IOP Conference Series: Earth and Environmental Science

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To cite this article: Hooi-Siang Kang *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **463** 012110

Dynamic behaviours of damaged stability for floating energy storage unit after accidental collision

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Abstract. The transient dynamic behaviour of floating energy storage unit (FESU) is a result of coupling between three non-linear effects, which are sloshing of floodwater, wave loading, and FESU dynamics. The coupling of these effects would result in the catastrophic failure of the FESU in extreme conditions. Computational Fluid Dynamics (CFD) has shown that it holds great potential in solving the problem in the time domain, which is suitable for the transient stage. In this study, CFD simulation of damaged stability was conducted by using OpenFOAM to determine the dynamic response of FESU under the effects of floodwater and wave in transient flooding. OpenFOAM CFD simulation was conducted for the flooding of barge shaped FESU with different water inlet and air outlet sizes in still water condition followed by damaged stability in Stokes' fifth-order beam wave and head wave condition. Dynamic responses of FESU, such as roll, pitch, heave, and floodwater volume flow rates were determined using the dynamic meshing solver of OpenFOAM. Simulation results showed similarity to experimental results within the time frame of 16 seconds. Reduction in water inlet area and air outlet area decreased the flooding time and flow rate of flood water. The amplitude of vibration of roll and pitch motion increased as the flood water volume was increased due to the force of floodwater exerted on the wall. Sloshing effects also caused the model to roll and pitch in secondary vibrational motion. Due to the coupling effect of the three non-linear criteria, the inflow and outflow of floodwater changed with time, which concludes that transient effects should not be ignored in the damaged stability assessment of FESU.

1. Introduction

Floating energy storage unit (FESU) is one of the most attractive sustainable energy storage methods, especially for preserving ocean renewable energy and liquefied natural gas. Since most of the FESUs are designed in ship-shaped or barge type, the damaged stability of FESU is of concern in case of accidental collisions. The survivability of a damaged ship shaped FESU can be influenced by the dynamic behavior of the ship under floodwater and waves [1]. During the flooding process, the vessel, floodwater, and sea waves affect each other interactively [2]. These effects will greatly increase the complexity of damaged stability assessment due to their non-linear behaviors. Computational fluid dynamics (CFD) simulation has been shown to possess the advantage to compliment experiments with regard to analysis on the dynamic behaviors of damage stability of FESU. At the transient stage, immediately after the formation of a damage opening during collision, floodwater rushes in, resulting in a sudden large angle of heel. There is a huge possibility that the FESU will capsize due to the sudden load, even with symmetrically flooded compartments. Previous study utilizes different mathematical models and analyze different parameters of the damage stability of the transient stage. This numerical simulation has been conducted to investigate the dynamic behaviors of the damage stability of FESU in the transient stage using CFD. The simulation includes flooding time, flow rate of flood water, and dynamic response of FESU in still and wave transient flooding.

2. Modelling of damaged stability

2.1 Assessment of damage stability

FESU faces the risk of flooding due to uncertainties such as the state of the sea during the accident, floodwater behavior and initial heeling angle after collision[5], which rises the complexity of FESU survivability assessment by hydrodynamic model. The damage stability of FESU relies on the dynamics of the wave and floodwater, covering three sub-problems, which are excitation of waves, floodwater behavior and the ingress of floodwater [6]. Prediction of the dynamic behavior of damaged FESU due to waves would be more accurate if the sub-problems mentioned are successfully modelled. Thereby, the solution of fluid flow using Navier-Stokes equation [7], as shown in Equation (1), which shows accurate fluid flow in the time domain, is important to be studied numerically.

$$\frac{\partial u}{\partial t} + u\cdot\nabla u = -\frac{\nabla P}{\rho} + v\nabla^2 u \tag{1}$$

u is the velocity vector, P is the pressure, while v is the kinematic viscosity and ρ is the density. ∇ indicates the gradient differential operator and ∇^2 is the Laplacian operator.

2.2 Simulation of transient stage of flooding

Vassalos et al. [8] determined roll motion and righting lever (GZ) curves at various stages of transient flooding with inaccuracy of accounting the rate of energy dissipation in roll motion modelling subjected to damage and the modelling of water flow using simplified Bernoulli equation. Manderbacka [9] considered planar free moving water surface for the floodwater and included the inflow momentum due to its impact in dynamic behavior of ship in transient flooding. The hydrodynamic performance assessment of a damaged vessel, which adopted CFD method based on volume of fluid (VOF), could predict the fully coupled roll motion with sloshing effect under wave load [1]. To simulate CFD using finite volume method, partial differential equations based on simplified mathematical model to describe flow behavior are numerically solved using discretization methods.

