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# Numerical simulation of the gas-fluid interaction in underwater explosion by the smoothed particle hydrodynamics method

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## 1. Abstract

Owing to the fact that the combination of adaptive, mesh free and Lagrangian natures of the smoothed particle hydrodynamics (SPH) method makes it proper in treating highly dynamic phenomena that occur in the extremely transient High-Explosive (HE) explosion process, In this study, a stabilized form of SPH method is applied for simulating the underwater explosion (UNDEX) process and its interacting problems such as free surface changes and bubble evolutions. In the present paper, prediction of free surface changes due to UNDEX bubble pulsations is performed by a newly developed stabilized SPH method, which adopts an innovative velocity field smoothing technique to stabilize the process, combined with an adaptive smoothing length scheme and an innovative Voronoi-based generated particle distribution.

## 2. Introduction

An underwater explosion produced by the detonation of a submerged high explosive poses a serious threat to the integrity of nearby structures, due to extreme sudden forces applied to them [1,2,3]. Gases arise in an underwater explosion, may lead to bubbles formation. The dynamics of explosive gas is the major difference between UNDEX and other types of explosions. The density difference between the water and explosion products, results in appearance of very specific pressure field in water, including the primary shock wave (first pulse) and the bubble pulsations (second pulses) which are complicated to analyze [1,2]. Therefore, reliable efficient solutions are required in order to accurately simulate this complex behavior which consists of a number of interacting phenomena such as shock wave propagation, gas-fluid interaction, free surface changes, and bubble evolutions.

Experimental studies are fairly expensive, impractical, and also very dangerous due to their destructive nature [1,2]; hence, far more researches are focused on the numerical simulations using modern computing techniques [3,4,5]. Numerical simulations of the HE explosions are generally very difficult for the conventional grid-based numerical methods. Traditional Lagrangian techniques such as FEM are capable of capturing the history of the detonation events associated with each material [3].

**Keywords:** Smoothed particle hydrodynamics (SPH), Underwater Explosion (UNDEX), Shock wave, Bubble, Free surface.

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It is, however, difficult to apply them practically, since the severely distorted mesh may result in very inefficient small time-step, and may even lead to the breakdown of the computation. Moreover, traditional Eulerian techniques, such as FDM and FVM, can well figure out the problem due to the large deformations in the global motions, but it is very difficult to analyze the details of the flow because of the lack of history and the smearing of information as the mass moves through the fixed-in-space Eulerian mesh [3,6]. As a result, a stabilized SPH method with a practical combination of stabilizer terms [7] and an appropriate particle distribution [8] would be able to analyze the process.

## 3. UNDEX Governing Equations

The SPH formulation is performed based on the Euler equations [1,3], as the explosion is an extremely fast phenomenon and the explosion process is adiabatic. Adopting an appropriate equation of state (Jones-Wilkins-Lee, and Mie-Gruneisen), the explosive core transition from solid into gaseous phase is performed, and the underwater explosion can be simplified as a fluid flow, which is governed by the following state variables: pressure, temperature, density and velocity. Simultaneous solution of conservation of density, internal energy, velocity and applicable equation of state (EOS), yield to determination of the four mentioned variables. The Euler system of equations is as follows and can be explained by the conservations of mass, momentum, and internal energy in addition to a practical EOS respectively [3,8]:

$$\frac{D\rho}{Dt} = -\rho\nabla.v \tag{1}$$

$$\frac{Dv}{Dt} = -\frac{1}{\rho}\nabla p \tag{2}$$

$$\frac{De}{Dt} = -\frac{p}{\rho}\nabla.v \tag{3}$$

$$p = function\ (\rho, e) \tag{4}$$

where $\boldsymbol{\rho}$ is the density, $\mathbf{v}$ is the velocity vector, $\mathbf{e}$ is the internal energy per unit mass, $\mathbf{p}$ is the pressure and $\mathbf{t}$ is the time indicator.

