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Physics-based simulation of offshore installation operations considering ocean environmental loads and operating conditions

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ABSTRACT

In general, an OSV (Offshore Support Vessel) installs an offshore structure which is laid on its deck or an adjacent transportation barge by lifting the offshore structure with its own crane, by moving in the air, and by lowering down into the sea. There are three major considerations during these operations. First, the collision does not occur due to the relative motion between the offshore structure and the OSV or the transportation barge when lifting the offshore structure. Second, the lifted offshore structure should be adequately moved without any significant and undesirable pendulum motions in the aspect of control. Third, at the moment that the offshore structure penetrates the water surface, the slamming impact force and the varying buoyancy force should be considered. Therefore, this study proposes a physics-based simulation system to consider these three major considerations. To evaluate the applicability of the system, it was applied to some examples.

1. INTRODUCTION

An offshore structure or subsea equipment is transported to the actual site after constructed on shore. The transported structure or subsea equipment is deployed in the way of something such as float-over, launching, and lifting. Among them, the lifting operation is usually carried out by an OSV and it consists of five steps (Nielsen 2003) as shown in Fig. 1.

There are some considerations on each step in lifting operation. On the first step 'Lifting off' (Fig. 1(a)), an OSV lifts off the structure which is laid on the deck or the adjacent transportation barge with its own crane. At this moment, one should avoid

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collision between the structure and others resulting from the relative motion among them. On the next step 'Lifting in the air' (Fig. 1(b)), the lifted structure is moved to the specified site in the air. In this process, the significant and undesirable pendulum motion should be avoided because it is very important to control the structure exactly. The structure penetrates the water surface on the step 'Crossing splash zone' (Fig. 1(c)). The varying buoyancy force and slamming impact force exerted on the structure should be considered on this step. On the step 'Deeply submerging' (Fig. 1(d)) on which the structure is submerged deeply, the motion of the lifted structure, in response to wave-induced motion of the vessel crane tip, is important because of the possibility of resonance. On the last step 'Landing' (Fig. 1(e)), one should land the structure exactly and there should not be large impact which could cause damage to the structure.

