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Fluid-Structure Interaction in Ocean Engineering

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ABSTRACT

In this paper, we introduce our recent studies on fluid-structure interaction in ocean engineering, which include hydroelastic analysis of very large floating structures, hydroelastic analysis of general floating structures, and hydroelastic analysis of submersed floating tunnels. We focus on developing numerical procedures for hydroelastic behaviors of various floating bodies. The analysis methods are based on boundary element method (BEM) for surrounding fluids and finite element method (FEM) for floating structures. The direct-coupled formulations for fluid-structure interaction problems were derived and implemented. Various numerical examples were solved and also experimental studies were performed to validate the numerical methods developed.

1. INTRODUCTION

Fluid-structure interaction has been an important issue for analysis of ocean engineering structures. For a long time, significant efforts have been made to develop more effective analysis scheme to obtain reliable solutions to solve fluid-structure interaction problems in ocean engineering. In this presentation, we review the results of our previous studies on the development of numerical procedures for hydroelastic analysis of floating structures focusing on fluid-structure interaction.

As floating bodies tend to be larger and larger in practice, hydroelastic analysis becomes increasingly important. The numerical methods presented here provides tools to design such large floating structures and to investigate their behaviors.

In the following sections, we consider three different topics: hydroelastic analysis of very large floating structures (Kim et. al, 2014, Yoon et. al, 2014), hydroelastic analysis of general floating structures (Kim et al, 2013, Lee et al, 2015), and hydroelastic analysis of submersed floating tunnels (Kim JH et al, 2015).

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2. HYDROELASTIC ANALYSIS OF VERY LARGE FLOATING STRUCTURES

For wave-floating plate interaction problems shown in Fig. 1, the coupled formulation by employing FEM for structures and BEM for regular waves (Kim et. al, 2014, Yoon et. al, 2014) is given by

$$\begin{bmatrix} -\omega^2 \mathbf{S}_M + \mathbf{S}_K & -\mathbf{C}_{up} \\ -\mathbf{C}_{up}{}^T & -\mathbf{F}_M - \mathbf{F}_G \end{bmatrix} \begin{bmatrix} \hat{\mathbf{u}} \\ \hat{\mathbf{p}} \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ \hat{\mathbf{R}}_\mathbf{I} \end{bmatrix}, \tag{1}$$

with

$$\omega^2 \int_V \rho_s \, u_i \, \delta u_i \, \mathrm{d}V = \delta\hat{\mathbf{u}}^T \, \omega^2 \, \mathbf{S}_M \, \hat{\mathbf{u}} \,, \; \int_V C_{ijkl} \, e_{kl} \, \delta e_{ij} \, \mathrm{d}V = \delta\hat{\mathbf{u}}^T \; \mathbf{S}_K \, \hat{\mathbf{u}} \,, \; \int_S p \, \delta u_3 \, \mathrm{d}S = \delta\hat{\mathbf{u}}^T \; \mathbf{C}_{up} \, \hat{\mathbf{p}} \,,$$
$$\frac{1}{\rho_w g} \int_S p \, \delta p \, \mathrm{d}S = \delta\hat{\mathbf{p}}^T \; \mathbf{F}_M \, \hat{\mathbf{p}} \,, \; \frac{\omega^2}{4\pi\rho_w g^2} \int_S \int_S pG \, \mathrm{d}S_\xi \delta p \, \mathrm{d}S_x = \delta\hat{\mathbf{p}}^T \; \mathbf{F}_G \, \hat{\mathbf{p}} \,,$$
$$j\frac{\omega}{g} \int_S \phi_\mathrm{I} \, \delta p \, \mathrm{d}S = \delta\hat{\mathbf{p}}^T \, \hat{\mathbf{R}}_I \,, \tag{2}$$

in which $\hat{\mathbf{u}}$ and $\hat{\mathbf{p}}$ are the unknown displacement and pressure vectors, ρ_w and ρ_s are the densities of fluid and structure, respectively, ω and j denote an angular frequency and an imaginary number ($j = \sqrt{-1}$), respectively, S is the wet surface of the floating plate, C_{ijkl} is the stress-strain relation tensor, e_{ij} is the linear strain tensor, G is the free surface Green's function, and ϕ_I is the velocity potential for the incident wave.

