Numerical Simulation Study of the Water Entry Slamming on Oscillating Buoys with Different Shapes

Xuejian Li¹, Xing Luo², Ruohong Wang¹ and Yanjun Liu¹,²,³,*

1 Institute of Marine Science and Technology, Shandong University, Qingdao, China
2 School of Mechanical Engineering, Shandong University, Jinan, China
3 Key Laboratory of High Efficiency and Clean Mechanical Manufacture, Ministry of Education, Shandong University, Jinan, China
E-mail: 17865192172@163.com

Abstract. Heaving buoys device is a commonly used form of wave energy utilization. When encountering extreme wind and waves, the float will rise away from the waves, and then fall back to the normal working position will be impacted by water. In this paper, numerical simulation studies are carried out on the slamming characteristics of three types of floats of cone, truncated cone and hemispherical shapes, and the influence of the bottom lift angle of the floating body on the peak acceleration and the peak slamming pressure is analyzed. The CFD method was used to simulate the slamming process of different shapes of floating bodies, and the velocity, pressure and flow field changes during the process of entering the water were obtained, resulting in the main conclusions as follows: The truncated cone-shaped floating body is subject to greater slamming pressure, and the bottom rise angle has little effect on the slamming pressure and speed changes; The slamming pressure on the conical floating body is smaller, and the larger the bottom lift angle, the smaller the slamming pressure; The slamming pressure of the hemispherical floating body is stronger than that of the conical shape, but its speed after entering the water is greater than that of the conical shape, and the kinetic energy loss is minimal.

1. Introduction
When the wave energy generating device encounters extreme wind and waves, the huge wave force causes the movement range of the buoy to exceed the normal working stroke, and it collides with the float and is damaged. In order to prevent damage, a common safety measure is to raise the buoy away from the waves, but after an extreme situation, when the buoy falls back to its normal working position, the bottom of the buoy will be slammed by water.

Slamming is an impact-type hydrodynamic load acting on the hull structure, which specifically involves the coupling process of a gas-liquid-solid three-phase medium. Model tests and numerical methods have gradually become the main means of studying wave slamming. Numerical simulation attempts to obtain accurate numerical solutions through the nonlinear boundary conditions imposed on the free surface in the instantaneous state. Due to problems such as the stability of qualitative algorithms, it is sometimes very difficult to obtain an accurate solution. Numerical simulation methods and theoretical methods are often used to study slamming problems.

Generally speaking, the boundary value problem can be discretely solved by the panel method to obtain the normal derivative of the velocity potential on the surface and the velocity potential on the free surface. Then the velocity component of the upper element of the boundary is calculated, and the position of the free surface and the velocity potential on the free surface can be updated step by step in...
the time domain. Wu et al. (2004) [1] studied the process of the wedge-shaped body falling into the water freely. They converted the boundary conditions of the free surface to its integral form, and obtained stable and convergent numerical solutions through iterative integration. Since then, the extended coordinate system and auxiliary functions have been widely used in the solution of slamming problems in two-dimensional and three-dimensional situations. For example, Xu, Duan & Wu (2011) [2], Sun & Wu (2013a) [3] and other articles have applied these two methods. Sun & Wu (2013b, 2015) [4, 5] also studied the slamming of non-axisymmetric objects obliquely into the water and the slamming of water surface waves and gravity on the process of wedge-shaped bodies entering the water.

The above-mentioned researches on slamming problems are mostly in the case of wedge-shaped bodies or cones where the wet surface is straight. On the other hand, there have been many research progresses on the slamming of curved objects into water. Scolan & Korobkin (2001) [6] solved the inverse problem of Wagner's problem combined with slice theory to obtain the solution of the slamming of the elliptical paraboloid into water. Tassin et al. (2012) [7] proposed his own algorithm based on Wagner method and boundary element method and used this method to solve the parabolic water entry slamming problem. Sun & Wu (2014) [8] used the potential flow theory combined with the boundary element method to give a similar solution for the expansion of the paraboloid into water. Yves—Marie (2014) [9] demonstrates the feasibility of Wagner's method in solving the problem of parabolic water entry slamming through oblique water entry slamming test of paraboloid in regular waves.