In simulating wave loads on FESU, turbulence modelling is more critically important compared to the laminar flow due to the disturbance in high Reynolds number flow. Turbulent flow applied in this study was the k-ω shear stress transport (k-ω SST) model, which is a hybrid solution, taking the advantage of k-ω model near the wall, and k-ε in the turbulent region far from the wall.

3. Model preparation for hydrodynamics testing of damaged FESU

3.1 Experimental setup

Figure 1 shows the design of the barge-type FESU model, and Figure 2 illustrates the experimental setup of FESU damaged stability test. The model had dimension of 600mm × 200mm × 100mm, with submerged draft of 50mm with wall thickness of 5mm.Four different sizes of water inlets and four different sizes of air outlet were drilled on the model.

In Figure 2, two cameras were used to capture the motions of barge-type FESU and floodwater. The camera at the front was Canon EOS 700D model to capture 4K 30 frames per second (fps) video outside the calm water tank, while the camera at the side was GoPro Hero Black 5 to capture 4K 30 fps video under the water. An accelerometer MPU6050 chip was attached at the top of the model and connected to Arduino UNO board to measure the roll and pitch motions of the FESU model with sampling rate of 100Hz. Ballast weight was placed in the centre compartment to ensure the centre of gravity wasin the center of model, with a draft of 50mm. Three rubber string mooring lines configuration were used to limit the surge, sway and yaw motions of the model with minimal effect to roll, pitch and heave motions. The dimension of the calm water tank was 90cm×40cm×45cm with water depth of 20cm.The unused air outlets were sealed with tape andwater was left to calm before each experiment was started.

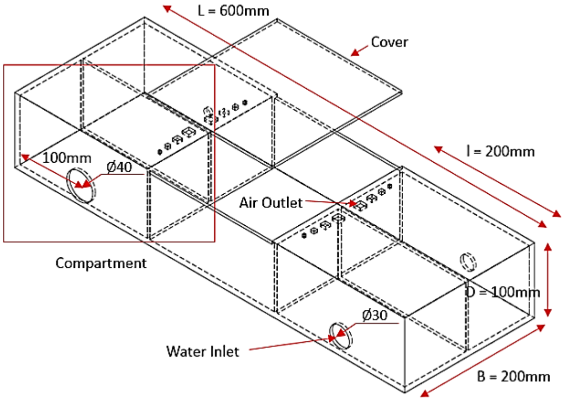

Figure 1. FESU model and its principal dimensions

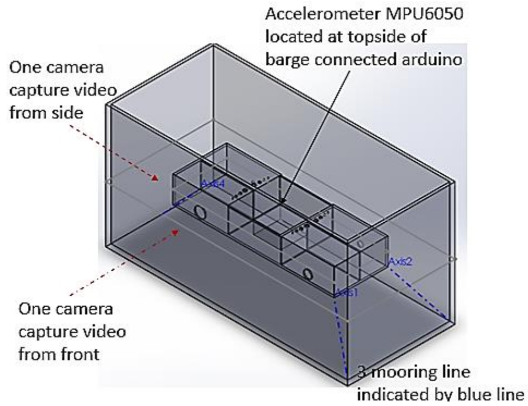

Figure 2. Experimental setup of damage stability in still water condition

3.2 *Numerical simulation setup*

The geometry data, initial conditions and and boundary conditions had been set in the OpenFOAM case folder, and written in *dict* file to be recalled by the solver in the next stage. Some important settings were added into the simulation case setup to simulate the dynamic motion of flooding of FESU, which were dynamic meshing, wave generation and turbulence flow. Different cases were coupled into the OpenFOAM v1806+, which included *floatingObject* (for dynamic meshing), *waveExampleStokeV* (for wave generation) and *DTCHull* (for turbulence model case).