From Eq. (1), the hinge connections can be easily modeled by releasing the rotational degrees of freedom of the plate finite elements, where the matrices of structural mass and stiffness and fluid-structure interaction are condensed (Yoon et. al, 2014).

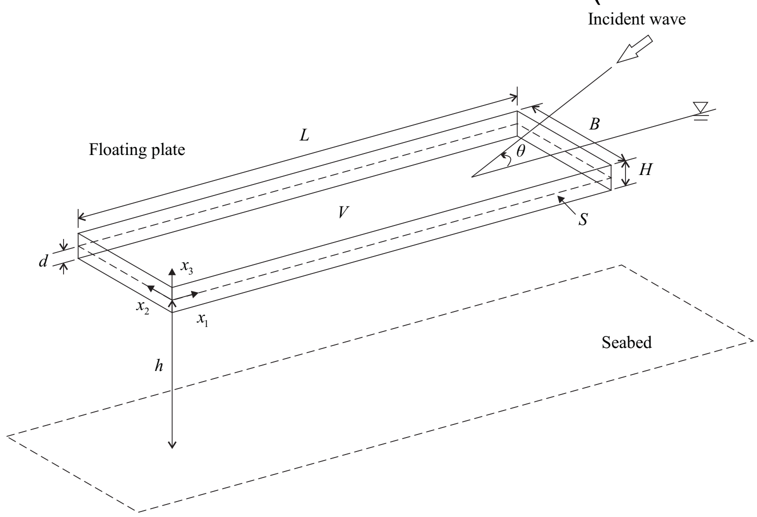

Figure 1. Problem description of a floating plate subjected to an incident wave (Yoon et. al, 2014)

In order to verify the proposed formulation, we conduct hydroelastic experiments of floating plates, which are made of two different layers (polycarbonate for upper layer and polyethylene foam for lower layer) with stainless steel hinge connections. The dimensionless bending stiffness ($\frac{EI}{\rho_w g L^5}$) of plate is 1.244×10^{-5}. We consider the floating plate subjected to regular waves with three different wavelength ratios ($\alpha = \lambda / L = 0.3$, 0.6 and 0.9). Compared to RAOs of deflection along the longitudinal lines of the plates for the experimental tests, the numerical results are in good agreement. Details of the result are presented in the reference, Yoon et. al, 2014.

3. HYDROELASTIC ANALYSIS OF GENERAL FLOATING STRUCTURES

Recently, the direct coupling method was generalized for the 3D linear hydroelastic analyses of floating structures (Kim et al, 2013) and it was extended for a problem of floating structures with liquid tanks (Lee et al, 2015) as shown in Fig. 3.

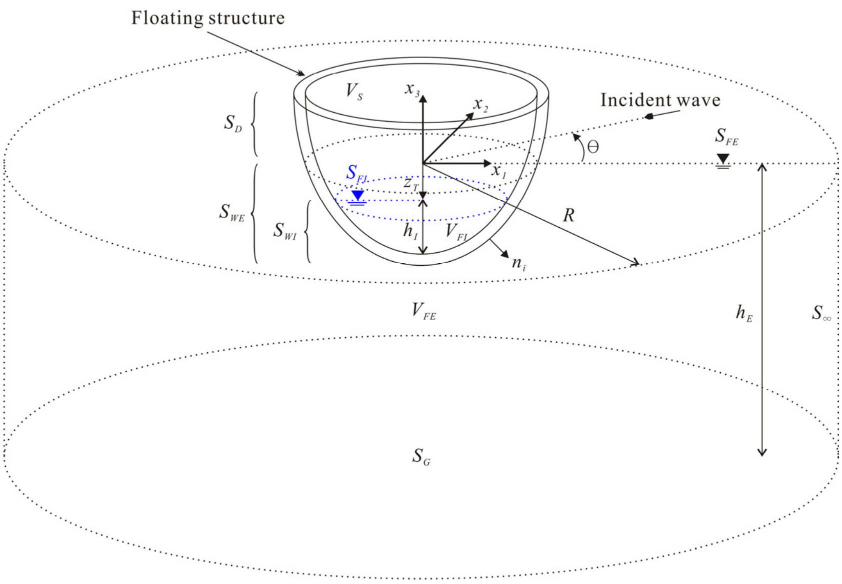

Figure 3. A floating structure with a liquid tank in an incident water wave (Lee et al, 2015)