Thanks to the rapid development of computer technology, various numerical simulation methods have been increasingly used in the research of wave slamming, and computational fluid dynamics method is one of them. CFD technology is more and more widely used in various problems of fluid mechanics, and new CFD algorithms are constantly emerging and applied to fluid-solid slamming problems. For example, finite difference method based on CIP technology (Hu & Kashiwagi, 2004) [10], VOF method (Lin, 2007) [11], immersion boundary element method (Wang et al, 2009) [12], SPH method (Liu et al, 2014) [13], Faccio et al. (2015, 2016) [14, 15] created a CFD extension toolkit specially used to accurately calculate the water entry slamming of a wedge.

In this paper, the commercial software Fluent based on the CFD method is used to conduct numerical simulation research on the slamming characteristics of different shapes of floats, and to discuss and analyze the influence of the shape of the floating body, the bottom lift angle and other factors on the peak acceleration and the peak slamming pressure. Analyze the rise of the free liquid surface and the changes of physical quantities in the flow field such as pressure and velocity during the slamming of the floating body, and study the temporal and spatial distribution characteristics of the slamming load. According to the calculation results of the buoy vertical entry into the water, the comparative analysis obtains the influence law of different shape parameters of the floating body during the water entry slamming process. At the same time, the flow field change law is summarized to provide a reference for the design of the buoy.

2. Verification of Numerical Simulation Method for the Water Entry Slamming

In order to prove the feasibility and accuracy of the numerical simulation analysis of float slamming by using Fluent, this paper first selects Zhao's test model and data for comparison and verification. By establishing the same geometric model as Zhao, using Fluent to simulate the water entry slamming, the numerical results are compared with the experimental data.

Model building

Figure 1 is a schematic diagram of Zhao's test model. The wedge-shaped model is 0.5 m long and has a ramp angle of 30°. The weight of the model is 241 kg, and the initial water entry speed is set to 6.15 m/s. There are five pressure sensors distributed on one side of the model to measure the slamming pressure changes during the wedge-shaped body entering the water; accelerometers are used to collect the acceleration changes of the model to calculate the overall slamming load.
Figure 1. Schematic diagram of Zhao's experimental model.

Figure 2 shows the meshing of the model. The minimum mesh of 2 mm, the computational domain length 5 m, high 5.2 m, below is water and the water level is 2.7 m. The initial position of the model is 90 mm away from the water surface, and the initial velocity is set to -6.015 m/s, so that the velocity when the model enters the water surface is 6.15 m/s. Choose VOF model for multiphase flow simulation, and use implicit volume force; choose achievable k-ε turbulence model, SIMPLEC pressure algorithm, use six-DOF model to define wedge motion mode, and use elastic smoothing and mesh reconstruction for dynamic mesh method.

2.1. Compare calculation results

2.2.1. Comparison of speed changes during water entry. Figure 3 shows the time history curve of the velocity change of the wedge-shaped body in the process of entering the water. The velocity of the wedge-shaped body at the initial moment of entering the water is 6.15 m/s, then begins to decrease, and the magnitude of the decrease gradually increases. It can be seen that the numerical calculation result is very close to the experimental value, and it is almost completely fitted before 0.015 s, and there is a slight deviation in the later stage. It shows that the numerical method can more accurately simulate the velocity and acceleration changes of the wedge-shaped body in the process of entering the water, and the calculation results have certain accuracy.

2.2.2. Slamming pressure comparison at monitoring points. Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8 show the time history curve of slamming pressure changes at 5 monitoring points during the wedge entering water. The pressures at P1-P5 have peaks in sequence, the peak pressure first increases and then decreases, and the peak pressure at P3 is the largest, about 100,000 Pa. The negative pressure appears before the pressure peak at P4, and the negative pressure at P5 is more obvious.
2.2.3. **Slamming pressure comparison at monitoring points.** Figure 9 (1)-(8) are the flow field changes at eight different moments in the water entering process. Figure 9 (1) is the initial moment of the wedge-shaped body entering the water. The pressure peak appears and the jet begins to form; In figure 9 (2)-(3), the pressure continues to rise and the jet develops upward; In figure 9 (4)-(8), the wedge-shaped body completely enters the water, the pressure begins to drop, and the jet diverges outward. It can be seen from the figure that the VOF model can clearly show the rise of the free liquid surface and the separation of jets during the wedge-shaped body entering the water.
3. Numerical Simulation Research on Water Entry Slamming Characteristics of Different Shaped Floats

On the basis of verifying the accuracy and effectiveness of the numerical simulation method, numerical simulation of different shapes of wave energy buoys water entry slamming was carried out. The time history curve of the slamming pressure and velocity of the pressure monitoring point during the free entry of the floating body model into the water is calculated. Analyze the influence of the shape of the floating body, the bottom lift angle and other factors on the slamming load.

