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São Paulo, September 11 th, 2018

TO
Defense Technical Information Center
8725 John J Kingman Road Ste 0944
Fort Belvoir, VA 22060-6218

REF: NICOP - Particle-based numerical offshore tank

Dear,

Please find attached the originals documents corresponding NICOP - Particle-based numerical offshore tank, as it was requested, these are:

- Final Technical Report with SF298.

Best Regards,

Jaqueline Lisa Dias Porto
Administração de Projetos

JL/igd

Final technical report

Particle-based numerical offshore tank

ONRG Grant number: N62909-16-1-2181
Period of Performance: September 10, 2016 to June 08, 2018
Report date: August 24, 2018

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PARTICLE-BASED NUMERICAL OFFSHORE TANK

Final technical report

ONRG Grant number: N62909-16-1-2181
Period of Performance: September 10, 2016 to June 08, 2018

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OBJECTIVES OF PROJECT AND LONG-TERM GOALS

The meshless particle-based computational fluid dynamics (CFD) methods are very flexible techniques that opened a new perspective for the investigation of highly complex and challenging hydrodynamic phenomena due their ability to easily deal with problems involving very large free surface deformations, fragmentation and merging, complex geometry bodies, multibody, multiphase flows and multi-physics. Nevertheless, these methods still present two major shortcomings: it is a compute-intensive technique and spurious numerical oscillations are observed in the computed pressure. Focusing on these two topics, the long-term goal of this work is to develop the next generation numerical offshore tank using particle-based numerical method for the simulation of complex hydrodynamic phenomena in naval, ocean and coastal engineering fields.

In order to investigate the theoretical and numerical basis of the two aforementioned bottlenecks of particle-based CFD methods, the specific research objectives were:

1) ***Proposal and evaluation of a new approach for mitigation of the spurious pressure oscillation.*** In the present research, new source terms for the pressure Poisson equation (PPE) are derived from the view point of the momentum conservation of particle-level collisions, and their performance were analyzed with respect to several aspects of the numerical computations.
2) ***Investigation on the feasibility of more efficient computer resources strategies.*** Since the processing time of a particle-based simulation is proportional to the number of particles of the numerical model, a multiresolution technique for particle-based methods is investigated in the present study. It aims to improve the computing efficiency and keep the result accuracy by increasing the resolution of critical regions of the model and adopting coarse resolution for the far field.

SUMMARY OF ACOMPLISHMENTS

In the present study, by considering momentum conservation for the time discontinuous collision/impact in particles level, new source terms were derived and proposed for stable assessment of pressure through pressure Poisson equation (PPE) computation in fully Lagrangian meshless particle-based methods.

- By introducing a correction factor for the mismatch between the numerical and physical times for the computation impulsive loads, the proposed source terms drastically suppressed the unphysical pressure oscillations.
- In addition to this, it is consistent in time domain because the computed pressure peaks do not increase with the decreases of the time step.
- From the practical point of view, instead of a pressure relaxation coefficient that requires empirical calibration and adjustment, the only numerical parameter required in the proposed source terms is the propagation speed of the perturbations, and its calibration is much more straightforward due to its physical meaning.
- Also, in comparison to the recent strategies to mitigate the spurious pressure oscillations based on higher order numerical operators, the proposed approach has much simpler implementation and is more computationally efficient.
- The proposed source terms were applied only for the MPS method in this study. However, they can be extended to other particle methods such as the Incompressible Smoothed Particle Hydrodynamics (ISPH) method.

Regarding the investigation of multiresolution technique for the MPS method, a new approach based on "border mapping" technique, which is divided into a simplification routine and a refinement routine for the treatment of the border between subdomains with different resolutions, was proposed:

- The verification of the *pnd* of the border particles indicated that the equivalent particle distributions obtained by the simplification and the refinement algorithms are satisfactory and the multiresolution formulation that leads to an asymmetric linear system is effective to reproduce the local results of the high single resolution models.
- Despite the overheads of the multiresolution processing and lower efficiency of the solver for asymmetrical linear system, multiresolution model with less particles leads to superior performance. The speed up is more evident for large models and the feasibility and the advantage of the proposed technique can be confirmed.
- Nevertheless, some challenges regarding the stability of the computation remain because the topology among the fluid particles may change dynamically and provokes sudden changes in the set of reference particles used for the determination of the fictitious particles. In addition to this, further investigation on multilevel multiresolution and extension to 3D modeling, as well as the optimization of the procedures, is required to achieve the long-term goals.