Coupling with a suitable EOS, the following equations of motion is derived from the equations (1) to (4) respectively and is known as one of the standard form of the SPH equations in which the viscosity term has been neglected due to an extremely fast phenomenon and can be used to simulate the HE explosions [3,7,8]:

$$\frac{D\rho_i}{Dt} = \sum_{j=1}^{N} m_j\, v_{ij} \frac{\partial W_{ij}}{\partial x_i} \tag{5}$$

$$\frac{Dv_i}{Dt} = -\sum_{j=1}^{N} m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \boldsymbol{\Pi}_{ij} + \boldsymbol{PB}_{ij}\right)\frac{\partial W_{ij}}{\partial x_i} \tag{6}$$

$$\frac{De_i}{Dt} = \frac{1}{2}\sum_{j=1}^{N} m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \boldsymbol{\Pi}_{ij}\right) v_{ij} \frac{\partial W_{ij}}{\partial x_i} \tag{7}$$

$$\frac{D\boldsymbol{x}_i}{Dt} = \boldsymbol{v}_i \tag{8}$$

*here,* $\boldsymbol{N}$ *is the total number of participated particles in support domain of central node* $\boldsymbol{i}$*,* $\boldsymbol{m}$ *is the particle mass,* $\boldsymbol{W}$ *is the SPH smoothing function and* $\boldsymbol{\Pi}_{ij}$ *is the Monaghan-type of artificial viscosity stabilizer*, and $\boldsymbol{PB}_{ij}$ is the penalty force applying in boundary interface treatment [3,7].

In this paper, the following EOS (JWL) is used for the TNT explosive gas [3,7,9]:

$$p = A\left(1 - \frac{\omega\eta}{R_1}\right)e^{\frac{-R_1}{\eta}} + B\left(1 - \frac{\omega\eta}{R_2}\right)e^{\frac{-R_2}{\eta}} + \omega\eta\rho_0 e \tag{9}$$

In which $\eta$ is the ratio of the density of the explosive gas to the initial density of the original explosive charge, $e$ is the internal energy of the high explosive per unit mass. $A$, $B$, $R_1$, $R_2$ and $\omega$ are coefficients obtained by fitting experimental data and are usually taken as 3.712E+11 N/m2, 3.21E+09 N/m2, 4.15, 0.95, and 0.3 respectively [3,7].

Also, the Mie-Gruneisen EOS is adopted for surrounding water particles[3,9]:

In the compression state:

$$p = a_1\mu + a_2\mu^2 + a_3\mu^3 + (b_0 + b_1\mu + b_1\mu^2)\rho_0 e \tag{10}$$

In the expansion state:

$$p = a_1\mu + (b_0 + b_1\mu)\rho_0 e \tag{11}$$

where $\rho_0$ is the initial density, $\eta$ is the ratio of the density after and before disturbance, and $\mu = \eta - 1$ . When $\mu > 0$, water is in the compression state, while $\mu < 0$, is associated with the expansion state. Necessary parameters of Gruneisen EOS for water are summarized in Table 1.

Table 1. Polynomial EOS parameters for water [3,8].

| EOS Parameter | Value |
|---|---|
| $a_1$ | $2.190 * 10^9$ N/m$^2$ |
| $a_2$ | $9.224 * 10^9$ N/m$^2$ |
| $a_3$ | $8.767 * 10^9$ N/m$^2$ |
| $b_0$ | 0.4934 |
| $b_1$ | 1.3937 |

There are three types of stabilizers which have been used in the proposed SPH simulation: artificial viscosity [3], velocity field smoothing [7] and penalty force [3]. These have been added properly to enhance the accuracy of the results by preventing particles unphysical penetration especially near the moving boundary layer (bubble boundary particles).

## 4. Numerical Simulations

In this example, a single bubble of underwater explosion near a free surface is considered. A 2D circular TNT explosive gas (radius=10cm), as depicted in figure 1, is located about 15cm below the free surface. This configuration is simulated for Interacting analysis of a single UNDEX bubble and free surface. Figure 2 illustrates the bubble boundaries positions and free surface changes just after the explosion. Corresponding to each case, the pressure contours have been demonstrated in the right side.

