CFD SIMULATION OF AN INTEGRATION SYSTEM OF OSCILLATING BUOY WEC WITH A FIXED BOX-TYPE BREAKWATER

YANJUN MAO[1], YONG CHENG[2], GANGJUN ZHAI[1,*]
[1]Deepwater engineering research center, Dalian University of Technology,
zhai@dlut.edu.cn
maoyanjun_dut@foxmail.com
[2]School of naval architecture and ocean engineering, Jiangsu University of Science and Technology,
chengyong@just.edu.cn

Keywords: Wave energy converter;Integrated system;OpenFOAM;Overset mesh;Nonlinear power take-off model

Introduction

With the advancement in the renewable energy, the wave energy converter devices have been opted broad research and utilization. But the high construction cost is still a significant problem. To deal with this problem, the cost-share concept has been introduced by many researchers in recent years. Integrating the wave energy converter(WEC) into some kinds of coastal and offshore structures can share the construction cost and also enhance the stability of the devices. Among these ideas, the integration of WEC with offshore breakwaters is more feasible [1–3]. This integration design model can be used to transform the existing breakwater or promote new structural concept designs for off-shore breakwaters. Ning et al [3], introduced an experiment with a buoy-type WEC combined with the pile-restrained floating breakwater. The results showed that a high energy-conversion efficiency and good wave attenuation performance can be achieved with appropriate dimensions and power take-off (PTO) damping setting. Focusing on this kind of integration system, Zhao et al [1, 2], gave the analytical solutions based on the linear potential theory to two kinds of the integration system, respectively. One is the integration of oscillating buoy WEC and a pile-restrained floating breakwater. The other is the integration of oscillating buoy WEC with a fixed box-type breakwater. The first one is a symmetric structure which has a limited wave capture width ratio(CWR) of 0.5. The later one is a floating buoy attached to a fixed box-type breakwater which is easy to assemble and extend to a large scale. Meanwhile, the analytical solution also shows that the reflection wave energy can be absorbed by the buoy. The CWR value can reach 0.8 or even higher. Thus the later one has more excellent performance. Since the above analytical solution is based on potential-flow theory in the frequency domain. It ignores the nonlinear wave conditions, the viscous effect, and the flow separation effect. Besides, only the linear PTO model is considered in the analytical solution. However, these factors usually have strong effects on the hydrodynamic performance of the devices in real sea conditions. There are many other kinds of PTO systems with good performance. Hence, aiming at above shortages, this integrated system of oscillating buoy WEC with a fixed box-type breakwater is simulated with OpenFOAM [4] in this paper. The reflection coefficient, the transmission coefficient and the CWR of the system are investigated to show the effectiveness of the device in viscous flow. Except for the linear damping PTO model which has been presented in OpenFOAM, two other types of PTO models are developed to consider the effect of different PTO systems. The quadratic damping model is formulated as $F_{pto} = C_{pto} \times V^2$ and the coulomb damping model is formulated as $F_{pto} = C_{pto} \times sign(V)$ which is often used as a simple model of a hydraulic PTO. The author hopes this development work of PTO system in OpenFOAM can extend the capability of the six degrees of freedom solver to simulate the WEC devices.
The challenge of modeling this integration system is to deal with the dynamic mesh. When the buoy gets resonance, high vibration can be expected. As the floating buoy is too close to the fixed box-type breakwater. Therefore, Using the dynamic mesh method without topology change, the mesh deformation will be very large between the floating buoy and the fixed boundary of the box-type breakwater. The large mesh deformation can easily get the simulation collapsed or lead to inaccurate results. The overset mesh method can handle this situation properly such as the work by ShenZhirong [5]. The overset mesh functionality was presented in OpenFOAM−V1706_PLUS. It can be more convenient for the simulation of floating objects, especially for ocean engineering structures. Thus the overset mesh method is applied in this paper. Also, wave input boundary and shallow water wave damping setting are presented in OpenFOAM−V1706_PLUS which can be used to construct the numerical wave tank.