OPPORTUNITIES FOR TRAINING AND DEVELOPMENT

Nothing to report

DISSEMINATION

Nothing to report

PLANS (FUTURE WORKS)

As continuity of the present research to achieve the long term goals, further study on the following topics can be listed:

- High order formulation and the proposed approach for less dissipative and more accurate numerical modeling of wave structure interactions.
- Extension of the proposed time-scale correction of the particle-level impulse to the modeling of fluid solid interaction with multibody.
- More stable solution that accounts for dynamic change of the topology among the fluid particles.
- Multilevel multiresolution modeling, as well as 3D modeling and the optimization of the procedures.

HONORS

Nothing to report

TECHNOLOGICAL TRANSFER

Nothing to report

PARTICIPANTS

Name	Role	Discipline	Person month	Country
Cheng Liang Yee	PI		0.05	Brazil
Márcio Michiharu Tsukamoto	Post-doctoral	Naval and Ocean Eng.	1.00	Brazil
Cezar Augusto Bellezi	Graduate student (Doctorate)	Naval and Ocean Eng.	0.50	Brazil
Rubens Augusto Amaro Junior	Graduate student (Doctorate)	Civil Eng.	0.50	Brazil
Gabriel Henrique de Souza Ribeiro	Graduate student (Master)	Naval and Ocean Eng.	0.25	Brazil

STUDENTS

Number Science, Technology, Engineering and Mathematics (STEM) participants	0
Number of participants that received STEM degree	4

PUBLICATIONS ARISING FROM THIS RESEARCH SUPPORT

1. Publication

- *Improving the stability of the particle-based hydrodynamic pressure assessment by time-scale correction of particle-level impulses.* International Journal for Numerical Methods in Fluids. Liang-Yee Cheng; Rubens Augusto Amaro Junior; Eric Henrique Favero. (paper being submitted to peer-reviewed journals).

2. Conference paper

- *Wave impact loads by MPS method with an improved pressure source term.* Liang-Yee Cheng; Rubens Augusto Amaro Junior; Cezar Augusto Bellezi. The Japan Society of Naval Architects and Ocean Engineers (JASNAOE) 2018 Annual Autumn Meeting, Kashiwa, Japan (paper submitted to Conference Proceeding).

PH.D. AND MS DISSERTATIONS ARISING FROM THIS RESEARCH SUPPORT

1. *Numerical towing tank modeling by particle method: MPS-BEM coupling and multiresolution MPS.* Ph. D. University of São Paulo. Cezar Augusto Bellezi. Thesis to be defended in 2019.
2. *Numerical analysis of fluid-solid interaction in free surface flows.* Ph. D. University of São Paulo. Rubens Augusto Amaro Junior. Thesis to be defended in 2020.

PARTICLE-BASED NUMERICAL OFFSHORE TANK

Final technical report

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SCIENTIFIC ACCOMPLISHEMENTS

1. NEW SOURCE TERM FOR PRESSURE POISSON EQUATION

Moving Particle Semi-implicit (MPS) method [1] and Incompressible Smoothed Particle Hydrodynamics (ISPH) method [2] are particle-based computational fluid dynamic methods that solve a PPE. Despite being compute-intensive methods, they are very effective for highly nonlinear interactions between water waves and marine structures. The approaches to achieve more stable computation, which is one of the shortcomings of the methods, are:

a) Enhance regular particle distributions [3], which has computational cost of resetting the particle positions;
b) High-order and/or modified differential operators [4][5], generally based on more complex formulations subject to increased computational costs;
c) New formulations for the source term of PPE, by combining incompressibility conditions [6][7] or introducing higher order source terms [8].

