12] experimentally verified the condition, noting however that the occurrence of unloading shocks may not affect the fairlead tension.

In gist, there have been a variety of seabed modelling methods proposed. For time-domain analysis, the spring mattress method is the most widely used due to its flexibility, simplicity, and completeness of analysis for the entire mooring line. However, previous studies have suggested that it is prone to numerical errors associated with line contact with the seabed.

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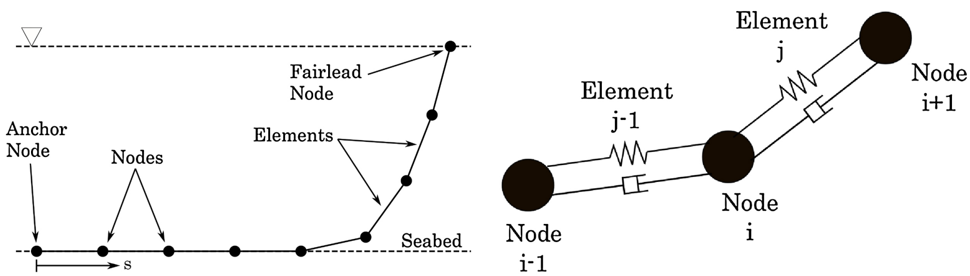

(a) Discretised catenary mooring line. (b) Node and element connectivity.

Fig. 1. Typical lumped mass mooring line discretisation.

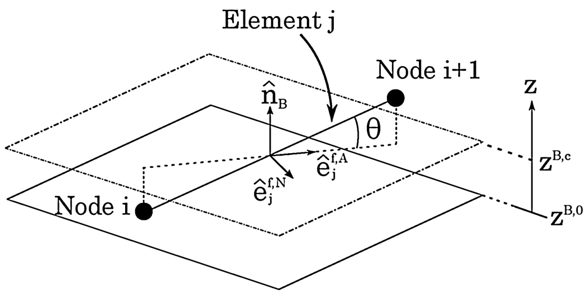

Fig. 2. Seabed coordinate system definitions.

The occurrence of line tension fluctuations due to nodal grounding in discrete, lumped mass mooring models is studied using an in-house code and Orcaflex [6] in this work. As noted by Yang et al. [13], such irregularities in the tension results have a direct impact on the assessment of the fatigue life of mooring lines. The spurious nature and cause of the fluctuations is determined, and the effectiveness of reducing the fluctuations using a modified spring-mattress model is evaluated.

2. Lumped mass mooring line model

The applicability of the lumped mass approach to mooring line modelling has been proven in many implementations [2,4,14]. In a lumped mass model, a mooring line is discretised into nodes and elements, and a typical configuration of a discretised catenary line is presented in Fig. 1a. Fig. 1b shows the connectivity between nodes and elements in the present model. The Orcaflex theory manual [6] documents the force calculation procedures used in that software, while the methods in the current in-house code is presented in this section.

2.1. Distribution of mass

The equations of motion are solved for the nodes. The mass of each element is distributed equally to the adjacent nodes by way of a diagonal mass matrix.

$$\mathbf{M}_i = \frac{m_{j-1}L_{j-1}}{2}\mathbf{I}_3 + \frac{m_j L_j}{2}\mathbf{I}_3 = \sum_{\xi=j,j-1}\frac{m_\xi L_\xi}{2}\mathbf{I}_3 \tag{1}$$

where m_ξ and L_{xi}, $\xi = \{j, j-1\}$ are the mass per unit length and lengths of the elements j and $j-1$, and $\mathbf{I}_3$ is a 3x3 identity matrix.

2.2. Line tension

The tension in a section of the line is represented as the tension, T_j, in the associated element j given by

$$T_j = \begin{cases} K_j\epsilon_j, & \epsilon_j > 0 \\ 0, & \epsilon_j \le 0 \end{cases} \tag{2}$$

where ϵ_j is the strain and K_j is the linear stiffness of the element. The element strain is calculated as

$$\epsilon_j = 1 - \frac{|\mathbf{r}_{i+1} - \mathbf{r}_i|}{L_j} \tag{3}$$

where $\mathbf{r}_{i+1}$ and $\mathbf{r}_i$ are the positions of the nodes bounding element j, and L_j is the unstretched element length. With reference to Fig. 1b, the resultant tension force vector acting on a node is the sum of the tension forces from its connected elements given by

$$\mathbf{T}_i = T_j = K_j\epsilon_j\hat{\mathbf{e}}_j - K_{j-1}\epsilon_{j-1}\hat{\mathbf{e}}_{j-1} \tag{4}$$

where the element unit direction vectors are given by $\hat{\mathbf{e}}_j = (\mathbf{r}_{i+1} - \mathbf{r}_i)/L_j$ and $\hat{\mathbf{e}}_{j-1} = (\mathbf{r}_i - \mathbf{r}_{i-1})/L_{j-1}$.

2.3. Seabed forces

Fig. 2 shows the seabed coordinate system and an element j in contact with the seabed. The seabed nominal elevation is $z^{B,0}$, while the seabed force cutoff elevation is $z_{B,c}$; the elevation at which the element section is not in contact with the seabed. The unit vector normal to the seabed is $\hat{\mathbf{n}}_B$.

The unit vector $\hat{\mathbf{e}}^{f,A}$ is a unit vector that is the projection of the element direction unit vector $\hat{\mathbf{e}}_j$ on the seabed tangent plane, while the unit vector $\hat{\mathbf{e}}^{f,N}$ is the unit vector orthogonal to both $\hat{\mathbf{e}}^{f,A}$ and $\hat{\mathbf{n}}_B$.

$$\hat{\mathbf{e}}_j^{f,A} = \frac{\hat{\mathbf{e}}_j - (\hat{\mathbf{e}}_j - \hat{\mathbf{e}}_j\cdot\hat{\mathbf{n}}_B)}{|\hat{\mathbf{e}}_j - (\hat{\mathbf{e}}_j - \hat{\mathbf{e}}_j\cdot\hat{\mathbf{n}}_B)|} \tag{5}$$

$$\hat{\mathbf{e}}_j^{f,N} = \frac{\hat{\mathbf{e}}_j^{f,A} \times \hat{\mathbf{n}}_B}{|\hat{\mathbf{e}}_j^{f,A} \times \hat{\mathbf{n}}_B|} \tag{6}$$

2.3.1. Spring mattress reaction force model

In the usual seabed spring mattress model as described by Webster [1] and Gobat and Grosenbaugh [5], a seabed reaction force is directly applied on a node as a function of its own vertical elevation,

$$\mathbf{F}_i^{B,r} = k_i^B(z_i^{B,c} - z_i)\hat{\mathbf{n}}_B \tag{7}$$

where k_i^B is the spring constant, $z_i^{B,c}$ is the seabed force cutoff elevation and z_i is the nodal elevation. A damping force proportional to nodal velocity may also be included [5]. The nodal seabed stiffness coefficient k_i^B is given by

$$k_i^B = \frac{W_i}{N^{B,c}D_i - z^{B,0}} \tag{8}$$

where W_i is the nodal weight, $z^{B,0}$ is the nominal seabed elevation, $N^{B,c}$ is the seabed thickness coefficient and D_i is the line diameter at the s-coordinate of Node i.

2.3.2. Modified spring mattress reaction force model

As will be discussed in Sections 4 and 5, the spring mattress model can We present a modified seabed spring mattress model in which an element can be in four states with respect to the seabed, as shown in