

Hydrodynamic Analysis of Wave-induced Nonlinear Motion of Backward Bent Buoy by the Use of the Particle Method

Mohammad Arif Hasan MAMUN, Shuichi NAGATA, Kazutaka TOYOTA,
Yasutaka IMAI and Toshiaki SETOGUCHI

Institute of Ocean Energy, Saga University
1 Honjo-machi, Saga 840-8502, Japan

A fluid-structure interactions simulation program has been developed by using moving particle semi-implicit (MPS) method for the hydrodynamic analysis of wave-induced nonlinear motion of backward bent buoy (BBDB). The BBDB is a floating oscillating water column type wave energy converter. The MPS method is based on the particle interaction models and discretizes the governing differential equation of continuum without the use of computational grid model. To satisfy the incompressibility the particle number density is implicitly required to be constant. A semi-implicit algorithm is used for two-dimensional incompressible non-viscous flow analysis. The MPS method is capable to simulate the complicated behavior of the free water surface. The particles whose particle number densities are below a set point are considered as on the free surface. To compute the motions of the BBDB, the equations of translational and rotational motions were integrated in time to determine the correct position of the BBDB surface at each time step of the time-domain calculation. The effect of numerical resolution on the results was checked by changing the number of particles. Simulation is done for different amplitude and frequency of the wave generator.

Key Words : Oscillating Water Column (OWC), Wave Energy Converter (WEC), Backward Bent Duct Buoy (BBDB), Moving particle semi-implicit (MPS) method

1. Introduction

The diminution of oil and global warming in future encouraged a major change in the renewable energies development and raised the interest in large-scale energy production from the waves. Wave energy from the sea is being increasingly considered in many countries as a major resource. The energy from ocean waves is a promising resource of renewable energy because of its high energy density. The waves are produced by wind action and are therefore an indirect form of solar energy. Several types of wave energy converters (WEC) have been developed in the recent years and detail review has been done by Falcao⁽¹⁾. Among these WEC the Backward Bent Duct Buoy (BBDB) was invented under the leadership of Masuda⁽²⁾ which has some advantages than others, i.e. primary conversion efficiency is high, a longer floating structure is not required, and the mooring force and mooring cost is less⁽³⁾.

In the BBDB, the oscillating water column (OWC) duct is bent backward from the incident wave direction (Fig. 1) which is reversed than that of the frontward facing duct version. By making the backward bent duct, the length of the water column could be made sufficiently large to achieve resonance, and the draught of the floating structure could be kept within acceptable limits. The research on BBDB converter (including model testing) has been carried out in several countries like Japan, China, Denmark, Korea, and Ireland. The BBDB converter has been used to produce power about one thousand navigation buoys in Japan and China^{(4),(5)}. A BBDB converter model equipped with a horizontal axis Wells turbine has been tested in the sheltered sea waters of Galway Bay (western Ireland) since the end of 2006⁽⁶⁾. A report has been prepared for the British Department of Trade and Industry (DTI) to compare three types of floating OWCs for electricity generation in an Atlantic environment: BBDB, Sloped Buoy and Spar Buoy⁽⁷⁾. They found that based on pure power capture performance the BBDB is superior to the Sloped buoy and Spar buoy, the comparison being for devices with the same capture width.

佐賀大学 海洋エネルギー研究センター
(〒840-8502 佐賀県佐賀市本庄町1)
E-mail: hasan@ioes.saga-u.ac.jp

To get the optimum design of the BBDB energy converter some numerical investigation should be done to estimate the motion of the floating body and mooring system, the fluctuation of air pressure in the air chamber etc., before starting the experiment. A number of theoretical models have been developed to simulate the energy conversion, from wave to turbine shaft, of fixed OWC plant equipped with a Wells air-turbine ^{(8),(9)}. A few works has been done on floating OWC-type wave energy converter. Hong et al. ⁽¹⁰⁾ used the linear wave theory to calculate the motions and time-mean horizontal drift forces of floating backward-bent duct buoy wave energy absorbers in regular waves taking account of the oscillating surface-pressure due to the pressure drop in the air chamber above the oscillating water column. Toyota et al. ⁽¹¹⁾ developed the equations of motion of a floating OWC-type wave energy converter in waves considering memory effect by air pressure in air chamber and some calculation results in frequency domain by 3D boundary element method. They have also done the experiments on exciting forces and radiation forces and calculation results have been compared with experimental results in frequency domain.