Although promising, the spurious oscillations obtained by existing solutions tend to increase with the decrease of time step, with the stability range sensitive to time domain discretization. The present work introduces a new formulation for the PPE based on a correction factor between numerical and physical time scale, which is derived from the momentum conservation regarding collisions in particle-level. In the proposed PPE, the computed pressure is stable and almost independent of time step. Moreover, no additional computational effort is required. For the purpose of the investigation, MPS method is considered.

The MPS method solves the governing equations of the incompressible flow by replacing the differential operators by discrete differential operators derived based on a weight function (ω_{ij}) that accounts the contributions of the particles in a neighboring region. The method predicts the particle velocity and position explicitly based on momentum conservation. Then the pressure (P) of all particles is determined by solving a linear system of PPE considering the particle number density (*pnd*) criterion as follows:

$$\langle \nabla^2 P \rangle_i^{t+\Delta t} = \gamma \frac{\rho}{\Delta t^2} \left(\frac{n_0 - n_i^*}{n_0} \right), \tag{1}$$

where n_0 is the initial *pnd*, n_i^* is the *pnd* of the particle distribution after the explicit calculations, ρ is the fluid density, Δt is the time step and γ is a relaxation coefficient to reduce spurious pressure oscillations. The particle number density is proportional to the fluid density, and is obtained as the summation of the weight of all neighbor particles. After solving the PPE, the fluid particle velocity and position are updated based on the pressure gradient.

Time scale correction

Numerically, the duration of time discontinuous phenomena such as collisions or impacts is about the simulation time step Δt because, the change of the status prior and after the event is only detected and processed in the instant when the change occurs. Nevertheless, considering collisions or impacts that occur in successive particles or grids with minimal spatial resolution l_0, the intervals between successive collisions are about the physical time interval $\delta t = l_o / c_s$, where c_s is propagation velocity. In explicit numerical scheme, due to the CFL stability condition, it is clear that $\Delta t < \delta t$. This means that the successive collisions or impacts that physically must last δt are numerically shortened to Δt.

As the momentum conservation is assured by the governing equations, the impulse $\mathbf{I}$ of a collision or impact computed numerically or recorded physically should be the same. So, the integration of the computed loads ($\mathbf{F}_n$) in the interval $[t,\ t + \Delta t]$ must be equivalent to the integration of the physical collision loads ($\mathbf{F}_p$) in $[t,\ t + \delta t]$. As result, the ratio between the numerical and the physical collision loads ($\mathbf{F}_n / \mathbf{F}_p$) yields the relation $\Delta t = C_r \delta t$. Therefore, the imposition of the stability criterion leads to much higher numerical pulses than the physical ones, with the magnitude amplification coefficient of $1/C_r$. In the other words, as the duration of the numerical pulses is much shorter than the physical ones, each of these discrete impacts shows a much larger magnitude of the impulsive loads, as previously observed by Cheng et al. [9] and illustrated in Fig. 1.

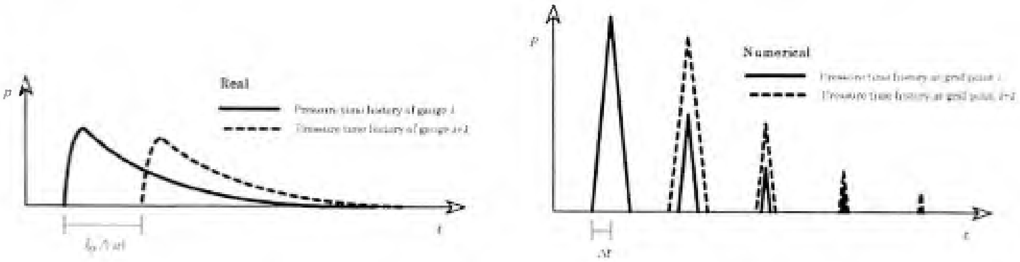


Figure 1 - Physical and numerical impact pressure [9].