The geometric modeling and meshing of 30° conical, 45° conical, 30° frusto-conical, 45° frusto-conical and hemispherical floating bodies are carried out. Assuming that the floating body rises to a position of 2.5 m under extreme sea conditions, the falling height is 2.5 m, and the water entry speed is about 7 m/s. The calculation domain is set the same as before, the initial position of the floating body is 90 mm from the water surface, and the initial velocity of the floating body is set as 6.873 m/s.

![Figure 9](image_url)

Figure 9. Change of flow field during water entry.
3.1. Water entry slamming of 30° conical floating body

3.1.1. Time history curve of speed change during water entry

Figure 10. Time history curve of 30° conical floating body entering water speed.

Figure 10 shows the time history curve of the velocity change of a conical floating body with a bottom lift angle of 30° during the slamming process. The velocity of the floating body continues to increase at a constant acceleration during the initial stage of entry into the water, and reaches the maximum value at about 0.018 s, and then rapidly decreases at about 0.03 s, the decreasing amplitude began to decrease, and the speed change gradually became flat. Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

3.1.2. Monitoring point slamming pressure time history curve. In order to study the temporal and spatial distribution of slamming load, five pressure monitoring points are set on the surface of the geometric model, and the distribution positions are shown in Figure 11. Figure 12 shows the time-history curve of the slamming pressure change at the monitoring points P1-P5 during the entry of the floating body into the water. Starting from 0.018 s, the five monitoring points have successively appeared peak pressures, the peak pressure first increases and then decreases, and the peak duration gradually changes Short; P2 has the highest peak pressure, about 144000 Pa; P5 is in the negative pressure zone before the pressure peak.

3.1.3. Changes of jet and flow field shape during slamming. Figure 13 (1)-(8) are the flow field changes at 8 different times during the floating body entering the water, Figure 13 (1) is the initial moment of the floating body entering the water, the pressure peak appears, and the jet begins to form; Figure 13 (2)-(4) The pressure continues to rise and the jet flows upward; the acceleration of the floating body in Figure 13 (5)-(8) decreases, the pressure begins to drop, and the jet diverges outward.
Figure 11. Time Distribution of pressure detection points.

Figure 12. Time history curve of slamming pressure of floating body entering water.

3.2. Water entry slamming of 45° conical floating body.
Time history curve of speed change during water entry. Figure 14 shows the time history curve of the velocity change of a conical floating body with a bottom lift angle of 45° during the slamming process. The velocity of the floating body continues to increase at a constant acceleration during the initial stage of entry into the water, and reaches the maximum value at about 0.018 s, and then rapidly decreases at about after 0.04 s, the decreasing amplitude began to decrease, and the speed change gradually became flat.
Figure 13. Change of flow field during water entry.

Figure 14. Time history curve of 45° conical floating body entering water speed.
3.3. Monitoring point slamming pressure time history curve. In order to study the temporal and spatial distribution of slamming load, five pressure monitoring points are set on the surface of the geometric model, and the distribution positions are shown in Figure 15.

![Figure 15. Distribution of pressure detection points.](image)

Figure 15. Distribution of pressure detection points.

Figure 16 shows the time-history curve of the slamming pressure change at the monitoring points P1-P5 during the entry of the floating body into the water. Starting from 0.018 s, the five monitoring points have successively appeared peak pressures, the peak pressure first increases and then decreases, and the peak duration gradually changes Short; P1 has the highest peak pressure, about 60000 Pa; P5 is in the negative pressure zone before the pressure peak.