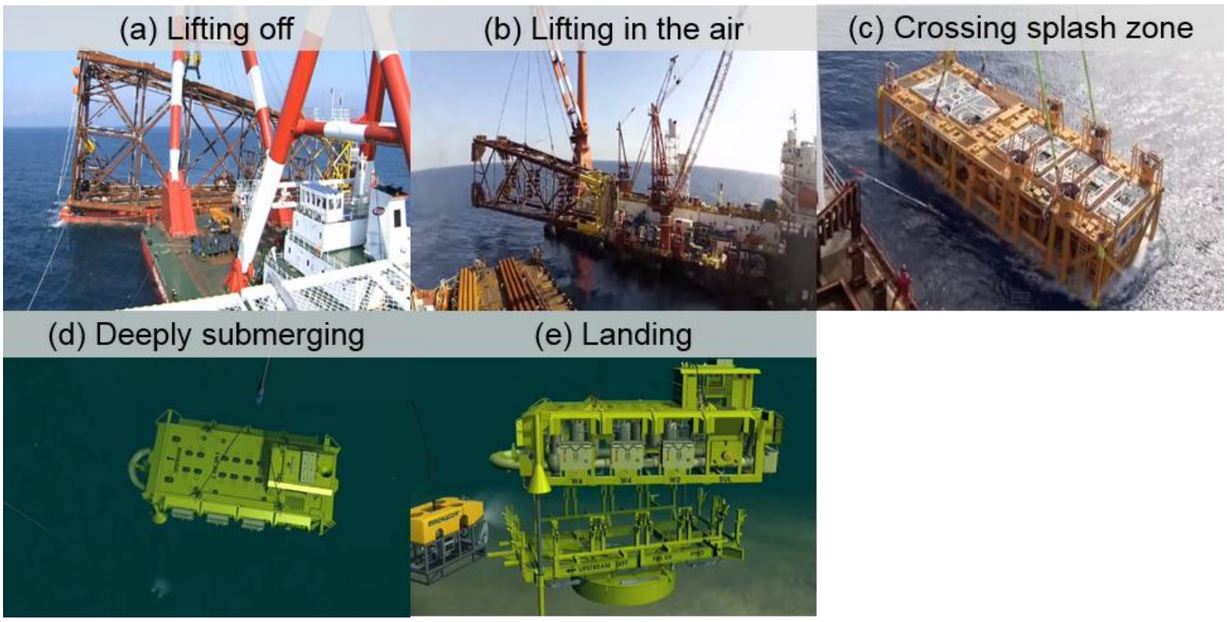

Fig. 1 Five steps of lifting operation by an OSV

If we can simulate each step in the aspect of the above considerations, we are able to verify the validity of operating conditions. Thus, this study proposes a physics-based simulation system whose main concept is multibody system dynamics considering hydrodynamic force. Using this simulation system, the three steps, from 'Lifting off' to 'Crossing splash zone' (Fig. 1(a)~(c)) are simulated and the related considerations are analyzed. These simulations are carried out in the various ocean environmental loads and operating conditions. The ocean environmental loads are composed of heading angles, wave heights, and wave periods. And, the operating conditions are composed of the hoisting speed, the speed for a crane to lift a structure vertically, and the moving speed, the speed for a crane to lift a structure horizontally.

Masoud (2000) applied delayed-position feedback together with luff-and-slew angle actuation to vessel crane to control pendulum motion of lifted load in the air. And, the effectiveness of this method was demonstrated with a fully nonlinear threedimensional computer simulation and with an experiment on a 1/24 scale model. Wu (2013) analyzed the dynamic performance of the template during the lifting operation through splash zone. Wu simulated a crane and a template suspended from the crane, and then carried out dynamic and static analysis by using SIMA (Simulation workbench for Marine Applications) which can simulate and analyze offshore operation. Boe & Nestegard (2010) developed the dynamic response equations of the lifted load in deep water and described how these equations can be applied in order to establish limiting sea-states for the lifting operation.

2. THEORETICAL BACKGROUNDS OF LIFTING SIMULATION

2.1 The equations of motion based on multibody system dynamics

A vessel-mounted crane can be regarded as multibody system which consists of interconnected rigid bodies. Thus the equations of motion based on multibody system dynamics are required to analyze motion of the object including crane system. In this section the equations of motion based on multibody system dynamics (Shabana 1994) are briefly explained.

Relative motion that is permitted between bodies in a multibody system is often constrained by the connections between those bodies. Therefore, Newton's equation of motion for the multibody system is

$$\boldsymbol{M}\ddot{\boldsymbol{r}} = \boldsymbol{F}^e + \boldsymbol{F}^c \tag{1}$$

The vectors in Eq. (1) are represented in terms of the Cartesian coordinates. $\boldsymbol{M}$ is the mass and mass moment of the inertia matrices and $\boldsymbol{r}$ is the position vector of the center of gravity of the bodies with respect to the Cartesian coordinates. The resultant force is composed of the external force $\boldsymbol{F}^e$ and the constraint force $\boldsymbol{F}^c$ caused by kinematic constraints.

The position vector $\boldsymbol{r}$ of the Cartesian coordinates can be presented as a function of the generalized coordinates $\boldsymbol{q}$ according to

$$\boldsymbol{r} = \boldsymbol{r}(\boldsymbol{q}) \tag{2}$$

Differentiating Eq. (2) yields the velocity relation

$$\dot{\boldsymbol{r}} = \boldsymbol{J}\dot{\boldsymbol{q}} \tag{3}$$

where the velocity transformation matrix $\boldsymbol{J}$ transforms the velocity of generalized coordinates $\dot{\boldsymbol{q}}$ into the velocity of the Cartesian coordinates.

Differentiating Eq. (3) yields the acceleration

$$\ddot{\boldsymbol{r}} = \boldsymbol{J}\ddot{\boldsymbol{q}} + \dot{\boldsymbol{J}}\dot{\boldsymbol{q}} \tag{4}$$

Substituting Eq. (4) into Eq. (1), we obtain the equation

$$\boldsymbol{M}\boldsymbol{J}\ddot{\boldsymbol{q}} + \boldsymbol{M}\dot{\boldsymbol{J}}\dot{\boldsymbol{q}} = \boldsymbol{F}^e + \boldsymbol{F}^c \tag{5}$$

Multiplying both sides of Eq. (5) by $\boldsymbol{J}^T$ yields

$$\boldsymbol{J}^T\boldsymbol{M}\boldsymbol{J}\ddot{\boldsymbol{q}} + \boldsymbol{J}^T\boldsymbol{M}\dot{\boldsymbol{J}}\dot{\boldsymbol{q}} = \boldsymbol{J}^T\boldsymbol{F}^e + \boldsymbol{J}^T\boldsymbol{F}^c \tag{6}$$

