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Organised by
Inst. Fluid Dynamics and Ship Theory
Hamburg University of Technology

Edited by
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Sponsored by
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Foreword to the 6th Int. SPHERIC Workshop

Dear Delegate,

The Institute for Fluid Dynamics and Ship Theory of the Hamburg University of Technology (TUHH) is honoured and pleased to organise the 6th international SPHERIC workshop. It is a great pleasure for us to welcome you to the exciting and cosmopolitan city of Hamburg and we look forward to sharing a successful and enjoyable meeting with you.

The SPHERIC workshop has taken a root as the primary annual event on Smoothed-Particle Hydrodynamics (SPH). It is organised under the aegis of the SPH EUROPEAN RESEARCH INTEREST COMMUNITY (SPHERIC) which forms part of the widely recognised ERCOFTAC network. The successful concept of SPHERIC is due to the strong methodological focus in an interdisciplinary application environment, integrating the know-how of physicists, mathematicians, IT experts and engineers from academia and industry.

The SPHERIC community plays an important role in the advancement and dissemination of SPH, an exciting scientific-computing method which has considerably matured over the past five years. The range of SPH applications is continuously growing and involves tsunami and landslide simulations, cosmic-structure formation and galaxy collisions, tank sloshing, pedestrian-crowd simulation, virtual-reality simulations, wave-energy generation, slamming loads on offshore structures, flooding of ships sections, decay of tip vortices behind an aircraft and lung-respiration simulations amongst others. Due to the large computational effort, a significant branch of SPH research is concerned with high-performance computing on the most recent hardware technologies.

Similar to previous years, a record number of abstracts was submitted (eighty-three in 2011) which clearly indicates the sustained increase in interest in the workshop. Dedicated to the aim of stimulating an enhanced direct exchange of ideas, we decided to continue with the workshop ethos of the event and the Scientific Committee had to confine the selection of presentations in order to allow everyone to view all presentations. In line with the constant growth of the workshop, the organisation becomes more demanding. This event would not be possible without the generous financial support provided by Deutsche Forschungsgemeinschaft (DFG) which is greatly acknowledged.

We are confident that the workshop series continues in its friendly and creative spirit and that you will leave Hamburg with new ideas and inspirations.

Thomas Rung, Christian Ulrich
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Non-Reflecting Boundary Conditions and Multi-Resolution SPH

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Abstract— For many problems in computational continuum mechanics an accurate treatment of non-reflecting boundaries that allows incoming waves to propagate out of a finite domain is important. One application is mesh-refinement; high frequency components of a solution on a fine mesh cannot be transmitted into a more coarsely meshed region and will reflect back in a non-physical manner. A robust non-reflecting boundary condition (NRBC) can therefore allow high spatial resolution to be used only where necessary without the need for a graduated transition region.

We propose a simple non-reflecting boundary formulation for SPH, efficacy is investigated in 2d and the NRBC will be applied to a multi-resolution simulation in 1d.

I. INTRODUCTION

There are two distinct approaches explored by researchers thus far for increasing spatial resolution in SPH. The particle splitting approach; where the particle distribution is refined adaptively by splitting particles into a set of child particles when some criterion is met. Or starting with an initial multi-resolution discretisation; where different particle density is used in zones where it is known a priori to be needed.

An adaptive SPH algorithm has to address the following issues:

- When to re-mesh; the adaptivity criterion or error estimate.
- How to re-discretise the zone where the adaptivity criterion is satisfied; the new particle distribution.
- How to interpolate field variables onto the new particles.

Dealing with each item in turn: [1] add particles in regions with high velocity gradients, removing them when the gradient is low. Eschewing calculation, in [2] fluid particles are split whenever they enter a refinement zone. In the examples given in the paper the particles are refined just before they leave a variety of tanks. For astrophysical simulations [3], using a variable smoothing length, refine a particle whenever its smoothing length exceeds twice the average smoothing length and [4] adapt based on the Jeans condition. The last two methods are rather specific to astrophysics.

The reproducing kernel particle method [5] is a mesh-free method closely related to SPH. To identify sub-domains in need of refinement the authors use the properties of the kernel function as a filter to find regions dominated by high-frequencies and therefore it high-gradients.