Validation and Result discussions

Validation

After the validation of wave generation, it shows that good quality waves can be generated in present numerical wave tank. Further verification work is focused on the simulation of floating object using the overset mesh method. A single 2D vertical pile-restrained box type floating breakwater model [3]is chosen for the verification work. The floating breakwater can only move freely in heave direction without any extra restraint. The dimensions of the floating breakwater model: the width 0.8m, the height 0.6m, the draft 0.8m. The water depth 1.0m, wave period $T = 1.79s$, wave height $H = 0.2m$. The heave motion response from 16s to 26s is shown in Figure1. It shows that the simulation can get a stable and reliable result compared with both the experimental data by Ref [6] and the simulation result by using the dynamic mesh without topology change.

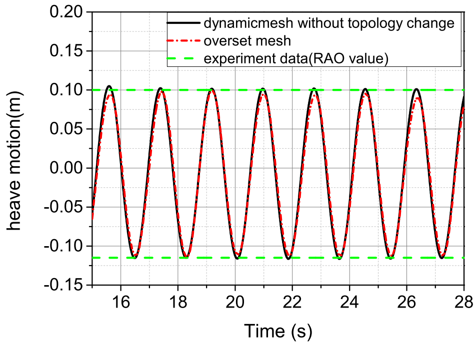

Figure 1: Heave motion response of the single bouy

The dimensions of the integrated system model are referenced from Ref [1]. The sketch of the integration of oscillating buoy WEC with a fixed box-type breakwater is shown in Figure2, the water depth $h = 10.0m$, the floating buoy $a_1/h = 0.2$, fixed breakwater $a_2/h = 0.6$, the gap between the floating buoy and the fixed breakwater $D/h = 0.1$. The total mesh number is 136050, To obtain accurate results, the meshes are refined near the free surface and around the overset zone as shown in Figure3.

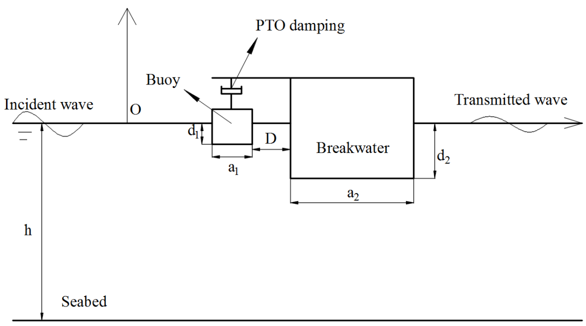

Figure 2: Sketch of the Intergated system

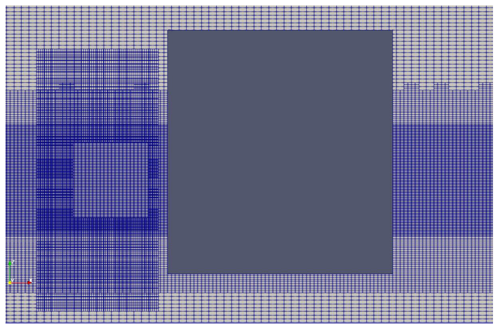

Figure 3: Refined mesh near the free surface and around the overset zone

Linear PTO damping model

The theoretical optimal linear PTO damping coefficient derived from the single floating breakwater was chosen as the PTO damping coefficient corresponding to different wave conditions in Ref [1]. However, considering the effect of viscous and the asymmetric structure which has different added mass coefficient and radiation damping coefficient compared with the single floating breakwater. The optimal PTO damping coefficient in this integrated system may have changed away from the single floating breakwater. The theoretical optimal linear PTO damping coefficients are also applied in this section. But to find out the optimal PTO damping coefficients in viscous flow, several simulations will be calculated with different times of theoretical optimal PTO damping coefficients in later work. Referencing the analytical solutions [1], several feature wave conditions are chosen in the simulation as in Table1. Figure4,5 show the reflection coefficients and the transmission coefficients obtained by present simulation compared with the analytical solution. The results are in accordance with the analytical solution except the reflection coefficient which is relatively small with the analytical solution when the