The constraint reaction forces are perpendicular to the path along which the bodies are constrained to move. This suggests that the constraint reaction force $\mathbf{F}^c$ may be suppressed by taking the scalar product of both sides of Newton's equation of motion with vectors that are tangent to the path. Then, we can derive

$$\breve{\boldsymbol{M}}\ddot{\boldsymbol{q}} + \breve{\boldsymbol{k}} = \breve{\boldsymbol{F}}^e \tag{7}$$

where $\breve{\boldsymbol{M}} = \boldsymbol{J}^T\boldsymbol{M}\boldsymbol{J}$, $\breve{\boldsymbol{k}} = \boldsymbol{J}^T\boldsymbol{M}\dot{\boldsymbol{J}}\dot{\boldsymbol{q}}$, and $\breve{\boldsymbol{F}}^e = \mathbf{J}^T\mathbf{F}^e$; $\breve{\boldsymbol{M}}$ is the mass and the generalized mass moment of the inertia matrix, $\breve{\boldsymbol{k}}$ is the generalized Coriolis and centrifugal force, $\breve{\boldsymbol{F}}^e$ is the generalized external force, $\boldsymbol{J}$ is the velocity transformation matrix, $\dot{\boldsymbol{J}}$ is the acceleration transformation matrix and $\boldsymbol{q}$ is the generalized coordinate of the multibody system.

2.2 Hydrodynamic force calculation

A hydrodynamic force can be divided into two parts as shown in Eq. (8); the wave exciting force exerted by the incident wave and the diffraction wave, and the radiation force from the wave generated by the motion of the floater itself.

$$\boldsymbol{F}_{Hydrodynamic} = \boldsymbol{F}_{Exciting} + \boldsymbol{F}_{Radiation} \tag{8}$$

$\boldsymbol{F}_{Exciting}$ can be calculated by the force RAO (Response Amplitude Operator) times the sinusoidal function at a given frequency. The force RAO can be obtained from a commercial solver. Cummins equation (Cummins 1962) can be used to calculate $\boldsymbol{F}_{Radiation}$ in the time domain. The added mass $a_{ij}(w)$ and the damping coefficient $b_{ij}(j)$ can also be obtained from the commercial solver. Fig. 2 summarizes the calculation procedure.

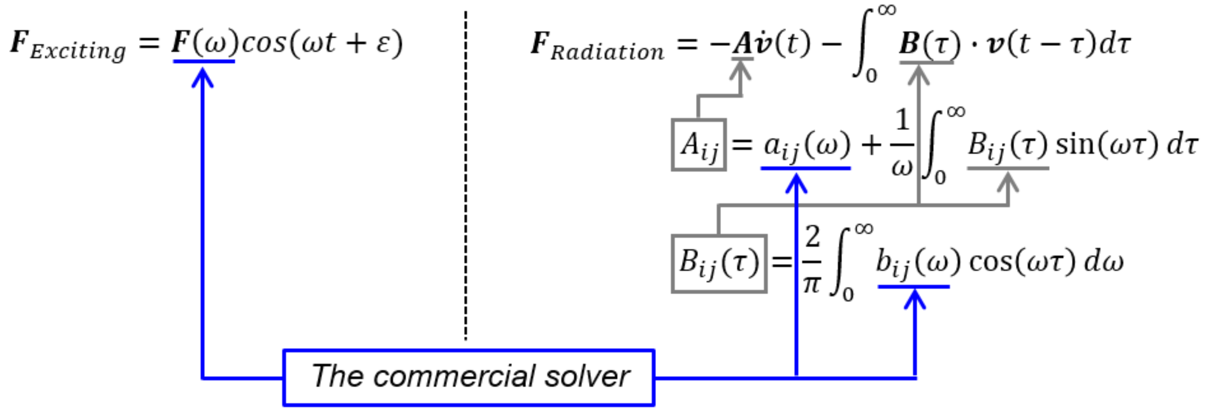

Fig. 2 The hydrodynamic force calculation procedure

2.3 Slamming impact force

The offshore structure or subsea equipment which penetrates the water surface may be prone to slamming impact force. This slamming impact force can be characterized as Eq. (9) (DNV-RP-H103 2011).

$$\boldsymbol{F}_{slam} = 0.5\rho \boldsymbol{C}_s \boldsymbol{A}_s {\boldsymbol{v}_s}^2 \tag{9}$$

where ρ is the density of sea water, $\boldsymbol{C}_s$ is the slamming coefficient which may be determined by theoretical and/or experimental methods, $\boldsymbol{A}_s$ is the slamming area, i.e. part of structure projected on a horizontal plane, $\boldsymbol{v}_s$ is the slamming impact velocity and calculated as Ep. (10).

$$\boldsymbol{v}_s = \boldsymbol{v}_c + \sqrt{{\boldsymbol{v}_{ct}}^2 + {\boldsymbol{v}_w}^2} \tag{10}$$

where $\boldsymbol{v}_c$ is the hook lowering velocity, $\boldsymbol{v}_{ct}$ is the characteristic single amplitude vertical velocity of the crane tip, $\boldsymbol{v}_w$ is the characteristic vertical water particle velocity.