Besides the dilemma of the numerical stability criterion that results in the unstable computation of the time discontinuous phenomena, the solution is inconsistent in time domain, with peak values very sensitive to Δt, because the numerical collision loads $\mathbf{F}_n \to \infty$ when the numerical time step $\Delta t \to 0$.

In the present work, the solution proposed to mitigate these issues of numerical modeling is the application of Courant number $C_r = (c_s \Delta t)/\delta t$ as a correction factor for the mismatch between the numerical and physical times and compute the impulsive loads correctly. Instead of using the numerical time step Δt in the source term (Eq. (1)), the physical time step $\delta t = c_s / l_0$ is preferred to adjust both the magnitude and duration of the impulses, which is the same as imposing $\gamma = C_r^2 = (c_s \Delta t / l_o)^2$, so that:

$$\langle \nabla^2 P \rangle_i^{t+\Delta t} = c_s^2 \frac{\rho}{l_o^2} \left(\frac{n_0 - n_i^*}{n_0} \right). \tag{2}$$

Another incompressible condition considered in the source term is that the divergence of the velocity field should be zero, as proposed by Tanaka e Matsunaga [7]:

$$\langle \nabla^2 P \rangle_i^{t+\Delta t} = \gamma \frac{\rho}{\Delta t^2} \left(\frac{n_0 - n_i^t}{n_0} \right) + \frac{\rho}{\Delta t} \nabla \cdot \mathbf{u}^* . \tag{3}$$

The introduction of the relaxation coefficient $\gamma = C_r^2$ and by using the physical time δt, a new source term considering the divergence of the velocity is obtained:

$$\langle \nabla^2 P \rangle_i^{t+\Delta t} = c_s^2 \frac{\rho}{l_o^2} \left(\frac{n_0 - n_i^t}{n_0} \right) + c_s \frac{\rho}{l_o} \nabla \cdot \mathbf{u}^* . \tag{4}$$

The classifications of the original and the improved source terms are summarized in Tab. 1.

Table 1: Description of the original and proposed source terms applied in this study.

Source term	**Abbreviation**
Original PND deviation Eq. (1)	O-PND
Proposed PND deviation Eq. (2)	P-PND
Original PND deviation and divergence-free condition Eq. (3)	O-PND-DF
Proposed PND deviation and divergence-free condition Eq. (4)	P-PND-DF

Performance of the new source terms

In order to evaluate the performance of the proposed source terms, hydrostatic and hydrodynamic cases were considered. As an example, hydrodynamic loads due dam breaking problem with a 60 x 30 cm water column hitting an opposite wall at 161 cm are shown here. The fluid properties are density of $\rho = 997\ kg/m^3$, and kinematic viscosity of $\nu = 0.89\ x\ 10^{-6} m^2/s$. The dimensionless time (τ) is defined as $\tau = t\sqrt{g/H}$.

Figure 2 provides the time histories of the pressure coefficient (C_p) computed by original and proposed source terms and measured at the bottom corner of the opposite sidewall. According to Fig. 2, the decrease of the time step or the ratio $\Delta t / l_o$ increases the amplitude of pressure oscillations computed by using the original source terms, while much more stable pressure, almost independent to the numerical parameters, were computed by using the proposed ones.