Table 1: Wave conditions

h(m)	T(s)	kh	$H_i(m)$
10.0	4.735,3.663,3.291,3.035, 2.572,2.387	7.072~1.882	0.5

dimensionless number kh is equal to 6.09. Figure6 shows the wave CWR value of the floating buoy compared with the analytical solution. The maximum CWR value can reach 0.7 that is almost twice times higher than the single floating buoy in Ref [3]. It shows great improvement in energy conversion efficiency. From the comparison of the CWR values obtained by present simulation and the analytical solution, It shows a difference between the present simulation and the analytical solution. When the dimensionless number $kh = 2.0 \sim 5.0$, the CWR value gets a significant decrease in the present simulation where the maximum analytical CWR value can reach 1.0. The difference shows that the viscous and flow separation have a significant effect on the wave energy conversion efficiency. Further observation of the simulated flow field shows that vortex generates at the corner of the buoy as it goes up. The flow separation is different when the buoy goes up and declines. It leads to the fluctuation of the instant energy conversion power. Further research will focus on how to adjust the PTO damping coefficient to be optimal in viscous flow. While different geometry parameters also need to be simulated in viscous flow to evaluate the performance of the integrated system.

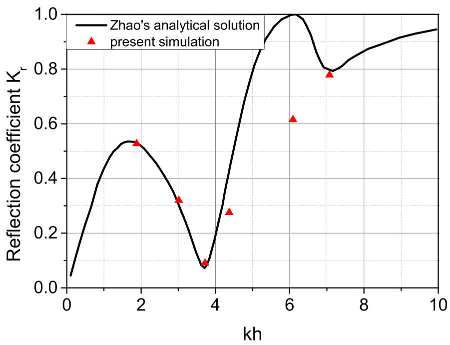

Figure 4: Comparison of the reflection coefficients obtained by present simulation and analytical solution

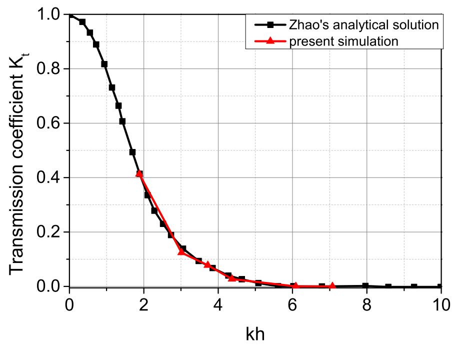

Figure 5: Comparison of the transmission coefficients obtained by present simulation and analytical solution

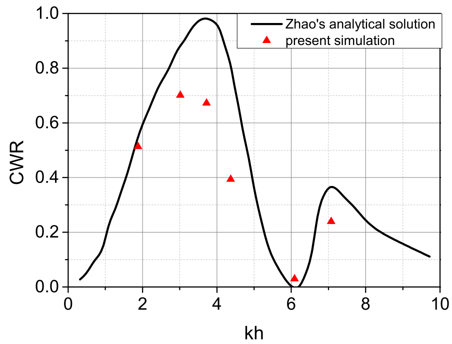

Figure 6: CWR of the intergrated system corresponding to chosen wave conditions

Nonlinear PTO damping model

The linear PTO model used in above section can obtain good results when the motion has small amplitude with a low velocity. But if the motion is strongly nonlinear, the nonlinear PTO model would be a better choice [7], the quadratic damping model and the Coulomb damping model are the typical nonlinear PTO model for WEC devices. The quadratic damping model can act as a drag force. The Coulomb damping model is a simple model of a hydraulic PTO system which is commonly used in many energy conversion devices. These two kinds of nonlinear PTO models are developed and validated in this section. The quadratic damping coefficient is $\lambda_{quadratic} = \lambda_{linear}$, the Coulomb damping coefficient is $\lambda_{coulomb} = \lambda_{linear} \times V_{max}$, the λ_{linear} value is equal to the theoretical optimal damping coefficient value$\lambda_{optimal} = 5720.91 kg/s$ when the dimensionless number $kh = 3.01$. And $V_{max} = 0.48 m/s$ is the maximum buoy velocity in the linear case. Figure7 shows the heave motion response of the buoy restrained by three kinds of PTO model under wave condition $T = 3.663s$,$H = 0.5m$. Figure8 shows the comparison of the PTO forces with three kinds of PTO model corresponding to the motion response in Figue7. From these figures, It shows that the quadratic PTO model and the Coulomb PTO model can both get stable motion responses as the linear PTO damping model. Because the velocity of the buoy is small than $1.0m/s$. So the restraint force by the quadratic PTO model is relatively small than the linear PTO model. As a result, the motion response is larger than the linear one. On the contrary, the restraint force by the Coulomb PTO model keeps a maximum constant value for the duration of the motion response. Thus the motion response is smaller than the linear one. These differences are all reasonable and according to our expectations. So these two kinds of nonlinear PTO models developed in the paper can be used for further research work. Further work will analyze the CWR, the reflection coefficient, and the transmission coefficient with the nonlinear PTO models.