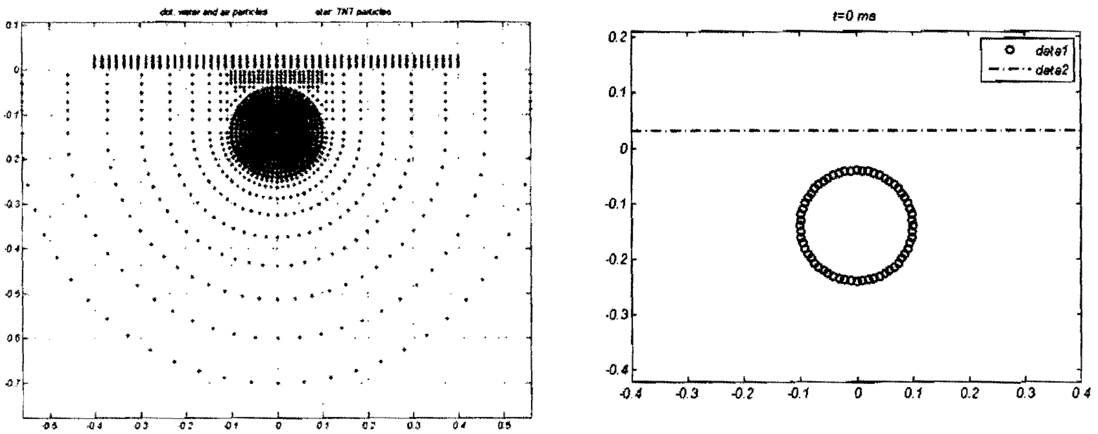

Figure 1 – Initial geometry of SPH particles distribution (Left) and initial bubble boundary particles (Right).

According to Figure 2, the impulsive shockwave and bubble pulsations force the surrounding water particles to move away from the high pressure field; resulting in creation of a dome-shaped free water surface.

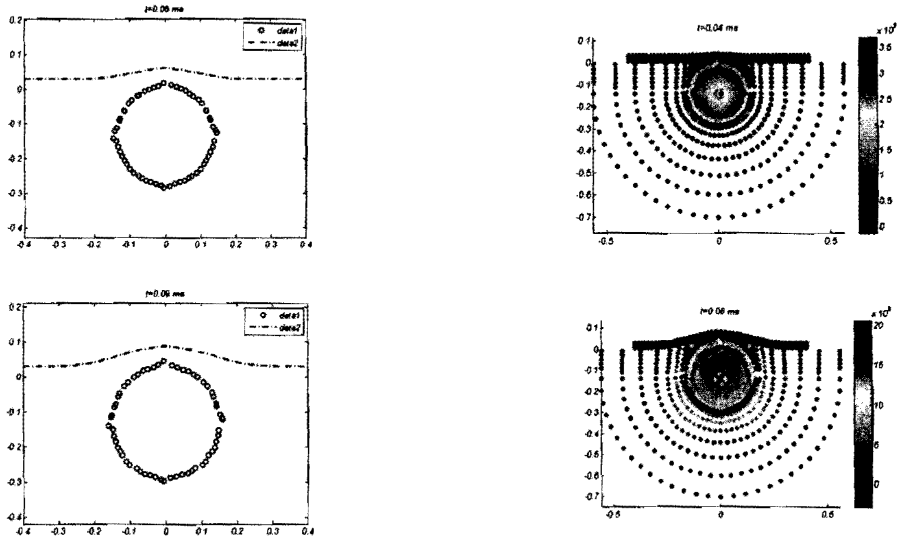

Figure 2 - Free surface changes (Left) and pressure contours (Right) due to expansion of UNDEX bubble.

The obtained results are verified with available data in dimensionless forms from the reference [10]. Comparable results are obtained in the dimensionless time of 0.063, which is approximately equivalent to 0.09 msec (Figure 3). In the right figure, the vertical axis is the dimensionless length which is resulted from division of depth per maximum radius of bubble at the corresponding time. The maximum bubble radius in the left figure is about 14cm and free surface displacement is in the order of 8cm. This is fairly comparable with the dimensionless parameter of 0.6 in curve 4 of the reference right figure.

