Establishment of an Improved Dynamic Model of the Total Deep Ocean Mining System and Its Integrated Operation Simulation

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ABSTRACT

An Improved dynamic model of the total deep ocean mining system is established. The pipeline subsystem is built as a 3D discrete element model, which is divided into 3D rigid elements linked by flexible connectors. The flexible connector without mass is represented by 6 spring-damper elements. The external hydrodynamic forces from the longitudinal and lateral directions are both considered and modeled based on the Morisson formula and applied to the mass center of each discrete rigid element. The seafloor tracked miner is built as a simplified 3D single-body model with 6 degrees of freedom. While the track-terrain interaction is modeled by partitioning the track-terrain interface into a certain number of mesh elements with three mutually perpendicular forces, including the normal force, the longitudinal and the lateral shear forces, acting on the center point of each mesh element. With consideration of the operational safety and collection efficiency, two new moving paths for the miner on the seafloor are proposed, which can be simulated with the newly established single-body dynamic model of the miner. Integrating the discrete element model of the pipeline and the single-body model of the miner, a new improved dynamic model of the total deep ocean mining system is finally formed. Two new mining operation process modes of the total mining system, which combine of the active straight-line and turning motions of the miner and the ship, and of the passive towed motions of the pipeline, are proposed and simulated with the new improved 3D dynamic model. Some critical simulation results are obtained, such as the motion trajectory of each key subsystem during the operation process and the velocities of the buoyancy module, which in a way can provide specific guidance and useful reference for the practical deep ocean mining system analysis, operation and control.

KEY WORDS: Deep ocean mining system; discrete element model; single-body model; track-terrain interaction model; moving path; mining operation process mode

INTRODUCTION

The strong increase in demand for metallic raw materials, combined with rising metal prices and gradual exhaustion of land-based resources, has fueled great interest in mining of seafloor deposits resources. A typical deep ocean mining system is an integration of a mining ship, rigid lifting pipes, submerged pumps, a buffer storage, flexible hoses and a self-propelled seafloor tracked miner.

For each subsystem of the deep ocean mining system, various studies and analysis have been carried out. To investigate the performance of tracked vehicles, a number of studies have been carried out since Bekker’s pioneering studies (1969). Wong et al (1989) developed an analytical method for predicting the normal pressure distribution under a moving tracked vehicle, taking into account the response of the terrain to repetitive shear loading. Murakami and Watanabe (1992) developed a mathematical model which predicted spatial motion of tracked vehicles on non-level terrains, and an advanced soil-track interaction model based upon soil plasticity theories. Rubinstein and Hitron (2004) developed a three-dimensional multi-body simulation model for simulating the dynamic behavior of tracked off-road vehicles using the commercial simulation program LMS-DADS and used user defined force elements to describe the interaction between each track link and the ground. Solis and Longoria (2008) described the integration of a realistic and efficient track-terrain interaction model with a multi-body dynamics model of a robotic tracked vehicle, and comparisons between simulated results and those obtained from field testing with a remotely-operated unmanned tracked vehicle. Hong et al. (2002) developed a simplified transient 3D dynamic analysis method for tracked vehicles crawling on extremely soft cohesive soil. Kim et al. (2003) performed a comparative study between the multi-body vehicle model and the single-body vehicle model on extremely cohesive soft seabed soil, analyzed the advantages and disadvantages of the two models with regard to computational efficiency and solution accuracy. Li et al. (2005) built the multi-body virtual prototype model with a scale of 1:1 to the actual size of China’s pilot-miner based on the theory of multi-rigid-body and considering the coupling effects of environment factors, and the kinematic and dynamic simulation analyses were performed to test the miner’s trafficability and maneuverability.

For the pipeline system, Chung et al. (1981) have done a great deal of work about long vertical pipes by finite element method. For example, a nonlinear finite element code was developed to model 3-D dynamic behavior of long vertical pipes by Chung and Cheng (1994). In addition, a new discrete element method which is somewhat simpler than the finite element method, has been developed by Mustoe, Hettemaier and Chung to solve the dynamic coupled bending-axial analysis of two-dimensional pipes. Subsequently, Cheng et al. (1997) proposed an