Geometry of the model was constructed using FreeCAD, which is an open source package, and meshed with the *blockMesh* and *snappyHexMesh* in OpenFOAM [10]. The *interFoam* solver was consolidated to merge with *interDyMFoam* to solve dynamic meshing problem, and separated into two stages. The first function stage of the solver was to solve the problem of initial sinking of object into water due to setting of zero pressure on the object surface at the initial setting. It allowed the pressure surrounding the object to develop and rise automatically without significant sink motion of object at the beginning that might radiate wave. The second stage of the solver took over by continuing the simulation until the end of simulation.

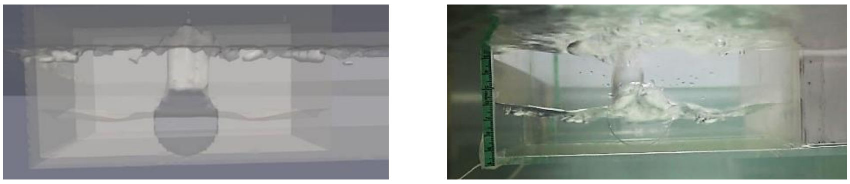

Figure 3. Flooding of FESU compartment (left: in simulation; right: in experiment)

4. Damage stability of FESU model

4.1 Visual comparison between experiment and simulation

The results of simulations and experiments had been compared in frame-to-frame. As shown in Figure 3, one typical case for progressive flooding of FESU was observed in both simulation and experiment. The simulation successfully simulated the air bubble formation on the top surface of the FESU damaged compartment. The flow rate and FESU roll angle matched well. It is noteworthy that the time of each case study was limited to 16 seconds because longer simulations had been found to diverge the accuracy of simulation results due to the highly skewed meshing during the yawing motion of the FESU model.

4.2 Time of flooding until new equilibrium state

The time of flood is an important parameter to determine survivability during a flooding incident. The compartment was assumed to be completely flooded when the water inflow rate reached below 5×10^{6} m^3s^{-1}, whereas time to flood for the cases longer than 16 seconds were not considered due to the limitation of the simulation time length. The plot of time to flood with respect to air outlet area and water inlet area is shown in Figure 4. The reduction of water inlet area resulted in reduction in water inflow time, while reduction of the air outlet area decreased the rate of air escaping from the compartment, hence it increased the time for the compartment to be flooded. The FESU model gained its new equilibrium state after 94.4% of the compartment had been flooded.

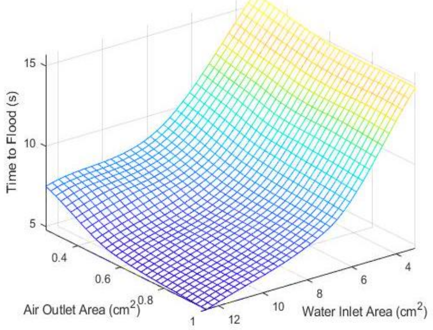

Figure 4. Surface plot of time to flood with respect to air outlet area and water inlet area

4.3 Flow rate of flood water into FESU

Figure 5 shows the flow rate for varying inlet diameter D with constant air outlet, A=1cm^2. It was observed that as area of the air outlet was kept constant at A=1cm^2 and the diameter of water inlet reduced, the maximum flow rate decreased accordingly, especially for the case of 1cm diameter, where the flow rate remained almost constant throughout the simulation period. Figure 6 shows the flow rate of varying air outlet area A with constant water inlet diameter D=4cm. A similar trend was observed as the flow rate initially rose until a maximum was achieved, then it decreased until the compartment was completely flooded. As the area of air outlet decreased, the maximum flow rate decreased. For the case of side length l_s=0.25cm, the flow rate dropped steeply from initial high value of 2.7×10^4 m^3s^{-1} at 0.15s to a low value of $1.0\times10^4 m^3s^{-1}$ at 2s. This was because the air bubbles were escaping from the water inlet hole due to the pressure of trapped air inside the damaged compartment.