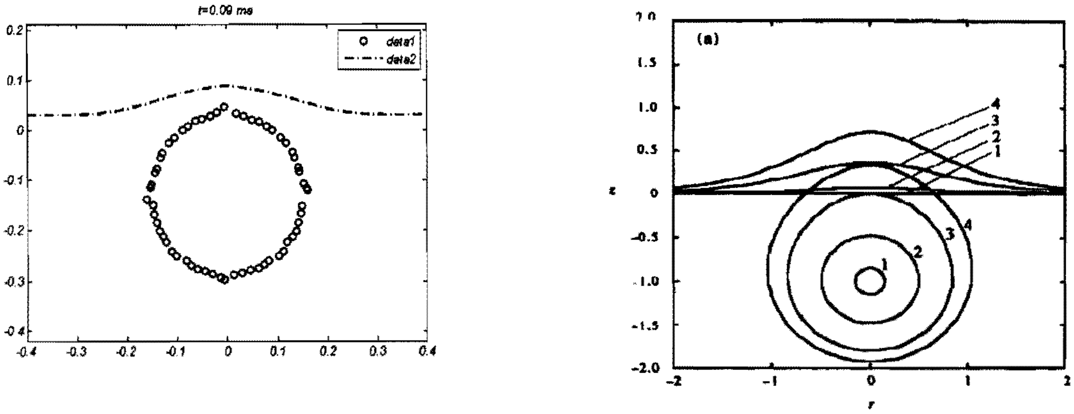

Figure 3 - Comparison between SPH results (left) and reference data (right) [10].

## 5. Conclusion

The proposed SPH simulations, have demonstrated that such a particle-based technique, after proper stabilization, can be used for modeling UNDEX shocks and following interacting problems such as the free surface changes and the moving interfaces considerations.

Though there are some oscillations around the gas-water interface due to nature of SPH numerical approach and probable instability near the boundaries, they do not influence the global shock response. The method will then be used to study the effects of various parameters of the gas-fluid and also the fluid-structure interaction and designing high-performance offshore structures such as jackets, jack up and semi-submersible platforms due to UNDEX effects.

## 5. References

[1] R.H. Cole, Underwater explosions, NJ. USA, Princeton University Press (1948).

[2] J. Henrych, The dynamics of explosion and its use, Elsevier Scientific Publishing Company (1979).

[3] G.R. Liu, M.B. Liu, Smoothed particle hydrodynamics a MeshFree particle method, World Scientific Publishing (2003).

[4] H. Xiong, L. Chen, J. Lin, Smoothed particle hydrodynamics modeling of free surface flow, Conference of Global Chinese Scholars on Hydrodynamics (2006).

[5] M.B. Liu, G.R. Liu, Z. Zong, K.Y. Lam, Computer simulation of high explosive explosion using smoothed particle hydrodynamics methodology, Computers & Fluids Vol.32 (2003).

[6] S.Y. Kadioglu, M. Sussman, Adaptive solution techniques for simulating underwater explosions and implosions, Journal of Computational Physics Vol.227 (2008).

[7] H. Ostad Hossein, Solid and gas interaction using meshfree particle methods, PhD Thesis, University of Tehran (2008).

[8] M.R. Afrasiabi, S. Mohammadi, Analysis of bubble pulsations of underwater explosions by the smoothed particle hydrodynamics method, ECCOMAS International Conference on Particle-Based Methods, Spain (2009).

[9] P. Taheri, Numerical simulation of underwater explosion bubble dynamics, MSc. Thesis, Tarbiat Modarres University (2002).

[10] Q.X. Wang, K.S. Yeo, B.C. Khoo, K.Y. Lam, Nonlinear interaction between gas bubble and free surface, Computers & Fluids Vol. 25, pp. 607-628 (1996).

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# Invitation to the GACM09 Colloquium

Dear Mr. Afrasiabi,

we hereby invite you to give a presentation at the GACM09 Colloquium taking place at the Leibniz Universität Hannover, Germany between September 21 and September 23. Your submitted contribution has been accepted for presentation during that conference.

We cannot, however, pay for any expenses you might have during your stay in Germany.

We hope you will enjoy the conference and have a pleasant stay in Germany.

With best regards

Dr.-Ing. Stefan Löhnert

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