The final discrete coupled equation for the steady state 3D hydroelastic analysis of floating structures with liquid tanks is given by

$$\begin{bmatrix} -\omega^2\mathbf{S}_M + \mathbf{S}_K + \mathbf{S}_{CH} & -j\omega\mathbf{S}_D^E & -j\omega\mathbf{S}_D^I \\ j\omega\mathbf{F}_G & \mathbf{F}_M^E - \mathbf{F}_{Gn} & 0 \\ -j\omega\mathbf{F}_W^I & 0 & \omega^2\mathbf{F}_M^I - \mathbf{F}_K^I \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \boldsymbol{\varphi}_E \\ \boldsymbol{\varphi}_I \end{bmatrix} = \begin{bmatrix} 0 \\ 4\pi\mathbf{R}^I \\ 0 \end{bmatrix}$$

with $\mathbf{S}_{CH} = \mathbf{S}_{KN} - \mathbf{S}_{HD}^{E} - \mathbf{S}_{HD}^{I} - \mathbf{S}_{HN}^{E} - \mathbf{S}_{HN}^{I}$, (3)

where the matrix $\mathbf{S}_{CH}$ is the complete hydrostatic stiffness of the floating liquid storage structure. The terms $\mathbf{S}_{HD}^{E}$, $\mathbf{S}_{HN}^{E}$, $\mathbf{S}_{HD}^{I}$, and $\mathbf{S}_{HN}^{I}$ are the hydrostatic pressure stiffnesses and $\mathbf{S}_{KN}$ is the geometric stiffness. In particular, the contributions of the internal fluid to the hydrostatic pressure stiffness are $\mathbf{S}_{HD}^{I}$ and $\mathbf{S}_{HN}^{I}$, and a hydrostatic analysis should be performed in advance to properly obtain the geometric stiffness $\mathbf{S}_{KN}$.

In order to verity the formulation, the 3D hydroelastic experiments were performed as shown in Fig. 4. Details of the FPU model and experimental setup are demonstrated in the reference, Lee et al, 2015.

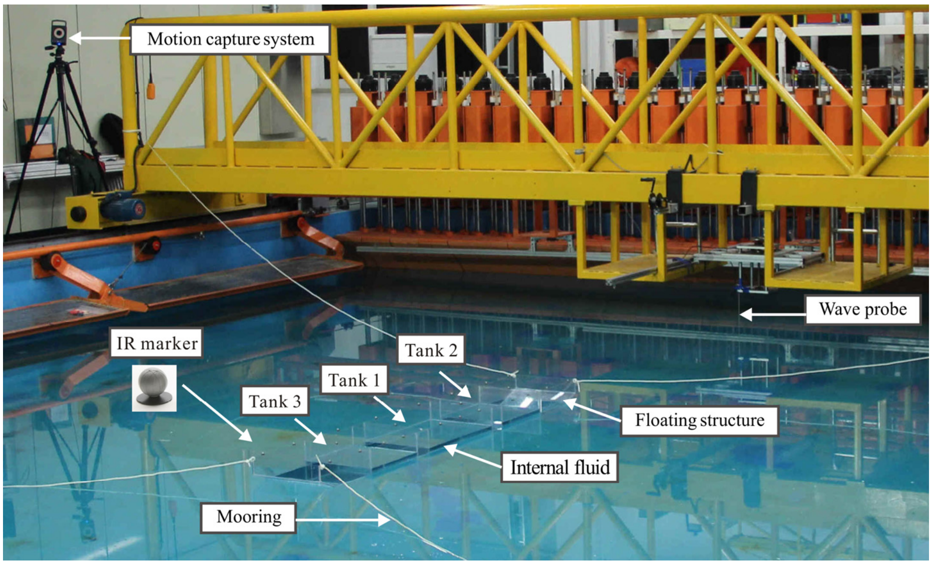

Figure 4. Hydroelastic experiment of the FPU model with three liquid tanks in an ocean basin (15m × 10m × 1.5m) (Lee et al, 2015).