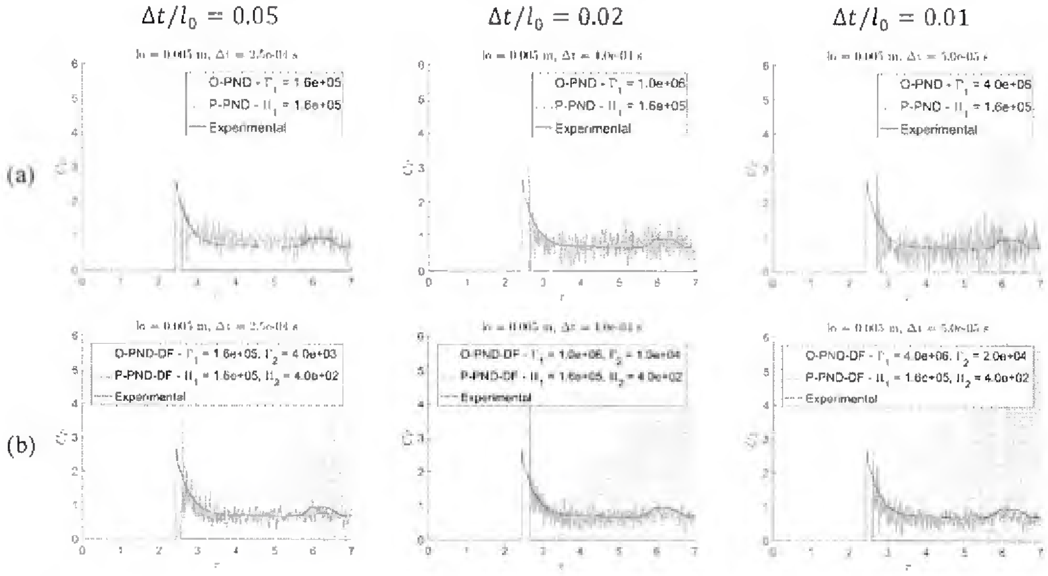


Figure 2 - Pressure at bottom corner of the opposite side wall. Distance between particles of *lo=0.005 m*. (a) Source terms O-PND and P-PND, (b) source terms O-PND-DF and P-PND-DF.

Figure 3 shows the comparison of the computed pressure fields of the collapsing water column. The improvement achieved by adopting P-PND-DF, with smooth pressure field against the unphysically oscillating pressure fields obtained using O-PND-DF, is evidenced.

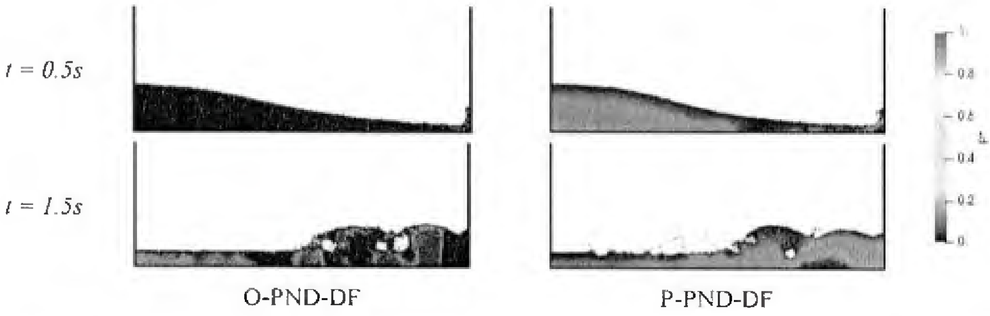
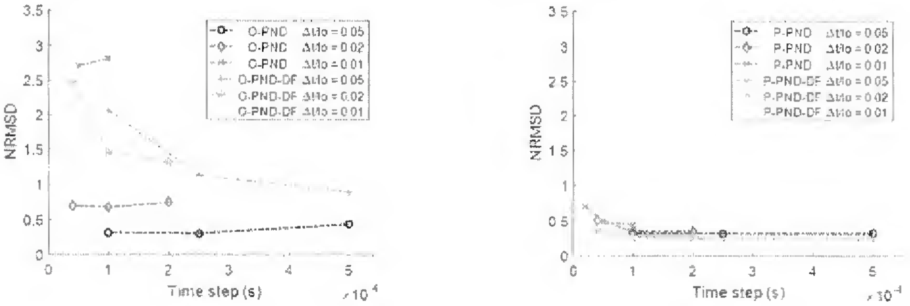


Figure 3 - Dam breaking. Source terms with the zero variation of the particle number density and velocity-divergence-free condition (O-PND-DF and P-PND-DF). Free surface profile and pressure fields at 0.5s and 1.5s (non-dimensional times 2.86, and 8.58).