3. Applications of the physics-based simulation system

This study simulates the steps of lifting operation; ‘Lifting off’ (Fig. 1(a)), ‘Lifting in the air’ (Fig. 1(b)), and ‘Crossing splash zone’ (Fig. 1(c)) by using the physics-based simulation system. Fig. 3 and Table 1 are about the models used in the ‘Lifting off’ simulation. Fig. 4 and Table 2 are about the models used in the ‘Lifting in the air’ simulation and the ‘Crossing splash zone’ simulation.

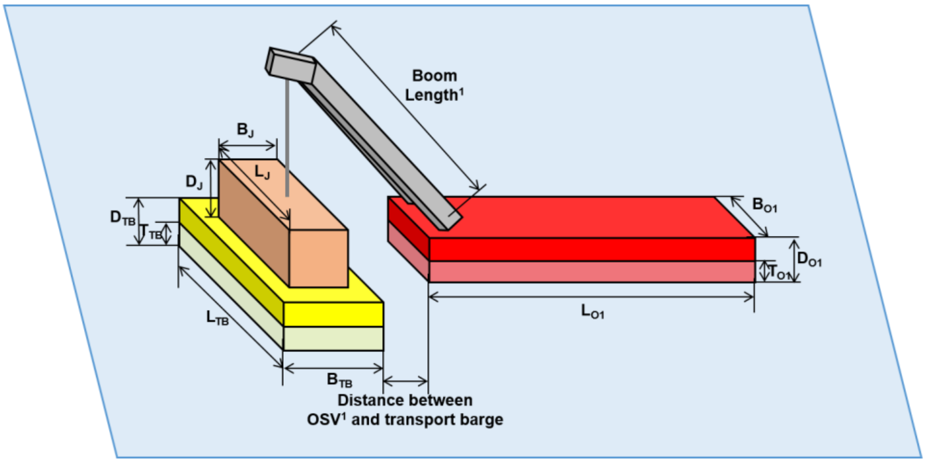

Fig. 3 Configuration of an OSV, a transportation barge, and a jacket for lifting off simulation

Table 1 Specification of an OSV, a transportation barge, and a jacket for lifting off simulation

OSV					
Length (L_{O1}) [m]	83	Draft (T_{O1}) [m]	4	Boom Length [m]	86
Breadth (B_{O1}) [m]	44	Displacement [ton]	14,973	Capacity [ton]	1,800
Depth (D_{O1}) [m]	6.4				
Transportation barge					
Length (L_{TB}) [m]	122.45	Draft (T_T) [m]			6
Breadth (B_{TB}) [m]	30.5	Displacement [ton]			21,969
Depth (D_{TB}) [m]	7.6	Distance between OSV and transportation barge			23.25
Jacket					
Length(L_J) [m]	70	Depth (D_J) [m]	20		
Breadth(B_J) [m]	20	Mass [ton]	1,000		

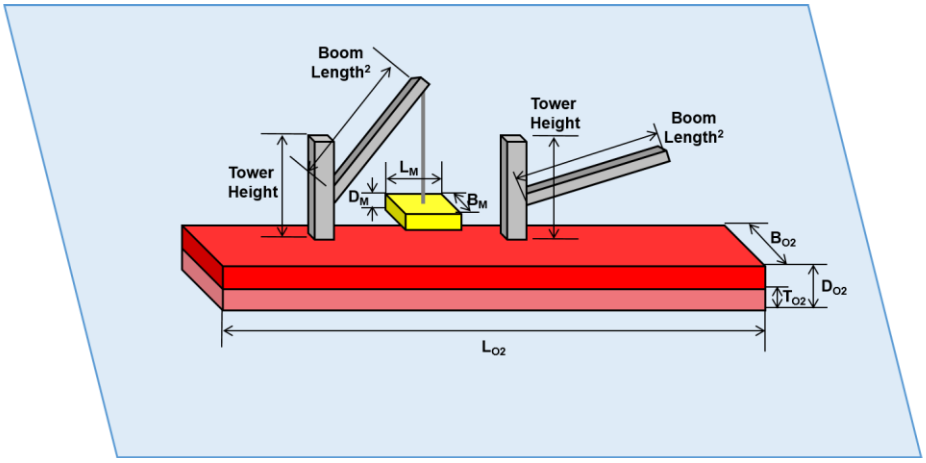

Fig. 4 Configuration of an OSV and a manifold for simulations of lifting in the air and crossing splash zone