Conclusion

The simulations in this paper are calculated by OpenFOAM. The results show the motion response of the integrated system, the wave energy conversion efficiency and the wave dissipation performance. Considering the effects of viscous and the flow separation, the integrated system can still obtain a high wave energy conversion efficiency, the CWR value reaches 0.7. A good use of the reflected wave energy can be seen from the decrease of the reflection coefficient on the wave conditions that resonate the buoy. Meanwhile, the transmission coefficient can be kept below 0.5 at a wide range of wave conditions when $kh > 1.8$ which promises an ideal wave dissipation performance. The development work of nonlinear PTO models in OpenFOAM extend the functions of OpenFOAM to model the WEC devices. the optimal PTO damping coefficient in viscous flow and the character of nonlinear PTO models need more research work as concluded in the above two sections.

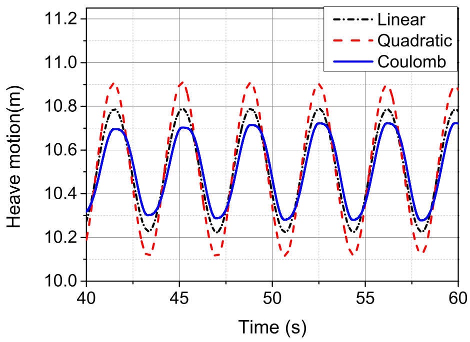

Figure 7: Motion response under three different kinds of PTO

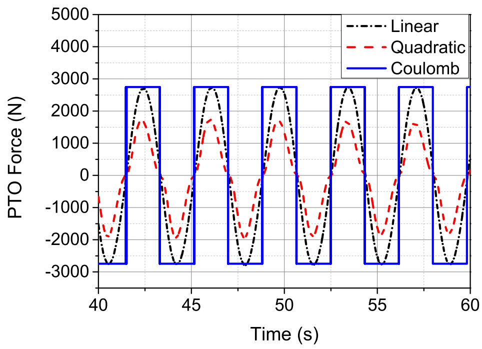

Figure 8: Instant PTO force under three different kinds of PTO

References

[1] X. Zhao, D. Ning, C. Zhang, Y. Liu, and H. Kang, "Analytical study on an oscillating buoy wave energy converter integrated into a fixed box-type breakwater," Mathematical Problems in Engineering,2017,(2017-5-30), vol. 2017, pp. 1–9, 2017.

[2] X. Zhao, D. Ning, C. Zhang, and H. Kang, "Hydrodynamic investigation of an oscillating buoy wave energy converter integrated into a pile-restrained floating breakwater," Energies, vol. 10, no. 712, pp. 1–16, 2017.

[3] D. Ning, X. Zhao, M. Göteman, and H. Kang, "Hydrodynamic performance of a pile-restrained wec-type floating breakwater: An experimental study," Renewable Energy, vol. 95, pp. 531–541, 2016.

[4] OpenCFD, OpenFOAM: The Open Source CFD Toolbox. User Guide Version 1.4, OpenCFD Limited. Reading UK, Apr. 2007.

[5] Z. Shen, P. M. Carrica, and D.-C. Wan, "Ship motions of kcs in head waves with rotating propeller using overset grid method," vol. 2, 06 2014.

[6] M. Isaacson, J. Baldwin, S. Bhat et al., "Wave propagation past a pile-restrained floating breakwater," International Journal of Offshore and Polar Engineering, vol. 8, no. 04, 1998.

[7] L. Sjökvist, "Wave loads and peak forces on moored wave energy devices in tsunamis and extreme waves," Ph.D. dissertation, Acta Universitatis Upsaliensis, 2017.