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A Study of Dynamic Analysis for Deep-seabed Integrated Mining System using Subsystem Synthesis Method

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Abstract

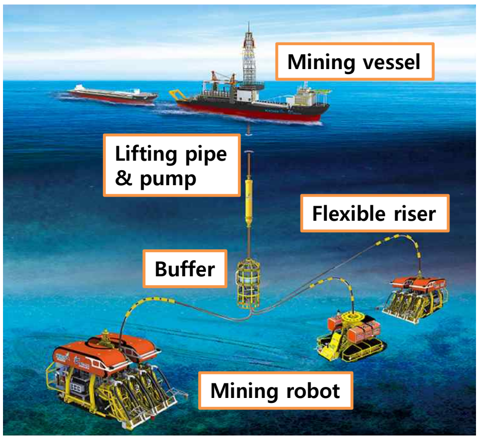

Figure 1: Concept of the deep-seabed integrated mining system.

A deep-seabed integrated mining system, which consists of four subsystems such as lifting pipe, buffer, flexible riser and tracked vehicles, is presented in Figure 1. In order to collect more manganese nodule, multiple tracked vehicle systems should be used in deep-seabed integrated mining system.
The equations of motion for this system model can be obtained as shown in Equation (1)

$$\begin{bmatrix} \mathbf{M}_1 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{\Phi}_{y1}^{1\,T} & \mathbf{\Phi}_{y1}^{2\,T} & \mathbf{\Phi}_{y1}^{3\,T} \\ \mathbf{0} & \mathbf{M}_2 & \mathbf{0} & \mathbf{0} & \mathbf{\Phi}_{y2}^{1\,T} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{M}_3 & \mathbf{0} & \mathbf{0} & \mathbf{\Phi}_{y3}^{2\,T} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{M}_4 & \mathbf{0} & \mathbf{0} & \mathbf{\Phi}_{y4}^{3\,T} \\ \mathbf{\Phi}_{y1}^{1} & \mathbf{\Phi}_{y2}^{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{\Phi}_{y1}^{2} & \mathbf{0} & \mathbf{\Phi}_{y3}^{2} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{\Phi}_{y1}^{3} & \mathbf{0} & \mathbf{0} & \mathbf{\Phi}_{y4}^{3} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{y}}_1 \\ \ddot{\mathbf{y}}_2 \\ \ddot{\mathbf{y}}_3 \\ \ddot{\mathbf{y}}_4 \\ \boldsymbol{\lambda}_1 \\ \boldsymbol{\lambda}_2 \\ \boldsymbol{\lambda}_3 \end{bmatrix} = \begin{bmatrix} \mathbf{Q}_1 \\ \mathbf{Q}_2 \\ \mathbf{Q}_3 \\ \mathbf{Q}_4 \\ \boldsymbol{\gamma}_1 \\ \boldsymbol{\gamma}_2 \\ \boldsymbol{\gamma}_3 \end{bmatrix} \tag{1}$$

where, subscript 1 is the buffer, subscript 2 is the lifting pipe, subscript 3 is the flexible riser and subscript 4 is the mining robot.
In equation (1), $\mathbf{M}$ is the composite inertia matrix of each subsystem, $\mathbf{Q}$ is the generalized force vector, $\mathbf{\Phi}_y$ is the Jacobian matrix of each joint constraint, $\ddot{\mathbf{y}}$ is acceleration vector, $\boldsymbol{\lambda}$ is the unknown Lagrange multiplier and $\boldsymbol{\gamma}$ is the right-hand side vector of the constraint acceleration.

The matrix size of equation (1) is determined by the summation of the number of generalized coordinates used in each subsystem and the number of constraint equations between each subsystem. Also the more elements of lifting pipe and flexible riser increase, the more the number of generalized coordinates increases. If multiple tracked vehicle systems are used, the number of generalized coordinates will grow. Thus, in this system model, the size of the matrix of the deep-seabed integrated mining system is very large. It is needed to allow more time for analysis of this system. In this paper, in order to solve the equation efficiently, total dynamic analysis method for deep-seabed integrated mining system is proposed using subsystem synthesis method [1][2] for the deep-seabed integrated mining system. The existing paper ranged over a rigid body, but in this paper, efficient method has been proposed for offshore system including flexible body. So far, very little has been done in this direction. In this paper, the finite difference method with lumped-mass method[3][4] is used in equations of motion of flexible body.

In equation (1), second equation can be transformed into the equations of motion in terms of acceleration as follows:

$$\ddot{\mathbf{y}}_2 = \mathbf{M}_2^{-1}\left(\mathbf{Q}_2 - \mathbf{\Phi}_{y2}^{1\,T}\boldsymbol{\lambda}_1\right) \tag{2}$$

If this expression is substituted into the fifth equation of equation (1), then Lagrange multipliers can also be obtained as follows:

$$\boldsymbol{\lambda}_1 = \left(\mathbf{\Phi}_{y2}^{1}\mathbf{M}_2^{-1}\mathbf{\Phi}_{y2}^{1\,T}\right)^{-1}\left(\mathbf{\Phi}_{y1}^{1}\ddot{\mathbf{y}}_1 + \mathbf{\Phi}_{y2}^{1}\mathbf{M}_2^{-1}\mathbf{Q}_2 - \boldsymbol{\gamma}_1\right) \tag{3}$$

Other Lagrange multipliers of each subsystem can be obtained in the same way. And then substituting the expression of Lagrange multipliers into the first equation of equation (1), the equation of motion for the base body (buffer system) can be obtained as,

$$\left\{\mathbf{M}_1 + \mathbf{M}_2^C + \mathbf{M}_3^C + \mathbf{M}_4^C\right\}\ddot{\mathbf{y}}_1 = \left\{\mathbf{Q}_1 + \mathbf{P}_2^C + \mathbf{P}_3^C + \mathbf{P}_4^C\right\} \tag{4}$$

where, $\mathbf{M}_i^C = \mathbf{\Phi}_{y1}^{i\text{-}1\,T}\left(\mathbf{\Phi}_{yi}^{i\text{-}1}\mathbf{M}_i^{-1}\mathbf{\Phi}_{yi}^{i\text{-}1\,T}\right)^{-1}\mathbf{\Phi}_{y1}^{i\text{-}1}\ (\mathbf{i} = \mathbf{2,3,4})$ and $\mathbf{P}^C = \mathbf{\Phi}_{y1}^{i\text{-}1\,T}\left(\mathbf{\Phi}_{yi}^{i\text{-}1}\mathbf{M}_i^{-1}\mathbf{\Phi}_{yi}^{i\text{-}1\,T}\right)^{-1}\left(\boldsymbol{\gamma}_{i-1} - \mathbf{\Phi}_{yi}^{i\text{-}1}\mathbf{M}_i^{-1}\mathbf{Q}_i\right)(\mathbf{i} = \mathbf{2,3,4})$. $\mathbf{M}^C$ is called effective mass matrix and $\mathbf{P}^C$ is called effective force vector of each subsystem.

If the number of subsystems increase, it is easy to connect added subsystem in numerical formula using equation (2)~(4).

In order to validate the proposed method, the deep-seabed integrated mining system has been modeled and simulation results from the proposed method are compared with the commercial software.

References

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