Table 2 Specification of an OSV and a manifold for simulations of lifting in the air and crossing splash zone

OSV					
Length(L_{O1})[m]	160.5	Draft (T_{O1}) [m]	9	Boom Length^2[m]	37
Breadth(B_{O1})[m]	27.5	Displacement[ton]	23,600	Tower height[m]	24
Depth(D_{O1})[m]	13.8	Capacity[ton]	1,800		
Jacket					
Length(L_M)[m]	12	Depth(D_M)[m]	6		
Breadth(B_M)[m]	12	Mass[ton]	120		

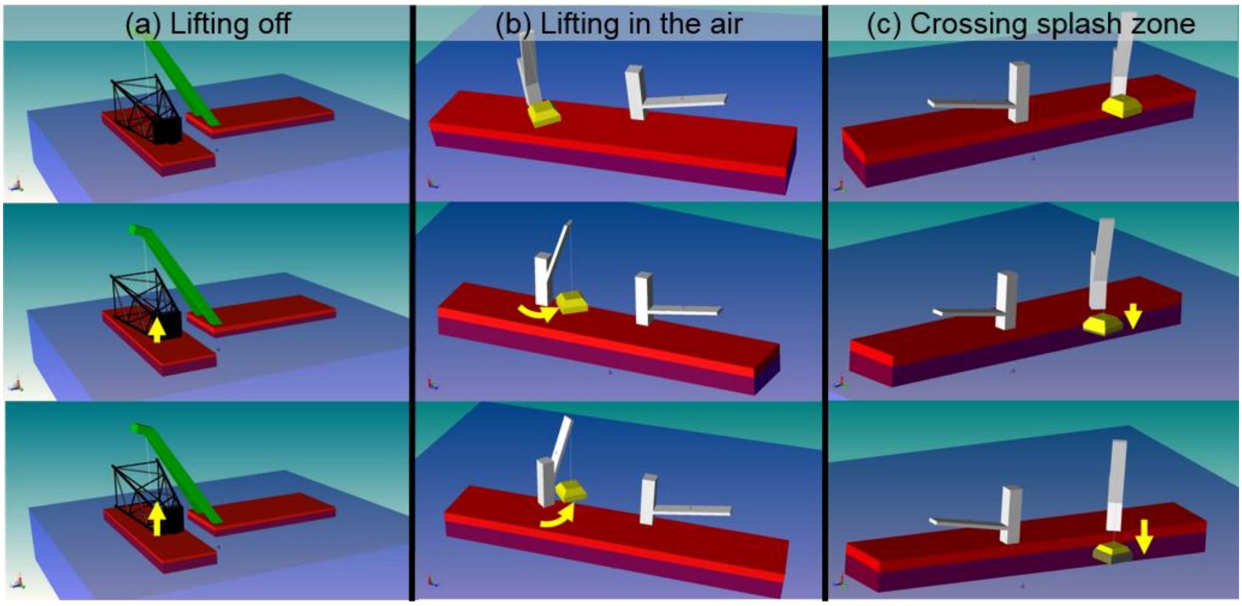

Fig. 5 Simulation results of ‘Lifting off’, ‘Lifting in the air’, and ‘Crossing splash zone’

Fig. 5 presents the simulations of the three steps; ‘Lifting off’, ‘Lifting in the air’, and ‘Crossing splash zone’.

All three simulations are carried out in the various ocean environmental loads and check the wire tension, the motion of the OSV, and the motion of the structure commonly. In the ‘Lifting off’ simulation (Fig. 5(a)), the OSV lifts the jacket which is laid on the adjacent transportation barge. The simulation tests whether the collision between the transportation barge and the jacket generates or not in the various hoisting speed. Next, in the ‘Lifting in the air’ simulation (Fig. 5(b)), changing the moving speed, the manifold is moved toward the sea from the OSV deck and the angle of pendulum motion of manifold is analyzed. Lastly, in the ‘Crossing splash zone’ simulation (Fig. 5(c)), the varying buoyancy force and slamming impact force exerted on the manifold are calculated in different hoisting speed.

4. Conclusion and future works

In this study, three steps of ‘Lifting off’, ‘Lifting in the air’, and ‘Crossing splash zone’ were simulated in various cases, using the physics-based simulation system. Through these simulations, the related considerations; the collision between the transportation barge and the jacket, the pendulum motion of the manifold, and the varying buoyancy force as well as the slamming impact force exerted on the manifold, were analyzed. In the future, dynamic positioning of OSV, ocean environmental loads by irregular wave, and interaction among floaters would be considered. And then, the remaining 2 steps of ‘Deeply submerging’ and ‘Landing’ would be simulated.

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