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Coupled DEM–FEM Analysis of Ice-Induced Vibrations of a Conical Jacket Platform Based on the Domain Decomposition Method

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The discrete-finite element coupling method is an effective approach to simulate the complex interactions between sea ice and offshore structures and ice-induced vibrations (IIVs) of structures. However, the small time step in the discrete element method, as the time step of the coupled method, is time-consuming. Adoption of a time multiscale strategy can solve this problem. This paper proposes a coupled discrete-finite element method based on a domain decomposition method to analyze the interactions between sea ice and a conical jacket platform. Moreover, IIVs of the platform were analyzed. The computational domain is split into several subdomains based on whether sea ice interacts with the platform. The subdomains directly impacted by sea ice use small time steps of the discrete element method. The numerical results show that the proposed time-efficient method is reliable and stable for the simulations of ice-platform interactions.

INTRODUCTION

In cold regions, the vibrations of offshore platforms induced by sea ice can be harmful for not only the routine production but also the serviceability and safety of platforms. Conical jacket platforms have been used considerably in the Bohai Sea of China. The forces induced by sea ice are the dominant environment loads acting on the platforms. Ice-induced vibrations (IIVs) of platforms have also been reported by Yue et al. (2009).

To overcome IIVs of platforms, some beneficial work including field measurements, model tests, and numerical simulations has been conducted on the interactions between sea ice and offshore platforms (Huang et al., 2013; Nord et al., 2015). Because field and scale tests are difficult and expensive, numerical simulations are usually adopted for investigating the dynamic behaviors of offshore platforms under ice loads (Hopkins, 1997; Paavilainen and Tuhkuri, 2013). Kärnä and Turunen (1989) calculated the IIVs of a narrow structure by assuming ice load to be a function of the relative displacement and relative velocity between ice and the structure. The finite element method (FEM) has also been utilized in ice load analyses in which the sea ice is approximated using the material's nonlinear model (Sand and Fransson, 2006). However, the continuum-based FEM is limited by the inherently discrete nature of sea ice, especially in the case of floe ice.

The discrete element method (DEM) was proposed in the 1970s (Cundall and Strack, 1979). It can effectively simulate the failure process of sea ice transforming from continuum to bulk, and it can reasonably reflect the characteristics of ice loads on different types of offshore structures (Polojärvi and Tuhkuri, 2013). In sea ice DEMs, the shapes of sea ice can be modeled using spheres (Ji et al., 2015), polyhedra (Selvadurai and Sepehr, 1999; Polojärvi and Tuhkuri, 2013), and dilated disks (Sun and Shen, 2012). Recently, a DEM installed with bonding–breaking elements was employed to simulate ice breakage and ice loads on conical structures (Ji et al., 2015). Meanwhile, the dynamic responses of an offshore platform can be solved using a well-developed FEM. Therefore, a coupled DEM–FEM is more suitable for analyzing the ice-structure interactions because it combines the advantages of the two methods.

The coupled DEM–FEM has been applied to a wide range of engineering problems. Failure of the structure was modeled using the combined DEM–FEM (Munjiza et al., 2004). Xu and Zang (2014) proposed a four-point combined DEM–FEM based on a penalty method to analyze the brittle fracture of a laminated glass. Michael et al. (2014) used the DEM–FEM to simulate the interactions between a tire tread and granular terrain. The coupling of the DEM and FEM is based on the interface shared by two spatially separated domains, on which the contact forces obtained by the DEM and deformations obtained by the FEM are external loads of the FEM and boundary conditions of the DEM, respectively (Chung and Ooi, 2011). However, the computational time step of these coupled methods must be considered to improve efficiency of the algorithm.

In the DEM simulations, the explicit central difference method requires a very small time step to ensure computational stability. On the other hand, the FEM, which employs the implicit Newmark scheme to obtain the dynamic responses of the structure, can use a larger time step. When conducting a coupled DEM–FEM analysis, a constant small time step throughout the simulation is not recommended, as it poses a huge disadvantage to the low computational efficiency. Thus, the adoption of a multiscale strategy with space and time appears to be advantageous to efficiently solve the problem. The domain decomposition method (DDM) was introduced into the coupled DEM–FEM with multiscale time steps, and it decomposes the computational domain into subdomains that can be solved individually with different time steps (Combescure and Gravouil, 2002; Bettinotti et al., 2014; Chantrait et al., 2014).

Therefore, this paper proposes a coupled DEM–FEM based on a DDM to analyze the dynamic responses of a conical jacket plat-

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