The pressure oscillation and the error in relation to the experimental pressure were quantified by the square root of the differences between numerical and experimental values (normalized root mean square deviation - NRMSD) between the instants $\tau_1 = 3.0$ and $\tau_2 = 5.0$, and the results are shown in Fig. 4. Figure 4-a shows that the original source terms are highly influenced by the time step, and the oscillation increases remarkably as Δt decreases. In contrast, Fig. 4-b illustrates the very lower dependence of the proposed source terms in relation to the time step and the particle distance and with a much lower NRMSD, which shows the remarkable improvements on the stability of the computations. Besides, while the pressure oscillations computed by original source terms are highly sensible to $\Delta t/l_o$ and the coefficients of the particle number density criterion ($\gamma/\Delta t^2$) and divergence of velocity ($1/\Delta t$), the pressures computed using proposed ones are almost independent to $\Delta t/l_o$ or the numerical parameters, which shows its consistence and the possibility of straightforward calibration provided by using the propagation speed c_s.

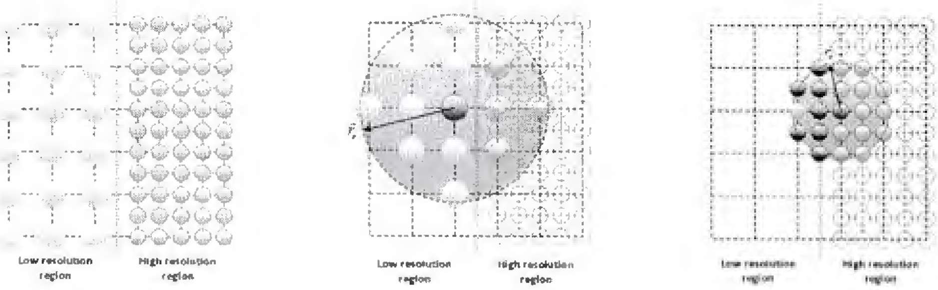


(a) (b)

Figure 4 - Dam breaking. Normalized root mean square deviation (NRMSD) of pressure. (a) Original O-PND and O-PND-DF, (b) proposed P-PND and P-PND-DF source terms.

2. MULTIRESOLUTION MPS METHOD

A new technique is proposed in the present study based on a "border mapping" technique.



Border Simplification Refinement

Figure 5 – Conceptual scheme of the proposed "border mapping" multiresolution technique.

The proposed technique is based on the concept of obtaining an equivalent particle distribution in each side of the border that delimits the sub-domains with different resolutions (Figure 5-a). With the equivalent particle distribution, a neighborhood initially containing particles with different sizes is replaced by a neighborhood with unique particle size, but with the same physical properties. As consequence, the original formulation of the MPS method could be applied. For a low-resolution particle close to the interface (Figure 5-b), the process to obtain an equivalent low-resolution particle distribution from the existing high-resolution particles on the other side of the border is called "simplification". For a high-resolution particle close to the border (Figure 5-c), an equivalent high-resolution particle distribution must be obtained from the existing low-resolution particle distribution on the other side of the border by a process called "refinement". As the particles move between sub-domains with different resolutions, the update of the particles on the border is carried out considering the particle distribution obtained by the "border mapping" process. For sake of simplicity, the ratio of the distances between particles in low and high-resolution domains was set to 2:1.

Table 2 enumerates several desirable features for a practical and consistent formulation of a multiresolution MPS method. The advantages and disadvantages of the techniques available in the literature are summarized and compared to the technique proposed herein.

Table 2 – Main features of the multi-resolution techniques for the MPS method

	Tanaka et al. [10]		**Shibata et al. [11]**	**Chen et al.**	**Proposed**
	Method 1	Method 2	**Tang et al.** [12]	[13]	**method**
Strong two-way coupling	yes	yes	no	yes	yes
Clearly defined subdomains	no	yes	yes	yes	yes
No mixing	no	yes	yes	yes	yes
Uniform resolutions	no	no	yes	change	yes
Intermediate sized particles	change	no	no	change	no
Correlated resolutions	yes	change	yes	change	yes
Newton's 3rd Law	yes	yes	yes	yes	yes
Uniform Kernel support	no	no	yes	yes	yes
Ease of implementation	interm.	complex	intermediate	complex	interm./complex
Original particle method	no	no	yes	no	yes

The formulation of the multiresolution technique was divided into three main challenges:

a) The simplification algorithm,
b) The refinement algorithm and
c) The calculation of pressure in the truncated border.