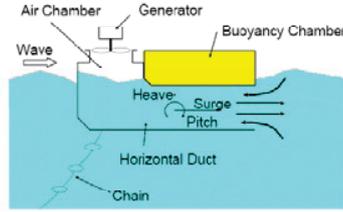


Figure 1: principle of BBDB

The purpose of our research is to develop a optimal design method for the floating OWC-type WEC such as BBDB, in order to do that as the first step, a wave generating tank has been simulated by moving Particle Semi-implicit method. Secondary, the exiting force by incident wave induced by the body motion and the air pressure fluctuation in chamber acting on BBDB are obtained by using the same method.

2. Moving Particle Semi-implicit Method

The moving particle semi-implicit (MPS) method has been designed to handle extremely complicated free-surface problems of incompressible fluids in the field of nuclear engineering ⁽¹²⁾. In the MPS method fluids are represented by particles and grids are not

necessary. To simulate incompressibility a semi-implicit algorithm has been employed. MPS method has proven useful in a wide variety of engineering applications including free-surface hydrodynamic flow.

In this method, the fluid is considered as assemblies of interacting particles, the motion of the particles are calculated through the interactions with neighboring particles and according to the governing equations of fluid motion, the continuity and Navier-Stokes equations:

$$\frac{1}{\rho} \frac{D\rho}{Dt} + \nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho} \nabla p + \mathbf{g} + \nu \nabla^2 \mathbf{u} \quad (2)$$

Where, \mathbf{u} = particle velocity vector;

t = time;

ρ = fluid density;

p = particle pressure;

\mathbf{g} = gravitational acceleration vector and

ν = kinematic viscosity.

Although Eq. (1) is written in the form of a compressible flow, but in this study, water is treated as incompressible and the density ρ is considered as constant. The left hand side of Eq. (2) denotes the Lagrangian time differentiation involving the advection term and in the MPS method, this term is automatically calculated through the tracking of particle motion.

The above equations are discretized by use of differential operator models, namely the gradient and Laplacian operators. The gradient operator is modeled by using the weight function. A particle interacts with its neighboring particles within some influence area covered with a weight function $w(r)$, where r is a distance between two particles. The weight or kernel function used in this study is as follows:

$$w(r) = \begin{cases} \frac{r_e}{r} - 1 & 0 \leq r \leq r_e \\ 0 & r_e \leq r \end{cases} \quad (3)$$

Where, r_e = radius of the influence area of each particle (kernel size).

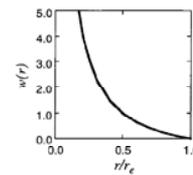


Figure 2: Profile of weight function $w(r)$

One important aspect of the weight function is that it is infinity at $r=0$. This is good for avoiding clustering of particles ⁽¹²⁾.

When a particle i and its neighbors j are located at \mathbf{r}_i and \mathbf{r}_j , particle number density is defined as,

$$\langle n \rangle_i = \sum_{j \neq i} w(|r_j - r_i|) \quad (4)$$

It is assumed that the fluid density is approximately proportional to the particle number density and for incompressible flow the fluid density is required to be constant; this is equivalent to the particle number density being constant. The constant value of the particle number density is denoted by n_0 .