3.4. Changes of jet and flow field shape during slamming. Figure 17 (1)-(8) are the flow field changes at 8 different times during the floating body entering the water, Figure 17 (1) is the initial moment of the floating body entering the water, the pressure peak appears, and the jet begins to form; Figure 17
(2)-(4) The pressure continues to rise and the jet flows upward; the acceleration of the floating body in Figure 17 (5)-(8) decreases, the pressure begins to drop, and the jet diverges outward.

Figure 17. Change of flow field during water entry.

3.5. Water entry slamming of 30° truncated cone-shaped floating body

Time history curve of speed change during water entry. Figure 18 shows the time history curve of the velocity change of a truncated cone-shaped floating body with a bottom lift angle of 30° during the slamming process. The velocity of the floating body continues to increase at a constant acceleration during the initial stage of entry into the water, and reaches the maximum value at about 0.016 s, and
then rapidly decreases at about After 0.02s, the decreasing amplitude began to decrease, and the speed change gradually became flat.

![Graph](image1.png)

**Figure 18.** Time history curve of 30° truncated cone-shaped floating body entering water speed.

**Monitoring point slamming pressure time history curve.** In order to study the temporal and spatial distribution of slamming load, five pressure monitoring points are set on the surface of the geometric model, and the distribution positions are shown in Figure 19.

Figure 20 shows the time-history curve of the slamming pressure change at the monitoring points P1-P5 during the entry of the floating body into the water. P1-P3 monitoring points appeared almost simultaneously at 0.016 s when the slamming pressure peak appeared, the peak pressure gradually decreased but the difference was small, and the peak duration was extremely short; The peak pressure at P1 is the largest, about 3700000 Pa; the slamming pressure peak appears at P4 and P5 later, and the peak pressure is smaller; there is obvious oscillation after the pressure peak at P5.

![Graph](image2.png)

**Figure 19.** Distribution of pressure detection points.

![Graph](image3.png)

**Figure 20.** Time history curve of slamming pressure of floating body entering water.
Changes of jet and flow field shape during slamming. Figure 21 (1)-(8) are the flow field changes at 8 different times during the floating body entering the water. Figure 21 (1) is the initial moment of the floating body entering the water, the pressure peak appears, and the jet begins to form; In Figure 21 (2)-(8), the pressure peak has passed, the acceleration of the floating body decreases, and the jet diverges outward.

![Figure 21. Change of flow field during water entry.](image)

3.6. Water entry slamming of 45° truncated cone-shaped floating body

Time history curve of speed change during water entry. Figure 22 shows the time history curve of the velocity change of a truncated cone-shaped floating body with a bottom lift angle of 45° during the slamming process. The velocity of the floating body continues to increase at a constant acceleration during the initial stage of entry into the water, and reaches the maximum value at about 0.016 s, and then rapidly decreases at about after 0.02s, the decreasing amplitude began to decrease, and the speed change gradually became flat.
Figure 22. Time history curve of 45° truncated cone-shaped floating body entering water speed.

*Monitoring point slamming pressure time history curve.* In order to study the temporal and spatial distribution of slamming load, five pressure monitoring points are set on the surface of the geometric model, and the distribution positions are shown in Figure 23.

Figure 23. Distribution of pressure detection points.

Figure 24. Time history curve of slamming pressure of floating body entering water.

Figure 24 shows the time-history curve of the slamming pressure change at the monitoring points P1-P5 during the entry of the floating body into the water. P1-P3 monitoring points appeared almost simultaneously at 0.016 s when the slamming pressure peak appeared, the peak pressures are almost the same, about 750000 Pa, and the peak duration is extremely short; There is a very short secondary peak after the peak. The secondary peak at P2 is the largest, about 1250000 Pa; the P4 and P5 monitoring points have negative pressure peaks at the same time, but they are relatively small.

*Changes of jet and flow field shape during slamming.* Figure 25 (1)-(8) are the flow field changes at 8 different times during the floating body entering the water, Figure 25 (1) is the initial moment of the
floating body entering the water, the pressure peak appears, and the jet begins to form; In Figure 25 (2)-(8), the pressure peak has passed, the acceleration of the floating body decreases, and the jet diverges outward.

