Coupled analysis of side-by-side offloading operation between two ships considering stability

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EXTENDED ABSTRACT

1 Introduction

As the International Maritime Organization (IMO) has strengthened regulations on the exhaust gas of ship fuel, ships using an eco-friendly fuel such as Liquefied Natural Gas (LNG) are attracting attention. Accordingly, the demand for the dynamic analysis of LNG bunkering operations, which refuels LNG as ship fuel, is also increasing. In LNG loading operations, two vessels are arranged side-by-side and connected through loading arms. Then, the LNG is transferred through inner pipes in the loading arms. During the operation, dynamic motion analysis is required to evaluate ship motion and the environmental loads exerted on the loading arms. In this study, the coupled analysis of two ships, a Floating Liquefied Natural Gas (FLNG) and LNG carrier, connected through loading arms has been performed considering the hydrodynamic interaction of two floating bodies.

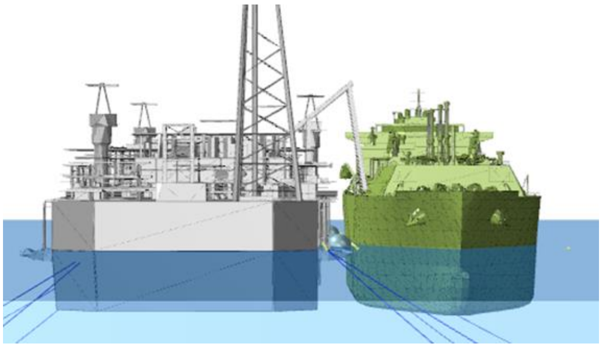

Figure 1 Two ships connected through loading arms

2 Theoretical backgrounds

The loading arms consist of three rigid bodies connected to each other with hinge joints that allow relative rotational motion about one axis. To analyze the environmental loads exerted on the joints of loading arms, the Discrete Euler-Lagrange Equation (DELE) [1, 2] was adopted. The final form of DELE can be represented as shown in equation (1):

$$\begin{bmatrix} \mathbf{M} & -\mathbf{G}_k^T \\ \mathbf{G}_k & \varepsilon \end{bmatrix} \begin{bmatrix} \mathbf{v}_{k+1} \\ h\boldsymbol{\lambda}_k \end{bmatrix} = \begin{bmatrix} \mathbf{M}\mathbf{v}_k - h\mathbf{F}\left(\mathbf{q}_k, \mathbf{q}_{k-1}\right) \\ -\mathbf{g}\left(\mathbf{q}_k\right)/h + \Gamma \mathbf{G}_k \mathbf{v}_k \end{bmatrix} \tag{1}$$

In the equation, **M** represents the mass matrix, **G** is Jacobian of constraint equations, **q** is generalized coordinates, **g** is constraint equations, h is time step, **F** is external forces, ε is regularization term, Γ is stabilization term, and $\boldsymbol{\lambda}$ is Lagrange multiplier. The multibody system consists of two ships, loading arms, and mooring lines that connect LNG to the seabed to keep the location. The mooring lines can be modeled as sets of flexible beam elements. The beam element can be expressed by shape function and nodal coordinates of the body. The contact between mooring lines and the seabed was modeled by using two constraint functions: non-interpenetration constraint and slope constraint [3].

Meanwhile, the calculation of the hydrodynamic forces due to waves is essential to analyze the motion of the floating bodies. In the case of an LNG offloading operation, two ships are located very closely, so the motion of one ship can affect the motion of the other ship. Therefore, the hydrodynamic interaction of the FLNG and the LNG carrier should be considered. For the hydrodynamic analysis of a floating body in the time domain, a Cummins equation is adopted as represented in equation (2):

$$\left(\mathbf{M}+\mathbf{A}\right)\ddot{\mathbf{x}}(t)+\int_0^{\infty}\mathbf{B}(\tau)\cdot\dot{\mathbf{x}}(t-\tau)\,d\tau+\mathbf{C}\mathbf{x}(t)=\mathbf{F}_{exciting} \tag{2}$$

, where **M** is a mass matrix, **A** is an added matrix, **B** is a damping matrix, **C** is a restoring matrix, **F** is the exciting forces, and **x** is the generalized coordinates of the ship. For a single floating body that has 6 degrees of freedom, 6 by 6 added mass, and damping matrices are formulated based on the frequency-dependent hydrodynamic results. In the case of two floating bodies with hydrodynamic interaction, the coupling term is included in 12 by 12 added mass and damping matrices. Based on the Cummins equation for two ships, the hydrodynamic forces exerted on the FLNG and the LNG carrier can be obtained and included in the multibody dynamic formulation in equation (1).

3 Application

For the verification, we compared the motion of two ships under various environmental loads to the results obtained in [4] that adopted a HOBEM (High-Order Boundary Element Method). Then, we developed a dynamic simulation program for ships based on rigid and flexible multibody dynamics and analyzed the dynamic motion of the ships and loading arms in the LNG offloading operation. We assumed four loading arms with 5 m spacing installed in the FLNG, each consisting of 3 rigid bodies. Two ships were arranged side-by-side and connected to each other with loading arms, floating fenders, and mooring lines that were modeled by incompressible springs. We assumed the spread-moored FLNG with 8 mooring lines and set the environmental loads under irregular waves using the JONSWAP wave spectrum. As a result, the relative motion of the FLNG and the LNG carrier, and the motion of the loading arms could be obtained as depicted in Figure 2. Especially, the loads exerted on the joints of the loading arms could be derived during the operation. In the case of the wave with a heading angle of 90 deg, the loads on the hinge joint of the outside arms were heavier due to the relative yaw motion of the two ships.

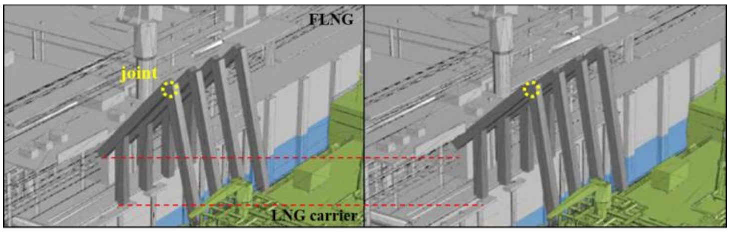

Figure 2 Two ships connected through loading arms

4 Conclusions and future works

In this study, the side-by-side moored offloading simulation was performed considering the hydrodynamic interaction of the FLNG and the LNG carrier. The dynamics of the flexible multibody system were solved by using DELE. The motion of two ships and loading arms were analyzed in the simulation for the optimal design of the loading arms in the future. The simulation results will be analyzed with varying parameters of the operations, and the effect of the operation design will be discussed.

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References

[1] S.H. Ham, M. I. Roh, H. Lee and S. Ha. Multibody dynamic analysis of a heavy load suspended by a floating crane with constraint-based wire rope. Ocean Engineering, 109(2015):145-160, 2015.

[2] C. Lacoursìere, Ghosts and Machines: Regularized Variational Methods for Interactive Simulations of Multibodies with Dry Frictional Contacts, Ph.D. Thesis, Umeå University, 2007.

[3] H.W. Lee, M.I. Roh, S.H. Ham and N.K. Ku. Coupled Analysis Method of a Mooring System and a Floating Crane Based on Flexible Multibody Dynamics Considering Contact with Seabed. Ocean Engineering, 163:555-569, 2018.

[4] B.W. Nam, Y. Kim and S.Y. Hong. Time-domain simulation of berthing problem between FPSO and shuttle tanker in waves. Applied Ocean Research, 58:49-61, 2016.