A gradient vector is estimated between two neighboring particles i and j as

$$\frac{(\Phi_j - \Phi_i)(r_j - r_i)}{|r_j - r_i|^2}$$

Where, Φ is a physical quantity. The gradient vector at \mathbf{r}_i is a weighted average of these vectors (Figure 3):

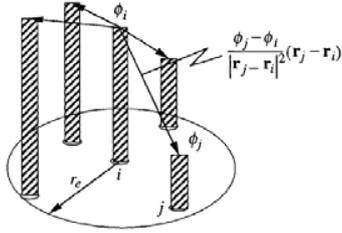


Figure 3: Concept of gradient operator in standard MPS

The gradient operator is a local weighted average of the gradient vectors between particles i and its neighboring particles j :

$$\langle \nabla \phi \rangle_i = \frac{D_s}{n_0} \sum_{j \neq i} \frac{\phi_j - \phi_i}{|r_j - r_i|^2} (r_j - r_i) w(|r_j - r_i|) \quad (5)$$

Where ϕ = an arbitrary scalar function,
 D_s = number of space dimensions,
 \mathbf{r} = coordinate vector of fluid particle,
 $w(r)$ = the kernel function and
 n_0 = the constant particle number density.

The pressure gradient is defined by replacing ϕ in Eq. (5) by the minimum value of ϕ among the neighboring particles, such as

$$\langle \nabla p \rangle_i = \frac{D_s}{n_0} \sum_{j \neq i} \frac{p_j - p_i}{|r_j - r_i|^2} (r_j - r_i) w(|r_j - r_i|) \quad (6)$$

$$\hat{p}_i = \min_{j \in J} (p_i, p_j) \quad , \quad J = \{j: w(|r_j - r_i|) \neq 0\} \quad (7)$$

The Laplacian operator is formulated as [12]:

$$\langle \nabla^2 \phi \rangle_i = \frac{2D_s}{n_0 \lambda} \sum_{j \neq i} (\phi_j - \phi_i) w(|r_j - r_i|) \quad (8)$$

Where

$$\lambda = \frac{\sum_{j \neq i} w(|r_j - r_i|) |r_j - r_i|^2}{\sum_{j \neq i} w(|r_j - r_i|)} \quad (9)$$

The MPS method is an iterative prediction-correction process consist of two main steps. The first step is an explicit calculation to obtain intermediate or temporal velocities under the given viscosity and gravity terms. But in this step, mass conservation is not satisfied; i.e. the number densities n^* that are calculated at the end of first process diverge from the constant n_0 . For this reason a second corrective process is required to adjust the number densities to initial constant values prior to the time step. In the second process, the intermediate particle velocities are updated implicitly through solving the Poisson Pressure Equation (PPE) derived as ⁽¹²⁾:

$$(\nabla^2 p_{k+1})_i$$

Where, Δt = calculation time step

k = step of calculation.

A particle whose particle number density satisfies $n_i < \beta n_0$ is regarded as the free surface. The zero pressure boundary condition is applied for the particle which is considered as a free-surface particle. The value of β can be chosen between 0.80 and 0.99 ⁽¹²⁾. We consider $\beta = 0.97$. Different sizes of the weight function have been used in this work. For the particle number density and the gradient model the size is $r_e = 2.1l_0$, where l_0 is the distance between two adjacent particles in the initial configuration. On the other hand, for the Laplacian model the size is $r_e = 3.1l_0$.

3. Wave Generating Tank

Before starting the simulation of BBDB, a wave generating water tank (as shown in Figure 4) has been simulated by MPS method which is similar to Toyota et al. ⁽¹¹⁾ experimental wave tank in size. This tank is 18 m in length and 1 m in depth.

Total 9000 particles have been used to simulate the tank. Reciprocating motion has been given to the left side wall to generate the wave.