3.7. Water entry slamming of Hemispherical floating body

*Time history curve of speed change during water entry.* Figure 26 shows the time history curve of the velocity change of a hemispherical floating body during the slamming process. The velocity of the floating body continues to increase at a constant acceleration during the initial stage of entry into the water, and reaches the maximum value at about 0.017 s, and then rapidly decreases at about After 0.05s, the decreasing amplitude began to decrease, and the speed change gradually became flat.
Figure 26. Time history curve of hemispherical floating body entering water speed.

Monitoring point slamming pressure time history curve. In order to study the temporal and spatial distribution of slamming load, five pressure monitoring points are set on the surface of the geometric model, and the distribution positions are shown in Figure 27.

Figure 27. Distribution of pressure detection points.

Figure 28. Time history curve of slamming pressure of floating body entering water.

Figure 28 shows the time-history curve of the slamming pressure change at the monitoring points P1-P5 during the entry of the floating body into the water. Starting from 0.017 s, the slamming pressure peaks appear successively at P1-P3, the peak pressure gradually decreases, and the peak duration gradually becomes longer; The peak pressure at P1 is the largest, about 300000 Pa; Negative pressure appears at P3 before the pressure peak; Negative pressure appears at P4 and P5 later, and it stabilizes after a short period of oscillation.
Changes of jet and flow field shape during slamming. Figure 29 (1)-(8) are the flow field changes at 8 different times during the floating body entering the water, Figure 29 (1) is the initial moment of the floating body entering the water, the pressure peak appears, and the jet begins to form; Figure 29 (2)-(3) The pressure continues to rise and the jet flows upward; the acceleration of the floating body in Figure 29 (4)-(8) decreases, the pressure begins to drop, and the jet diverges outward.

![Figure 29](image_url)

Figure 29. Change of flow field during water entry.

4. Comparison of water slamming characteristics of different shaped floating bodies

Comparison of water entry speed of different shapes of floating bodies. Figure 30 shows the time history curve of the speed change of different shapes of floating bodies entering the water. The speed of the 45° conical floating body decreases more slowly than the 30° conical floating body, that is, the acceleration is smaller, indicating that the slamming load is smaller; There is not much difference in the speed change of the truncated cone-shaped floating body with different bottom elevation angles. Both of them are reduced to about 5 m/s at a great acceleration, and then they become gentle. It shows that when the truncated cone-shaped floating body enters the water, the bottom surface bears the main slamming load, and the smaller conical transition surface cannot reduce the slamming load of the floating body when it enters the water; The slamming load of the hemispherical floating body at the
initial stage of entering the water is between the conical shape and the truncated cone shape, and the speed after it stabilizes is the largest, indicating that the kinetic energy loss is the smallest.

![Figure 30. Time history curve of different shapes floating body entering water speed.](image)

Comparison of peak slamming pressure of different shapes of floating bodies. In practical engineering applications, due to the need to coordinate the floating body with the guide column or other parts, the ideal conical or hemispherical floating body is difficult to apply, and the truncated cone-shaped floating body is the most widely used. However, according to Table 1, it can be seen that the peak slamming pressure of the truncated cone-shaped float is much greater than that of the conical and hemispherical shapes, and the bottom lift angle of 30° and the bottom lift angle of 45° are not much different. It shows that when the conical transition surface of the truncated cone-shaped floating body is small, the influence of the bottom rise angle is not large. For the truncated cone-shaped floating body, in order to reduce the bottom slamming pressure, the area of the truncated bottom surface should be reduced as much as possible, and the area of the cone transition surface should be increased. The peak slamming pressure of the 45° conical floating body is less than half of that of the 30° conical floating body, indicating that the bottom rise angle has a greater slamming on the slamming pressure of the conical floating body. The smaller the bottom rise angle, the greater the slamming pressure. The slamming pressure of the hemispherical floating body is stronger than that of the conical shape.

| Floating body shape      | Peak pressure (Pa) |
|--------------------------|--------------------|
| 30°conical               | 143251             |
| 45°conical               | 59141              |
| 30°truncated cone-shaped | 6348607            |
| 45°truncated cone-shaped | 7504067            |
| hemispherical            | 300515             |

5. Conclusion
The CFD method was used to simulate the slamming process of different shapes of floating bodies, and the velocity, pressure and flow field changes during the process of entering the water were obtained. The truncated cone-shaped floating body is subject to greater slamming pressure, and the bottom rise angle has little effect on the slamming pressure and speed changes; The slamming pressure on the conical floating body is smaller, and the larger the bottom lift angle, the smaller the slamming pressure; The slamming pressure of the hemispherical floating body is stronger than that of the conical
shape, but its speed after entering the water is greater than that of the conical shape, and the kinetic energy loss is minimal.