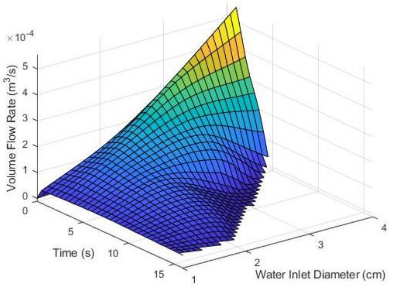

Figure 5. Flow rate for varying inlet diameter D with constant air outlet, A_a=1 cm^2

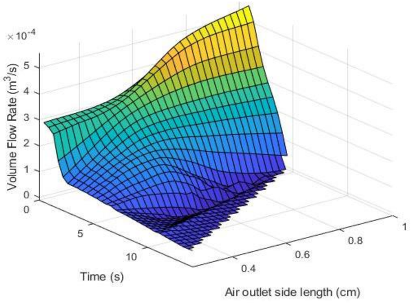

Figure 6. Flow rate of varying air outlet area A with constant water inlet diameter D_w=4cm

4.4 Pitch and roll motions of FESU

In the transient stage of damage condition, the experiment and simulation results of pitch and roll of the FESU model in still water had been compared. A similar trend was observed although simulation results deviated. Maximum pitch angle θ=15° and maximum roll angle ϕ=5° were recorded for the motions of FESU under the damage condition. However, the cases took longer duration than the simulation and experiment time-length to reach these maximum angles when the air outlet (A_a=0.0625cm^2) or water inlet (A_w=0.79cm^2) was too small. There was a deviation due to unavoidable initial fluctuation exerted on the floating FESU model in the experiment when the blockage of water inlet was removed and due to the wall effect of the reflective waves. The air bubble flowing out from water inlet could cause large variations in the experiment for the roll and pitch motions of FESU.

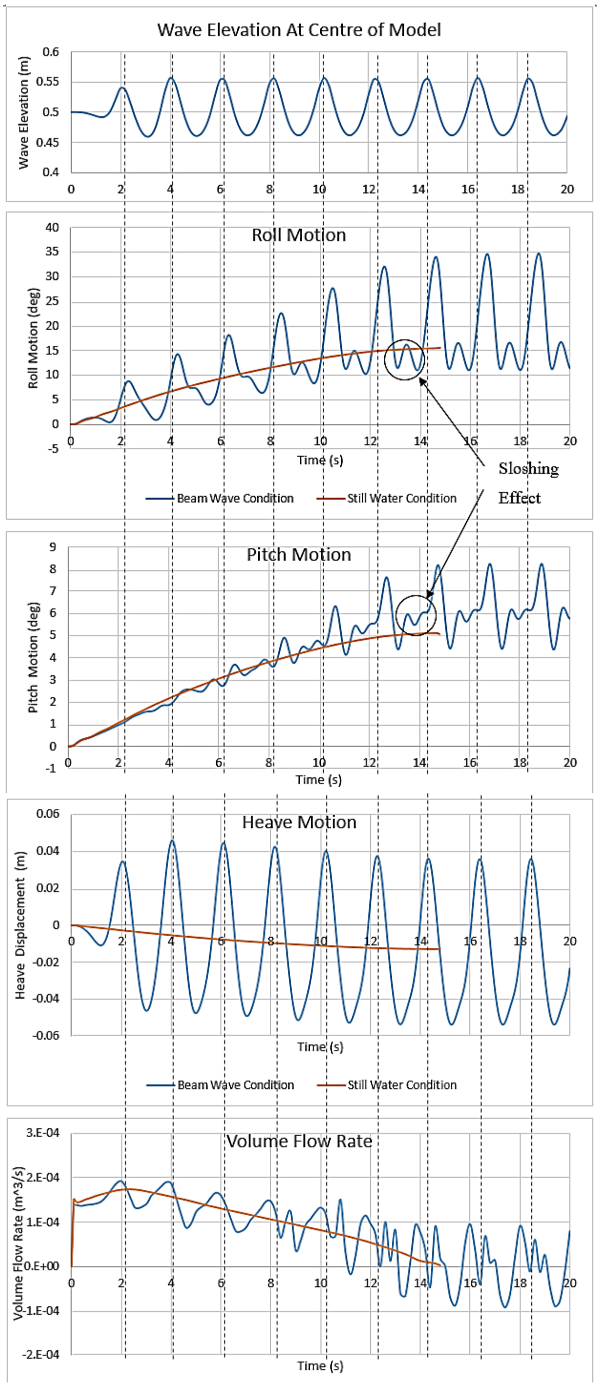

Figure 7. Pitch, roll and heave motion, and flow rate of flood water in beam wave condition