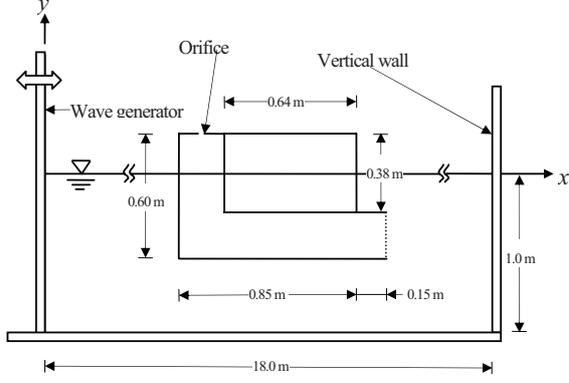


Figure 4: Basic BBDB model inside wave generating tank

The particles of the left side wall moved according to the following equations:

$$\frac{dx}{dt} = u = A\omega \frac{\cosh k(h+y)}{\sinh kh} \cos(kx - \omega t) \quad (11)$$

Where, u = velocity of the wave generator
 A = amplitude of the wave generator

$$\omega = \text{angular Frequency} = \frac{2\pi}{T}$$

k = wave number

h = water depth

x = axis in the direction of propagation

y = axis in the vertically upward direction

t = time simulation

T = wave period

The wave number, k , is determined from the following equation,

$$\frac{\omega^2 h}{g} = kh \tanh(kh) \quad (12)$$

The wave profile is,

$$\eta = A \sin(k(x - a) - \omega t) + b \quad (13)$$

Where a and b are constants and g is the acceleration due to gravity.

4. Simulation of BBDB

At first the movement of solid particles of the BBDB is computed as ordinary fluid particles and then the position of each particle is corrected so as to form the shape of a solid body in view of the conservation of momentum.

Figure 4 shows the basic BBDB model inside the wave tank. When the solid consists of particles i , relationships among co-ordinates of solid particles \mathbf{r}_i , the centre of solid \mathbf{r}_g , relative co-ordinates of solid particles \mathbf{q}_i and the moment of inertia I are represented by

$$\mathbf{r}_g = \frac{1}{n} \sum_{i=1}^n \mathbf{r}_i$$

$$\mathbf{q}_i = \mathbf{r}_i - \mathbf{r}_g$$

$$I = \sum_{i=1}^n |\mathbf{q}_i|^2$$

The solid particles are calculated in each time step by using the same procedure with the fluid particles and then translation and rotation velocity vectors of the solid are calculated by

$$\mathbf{T} = \frac{1}{n} \sum_{i=1}^n \mathbf{u}_i$$

$$\mathbf{R} = \frac{1}{I} \sum_{i=1}^n \mathbf{u}_i \times \mathbf{q}_i$$

Then the velocity vectors of the solid particles are replaced by those of the solid motion:

$$\mathbf{u}_i = \mathbf{T} + \mathbf{q}_i \times \mathbf{R}$$

The boundary conditions are given on the free surface and the solid surface. The free surface may be detected using the particle number density only, i.e., when the particle number density is below $0.97n_0$, the particle is regarded as being on the free surface. Then a Dirichlet condition for the pressure, equal to the atmospheric pressure P_0 , is given to this particle on the free surface. On the solid surface, the fluid velocity is given as equal to the velocity of the boundary.

5. Results and Discussions

Two-dimensional calculation of the wave generating tank and the exiting force by incident wave induced by the body motion on BBDB has been done by moving particle semi-implicit method with the following parameters: distance between neighboring particles in the initial configuration, l_0 , is 0.05m, the amplitude of the wave generator is 0.2 m, wave period is 2 sec. Figure 5 shows the free surface profile, the motion of the wave generator and BBDB at different times.

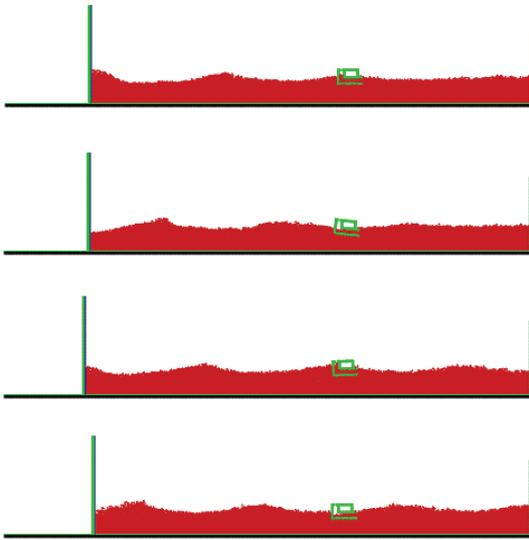


Figure 5: The free surface profile, the motion of wave generator and BBDB at different times.