The measured dynamic responses are compared with the numerical results obtained using the proposed formulation. It is observed that the sloshing motion is not beyond the linear potential theory and the tendency of free surface profiles agrees well with the numerical results. See the reference, Lee et al, 2015 for details of the result.

4. HYDROELASTIC ANALYSIS OF SUBMERSED FLOATING TUNNEL

The sectional plane of model and discretized 3D finite element model of SFT are illustrated in Fig. 5. The dynamic motion of SFT located in a seismic zone is governed by its supporting cables, which are spaced regularly from tens to hundreds of meters.

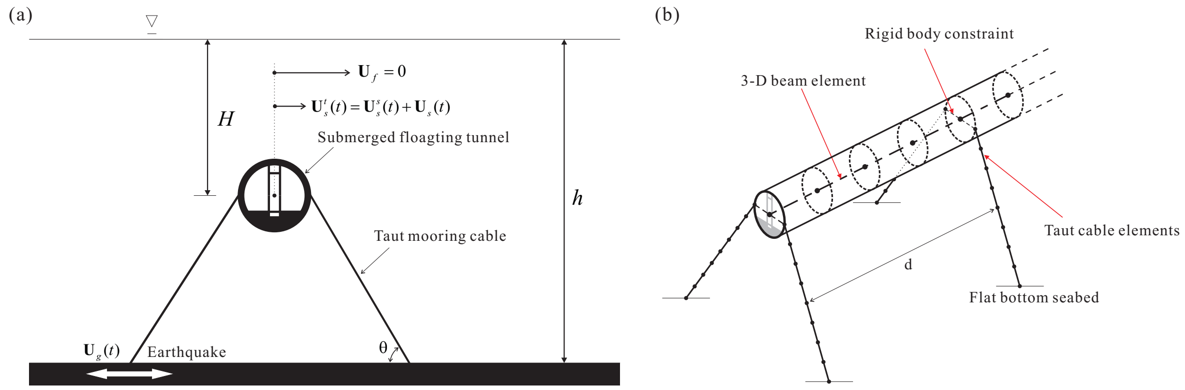

Figure 5. – (a) Sectional plane of SFT model, (b) 3D finite element model of SFT (Kim JH et al, 2015)

The governing equation of motion for the entire structure can be formulated as:

$$(\mathbf{M}_s + \mathbf{M}_a)\ddot{\mathbf{U}}_s(t) + \mathbf{C}_s\dot{\mathbf{U}}_s(t) + \mathbf{K}_s\mathbf{U}_s(t) = -(\mathbf{M}_s + \mathbf{M}_a)\mathbf{I}_f\ddot{\mathbf{U}}_g(t), \tag{4}$$

where subscript 's' and 'g' denote the superstructure and supporting ground. Mass, damping, and stiffness matrices are denoted by $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$, respectively. The relative value of structure acceleration, velocity and displacement are denoted by $\ddot{\mathbf{U}}_s$, $\dot{\mathbf{U}}_s$ and $\mathbf{U}_s$, respectively. The hydrodynamic force applied on the structure due to the relative motion of fluid can be obtained using Morison equation (Dawson TH, 1983). $\mathbf{M}_a$ is the added mass coefficient matrix. No incident wave or current were considered in this study and thus the water particles acceleration and velocity become zero. For the external force on the structure due to seismic ground motion is calculated by the multiplication of total mass and ground acceleration. Furthermore, the influence of ground accelerations $\ddot{\mathbf{U}}_g$ on the structural degrees of freedom is decided by the influence matrix $\mathbf{I}_f$.