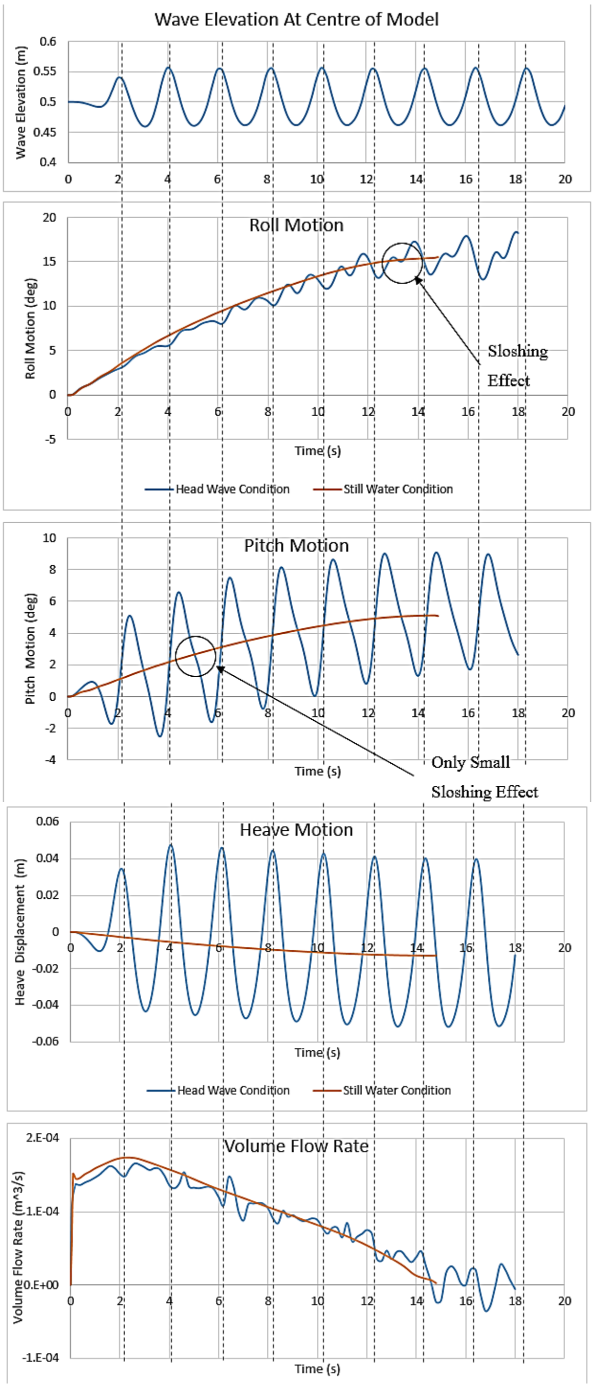

Figure 8. Pitch, roll and heave motion, and flow rate of flood water in head wave condition

4.5 Damaged stability of FESU in beam wave and head wave

Figure 7 and Figure 8 shows that the motion of the FESU and the flow rate of flood water under beam wave and head wave conditions, respectively, which vibrated along a similar path as in the case of still water condition. The roll and pitch motions were affected by the flood water and inner free surface sloshing, which induced vibration along the initial path. A lagging time existed between the wave elevation and motions of the FESU. As the amplitude of vibration in roll and pitch motions increased with time, the amplitude increased. In Figure 8, the volume flow rate for the head wave condition fluctuated in a non-repeating pattern, as a large final yaw angle was obtained. The pitching amplitude was much higher compared to the rolling amplitude as the induced wave was in the head wave direction. The roll motion was slightly affected by the flood water and sloshing effect, where only limited effects were observed in the first 10 seconds.

5. Conclusion

The simulation results of the damage stability in calm water followed a similar trend shown by the experimental results. The volume flow rate and time of flooding are dependent on the water inlet area and air outlet area. Air bubbles are useful to reduce the time of flooding. At higher flood water volume, amplitude of roll and pitch motion in the waves are higher. Sloshing of floodwater can also cause the ship's structure to vibrate in a secondary vibrational motion. The coupling effect of wave loading, ship dynamic and flood water movement, resulted in changing water pressure near the damage hole. Effects of the damage area could be simulated for the FESU model, implying the suitability of studying the dynamic behaviours of a damaged FESU in the transient state under varying damage scenarios by OpenFOAM simulation. Simulation should also be conducted for different ship models to investigate the dynamic behaviours of different floating structures, to assess the survivability of various structures under damage scenario.

Acknowledgments

The authors would like to appreciate Universiti Teknologi Malaysia (GUP-Centre of Excellence Grant Vot 03G92) for the supports in preparing this paper.

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