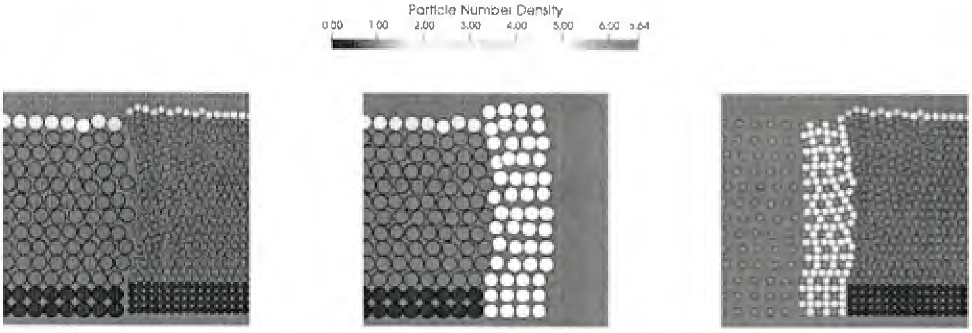
In its turn, the investigations of the above three tasks comprise three main stages:

1) The conceptual and mathematical formulation,
2) Standalone tests and verification of the proposed algorithms considering typical particle distributions at a given time step,
3) Integrated tests in the system with time domain simulations.

Border mapping: Simplification and Refinement

In the simplification, the high-resolution particles are classified into two types: the "simplified particles" and the "not simplified particles". The particle distribution of the simplified particles is considered for the calculation of the pressure of the low-resolution particles close to the border because it closely resembles a low-resolution particle grid.

The refinement of the low-resolution particles distribution adjacent to the border starts by performing the triangulation of the low-resolution particle grid close to the border, using them as "reference particles". Then, the equivalent high-resolution particle distribution is obtained by placing "fictitious particles" in the center of the edges of each triangle.



(a) (b) (c)

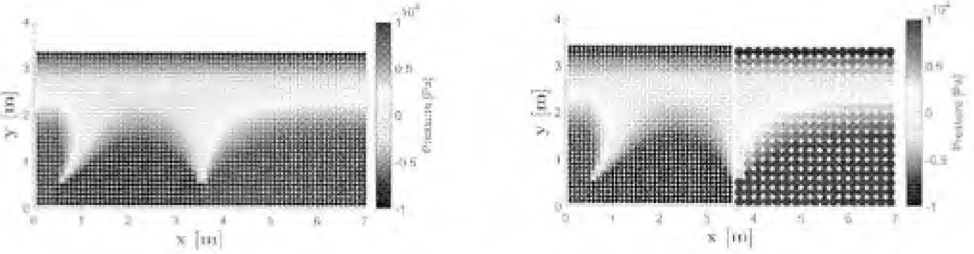
Figure 6 – Border mapping: arbitrary arrangement with (b) simplified particles and (c) refined fictitious particles in white color.

Figure 6 shows the region between two subdomains with different resolutions. The color scale indicates the particle number density (*pnd*) parameter. For this case, a consistent particle distribution should present a *pnd* around 6.5 for the fully submerged fluid particles. In Fig. 6-b, the simplified particles are colored white and the *pnd* value calculated for the low-resolution particles close to the border agree with the expected value. In Fig. 6-c, the fictitious particles are white ones while the low-resolution particles are in pink. The *pnd* of the high-resolution particles close to the border in Fig. 6-c agrees with the expected value as well. The *pnd* values for the irregular particle grid confirmed the capability of the simplification and the refinement routines in providing equivalent particle distributions outside the border.