The continuum mechanics based 3D beam finite elements (Yoon and Lee, 2014) and taut cable elements are used to model the tunnel and mooring cables, respectively. Beam element and discretization of applied cross-section of tunnel is illustrated at Fig. 6.

We studied a 10km span length SFT, which has the outer diameter of tunnel cross-section 15.7m. Mooring cables are installed with uniform spacing (d=100m) and its diameter is 0.15m. The tunnel cross-section is a composite structure consisting of outer steel and inner concrete (Long et. al, 2009). The equivalent Young's modulus considered is 34 GPa for tunnel, and that of cables is 210 GPa. We consider two cases of cable angles θ from the seabed: 45 and 60 degrees.

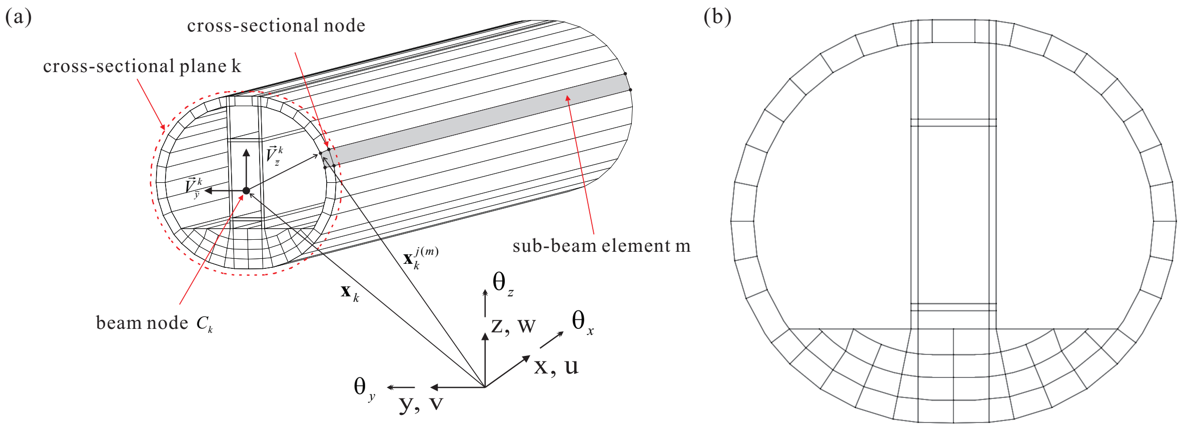

Figure 6. – (a) 3D beam finite element, (b) tunnel cross-section discretization (Kim JH et al, 2015)

Water depth h is 120m and the depth from the water surface to the center of tunnel (H) is 40m. For the input seismic motion, El Centro and Kobe earthquakes are selected for the input seismic acceleration. The input seismic ground motions are assumed be homogeneous.

In the reference (Kim JH et al, 2015) the displacement time histories at tunnel center and the maximum displacement response envelopes through the span length are given for each seismic excitation. The displacement history appears the maximum transverse displacements of the tunnel are very similar for the two cable angle cases.

The peak ground acceleration PGA) of Kobe earthquake is bigger than that of El Centro earthquake and the maximum magnitude of responses also shows the same trend. However, the locations of maximum displacement response are different. The maximum displacements calculated are much smaller than the total tunnel length, rarely exceeding 0.3 m.

5. CONCLUSIONS

In this presentation, we introduced our recent works on the analysis of fluid-structure interaction problems in ocean engineering. Numerical methods for hydroelastic analysis of very large floating structures, hydroelastic analysis of general floating structures, and hydroelastic analysis of submersed floating tunnels were presented. Their formulations were briefly reviewed and the numerical results were presented through representative numerical examples. Also, the results were compared with available experimental results and those in previous studies. The numerical methods developed here can be used be widely utilized in various ocean engineering practices, especially, for design of VLFS (Very Large Floating Structures), very large crude carriers, very large container ships and long submersed tunnels.

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