6. References
[1] Wu G X, Sun H, He Y S. Numerical simulation and experimental study of water entry of a wedge in free fall motion[J]. Journal of Fluids & Structures, 2004, 19(3):277-289.
[2] Xu G D, Duan W Y, Wu G X. Numerical Simulation of Water Entry of A Cone in Free-Fall Motion[J]. Quarterly Journal of Mechanics & Applied Mathematics, 2011, 64(3):265-285(21).
[3] Sun S L, Wu G X. Oblique water entry of a cone by a fully three-dimensional nonlinear method[J]. Journal of Fluids & Structures, 2013a, 42(4):313-332.
[4] Sun S L, Wu G X. Oblique water-entry of non-axisymmetric bodies at varying speed by a fully nonlinear method[J]. Quarterly Journal of Mechanics & Applied Mathematics, 2013b, 66(3):365-393.
[5] Sun, S.Y., Sun, S.L., Wu, G.X. Oblique water entry of a wedge into waves with gravity effect[J]. Fluid Struct. 2015, 52:49-64.
[6] Scolan Y M, Korobkin A A. Three-dimensional theory of water impact, part 1: Inverse Wanger problem[J]. Journal of Mechanics, 2001, 440:293-326.
[7] A. Tassin a,b, N. Jacques a,n, A. El Malik Alaloui a, A. Neme a, B. Leble b Hydrodynamic loads during water impact of three-dimensional solids: Modelling and experiments[J]. Journal of Fluids and Structures, 2012, 28:211-231.
[8] Wu G X, Sun S L. Similarity solution for oblique water entry of all expanding paraboloid[J]. Journal of Fluid Mechanics, 2014, 745:398-408.
[9] Yves-Marie, S. Oblique water entry of a three dimensional body. Int. J. Nav. Archit. Ocean Eng. 2014, 6(4):1197-1208.
[10] Hu C, Kashiwagi M. A CIP-based method for numerical simulations of violent free-surface flows[J]. Journal of Marine Science & Technology, 2004, 9(4):143-157.
[11] Lin P. A fixed-grid model for simulation of a moving body in free surface flows[J]. Computers & Fluids, 2007, 36(3):549-561.
[12] Wang W, Wang Y. An improved free surface capturing method based on Cartesian cut cell mesh for water-entry and -exit problems[J]. Proceedings Mathematical Physical & Engineering Sciences, 2009, 465:1843-1868.
[13] Liu M B, Shao J R, Li H Q. An SPH model for free surface flows with moving rigid objects[J]. Internation Journal for Numerical Methods in Fluid, 2014, 74(9):684-697.
[14] Facci, A. L., Panciroli, R., Ubertini, S., Porfiri, M. Assessment of PIV-based analysis of water entry problems through synthetic numerical datasets. Journal of Fluids and Structures, 2015, 55:484-500.
[15] Facci, A. L., Porfiri, M., Ubertini, S. Three-dimensional water entry of a solid body: a computational study[J]. Fluid Struct. 2016, 66:36-53.

Acknowledgments
This project is supported by the 2018 Shandong Major Science and Technology Innovation Project (No. 2018CXGC0104) “Design and Key Technologies of Supporting Platform for Deep Sea Cage Culture”, the 2017 NSFC-Shandong Joint Fund Project (U1706230) “Research on Mechanism and Key Technology of Energy Efficiency Enhancement in Floating Hydraulic Wave Power Generation System” and 2017 Marine Renewable Energy Funds Project (No.GHME2017YY01) “Demonstration of Marine Power Supply System for Marine Instruments and Equipment – Wave Energy and Tidal Current Energy Complementary Instruments and Equipment Power Supply System Based on Mooring Platform”. At the same time, thanks to the corresponding author Professor Yanjun Liu (Email: lyj111ky@163.com) for his guidance on this paper.