The left wall particles are moving with a velocity given by Eq. (11) to generate the waves. The right and bottom walls particles are fixed and velocities are zero. The particles on the inner first line of the walls participate in the pressure calculation along with other inside water particles. The particles of the BBDB follow the same procedure of the other water particles and then translate and rotate according to the calculation of a floating solid body. The water particles close to the left wall move towards the right wall and produce the free surface profile. Along with the free surface movement, the BBDB is moving ups and down and the water column height inside the BBDB is changing accordingly. In this way the oscillating water column is produced inside the BBDB which can be used to estimate power by providing generator near the orifice of the BBDB.

6. Conclusions

Hydrodynamic analysis of wave-induced nonlinear motion of the Backward Bent Duct Buoy (BBDB) inside a wave generating tank has been done by the moving particle semi-implicit (MPS) method. The free surface profile generated by the motion of the left wall has been shown with the oscillating water column inside the BBDB at different times. To check the numerical resolution the simulations were performed with a larger number of particles. However, no obvious improvement

could be seen in the body motions, even for the shorter wave period.

References

- (1) Falcao, A.F. de O., "Wave energy utilization: A review of the technologies", *Renewable and Sustainable Energy Reviews*, Vol.14, pp. 899–918, 2010.
- (2) Masuda Y, McCormick ME., "Experiences in pneumatic wave energy conversion in Japan", *Utilization of ocean waves-wave to energy conversion ASCE*, pp. 1-33, 1986.
- (3) Nagata, S., Toyota, K., Imai, I., and Setoguchi, T., "Numerical Simulation for Evaluation of Primary Energy Conversion of Floating OWC-type Wave Energy Converter", *Proceedings of the Nineteenth (2009) International Offshore and Polar Engineering Conference*, pp 300-307, 2009.
- (4) Masuda Y, Xiangfang L, Xiangfan G., "High performance of cylinder float backward bent duct buoy (BBDB) and its use in European seas", *Proceedings of (First) European Wave Energy Symposium*; pp. 323–37, 1993.
- (5) Masuda Y, Kimura H, Liang X, Gao X, Mogensen RM, Andersen T., "Regarding BBDB wave power generation plant", *Proceedings of 2nd European Wave Power Conference*, pp. 69–76, 1995.
- (6) Ocean Energy. Available online at: <http://www.oceanenergy.ie>.
- (7) DTI. Near shore floating oscillating water column: prototype development and evaluation. Rep URN 05/581; 2005. Available online at: <http://www.berr.gov.uk/files/file17347.pdf>.
- (8) Suzuki, M., Analysis of Wave Energy Converting Characteristics of Wave Power Generating System Installed in Breakwater, *Transactions of the Japan Society of Mechanical Engineers*, Vol.70, No.700, pp.3166-3173, 2004.
- (9) Falcao, A.F. de O., Justino, P.A.P., "OWC wave energy devices with air flow control", *Ocean Engineering*, Vol. 26, pp. 1275–1295, 1999.
- (10) Hong, D.C., Hong, S.Y. and Hong, S.W., "Numerical Study of the Motions and Drift Force of a Floating OWC Device," *Ocean Engineering*, Vol. 30, pp 139-164, 2004.
- (11) Toyota1, K., Nagata1, S., Imai, Y., and Setoguchi, T., "Research for evaluating performance of OWC-type Wave Energy Converter "Backward Bent Duct Buoy", *Proceedings of the 8th European Wave and Tidal Energy Conference*, pp. 901-913, 2009.
- (12) Koshizuka, S. and Oka, Y., "Moving-Particle Semi-Implicit Method for Fragmentation of Incompressible Fluid", *Nuclear Science and Engineering*, Vol. 123, pp. 421-434, 1996.