Pressure calculation

In the proposed multiresolution technique, the solution of the PPE was reformulated to consider different particle sizes in the vicinity of the border between two domains of different resolutions. For particles of the high-resolution domain but located close to the border, their neighborhood region may contain particles of low-resolution domain and fictitious particles that emulate the particle distribution of the high-resolution domain. As the fictitious particles do not actually exist, their pressures are calculated from the respective neighbor particles in the PPE linear system Particles of low-resolution domain near the border may have particles of the high-resolution domain in their neighborhood region and to maintain low-resolution particle distribution, only simplified particles are taking into account in the linear system. This leads to a bandwidth but asymmetrical matrix for the solution of the linear system.

Figs. 7 shows test results using a boundary value problem with a domain of 6.0 m by 2.0 m. Figs. 7-a and Figs. 7-b show, respectively, the pressure field calculated by the original MPS formulation using a single high-resolution model and other calculated by the proposed technique using half and half high and low-resolution model. The excellent agreement in the high-resolution domain shows the effectiveness of the proposed technique in reproducing accurately, with lower number of particles, high-resolution results of the original method.



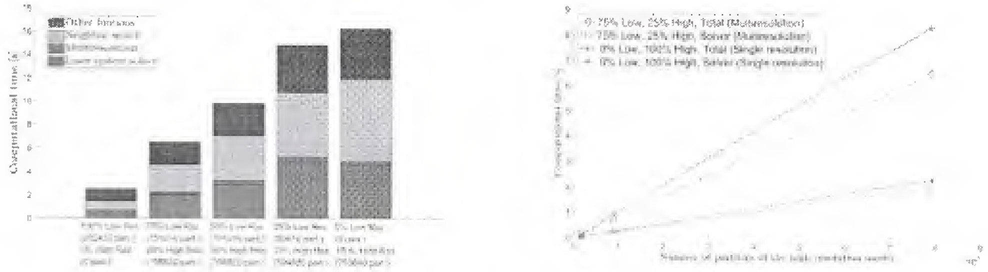
(a)

(b)

Figure 7 – Pressure field of the boundary value problem with suction on the bottom left side using (a) the original MPS with high-resolution particles and (b) the proposed multiresolution technique.

Multiresolution technique performance

Figure 8-a shows examples of time domain computation performance test results of the proposed multiresolution techniques integrated to the main MPS program. A tank with 120.0 m-length and 10.0 m-height and filled up to 8.0 m was initially used to run these tests. The first 20 time steps were considered to obtain the averaged processing times.



(a)

(b)

Figure 8 – (a) Processing time of models with low and high resolution and 3 setups of multiresolution and (b) computational time consumed to simulate one step for models with different sizes.

Figure 8-a shows the computational time of the models equivalent to 793640 high-resolution particles in the entire domain. The results were obtained with only one processing core and Generalized Minimal Residual Method (GMRES) as the asymmetrical linear system solver. The total processing time increases almost linearly as the proportion of the high-resolution domain increases, and significant speed up can be achieved by confining the high-resolution domain locally, in a small area of interest.

The comparisons of processing times between the high-resolution model solved using original single resolution MPS method (Conjugate Gradient method for solving linear system) and the proposed multiresolution technique applied to a model with 75% of domain with low-resolution particles are shown in Figure 8-b. Despite the overheads of multiresolution processing and less efficient asymmetrical linear system solver, the multiresolution model with less particles leads to superior performance.

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6. AUTHOR(S) Cheng Yee	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

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This study is focused on two critical issues of the flexible but compute-intensive particle-based CFD methods. Based on the particle-level momentum conservation, new source terms were derived for pressure Poisson equation. Besides the suppression of spurious pressure oscillations, the proposed approach is computationally efficient, consistent in time domain, has easily calibratable numerical parameter and simple implementation. Also, a new multiresolution technique based on "border mapping" was proposed to reduce the computational cost. Despite the overheads due to multiresolution processing and asymmetrical linear system, its feasibility and speed up capability were confirmed.

15. SUBJECT TERMS

Particle-based method, computational fluid dynamics, hydrodynamic loads, Multi-resolution technique

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