Increasing resolution is most often done by splitting a particle into a number of smaller child particles. As long as the parent particle’s mass is distributed evenly between the children conservation of mass is guaranteed. The spatial distribution of the child particles affects the density distribution and the splitting procedure can introduce extra errors in this way. Generally a particle is split by having one particle in the same position as the parent and placing the others evenly around it. Assuming the particle is split into equally sized child particles and that the are placed symmetrically around the original particle’s position, it is only left to decide on the new particles’ smoothing lengths and separation, \( l \), from the centre particle. Kitsionas et al. [4] split the particle into 13 child particles and decide that the new smoothing length will be \( h_{new} = 13^{-1/3} h_{old} \). After some experimental analysis the authors settle for a \( l = 1.5 h_{ref} \) as the particle separation. In a similar way [2] define a density error function depending on two parameters, the new smoothing length and the separation, the minimisation of this function is used to find approximately optimal pairs of values. Alternatively [1] simply insert an extra particle where needed. The difficulty with this approach is that the new particle’s position and the masses and smoothing lengths of its neighbours are calculated to approximate the original density distribution instead of being pre-determined by a splitting algorithm. This procedure is more complex and mass conservation is no longer automatic. The benefit is that it avoids the difficulties associated with abrupt steps in the smoothing lengths that may arise when simply splitting particles.

The final step is interpolating the field variables on to the refined particle distribution. The interpolation procedures vary from a simple weighted average; in [6] the child particle’s velocities are given by,

\[
\mathbf{v}_c = \sum_{k \in I_\epsilon} v_k W_h \left(h \right) \Delta \mathbf{v}_k
\]
where the sum includes the old coarser parent particle. Other authors have used higher order interpolation; 1st order consistent kernel interpolation [1] or 2nd order (quadratic) weighted least squares [7]. It can be shown [2] that after splitting a particle the only way to conserve momentum and kinetic energy is to assign all of the child particles the velocity of the parent. Unfortunately the new velocity field, that is after refinement, may not approximate the pre-refinement field particularly closely. However the proof does not admit the possibility of modifying the velocities (and perhaps positions) of other, neighbouring, particles and therefore other interpolation methods could be designed to be conservative.

Splitting particles to increase resolution as discussed above can introduce new difficulties and in situations where it is known a priori that extra resolution is desired, for example near an impact, it is perhaps simpler to start with a discretisation with variable resolution. Abrupt changes in smoothing length can cause spurious reflection and oscillation, few papers address this explicitly. Børve et al. [7] mitigate this problem by having particles only interact with other particles with the same smoothing length. Particles are added to the boundaries of the fine scale and coarse scale domains at their interface creating an overlapping interface domain. Field variables are interpolated at these extra, auxiliary, particles using information from the surrounding particles of both types. Finally the linear momentum is corrected to ensure conservation. This method is presented as an enhancement to regularised SPH (RSPH) where the particle distribution is re-meshed at regular intervals. As such it is not necessarily meant regular meshed at regular intervals. As such it is not necessarily meant regular meshing keeping shock fronts within the high-resolution region.

The Bridging Scale Method (BSM) [8; 9] and the Bridging Domain Method (BDM) [10] have been used to couple the molecular dynamics (MD) and finite elements (FE). Both use what is effectively a non-reflecting boundary to absorb unresolvable high frequencies from the MD region as information leaves. The BSM uses a spatially and temporally non-local method involving a integral transforms and the BDM uses a transition layer where one solution is gradually blended into the other – effectively a damping layer.

In this work a method is proposed that uses a very simple, local NRBC. Such a simple approach is most likely to be less accurate but excepting the need to identify the boundary particles this method imposes little extra computational cost.

II. NON-REFLECTING BOUNDARY CONDITION

A. Method

There are different approaches to producing a NRBC see [11] for an example of a dissipative volume where incoming water-waves a damped gradually as they enter specified boundary region. Lastwika et al [12] present a method for fluid flow down a channel. Particle are removed from an outflow zone and inserted into an inflow zone continuously so that the flow is effectively infinite. Additionally a non-reflecting boundary condition based on the method of characteristics is used to prevent spurious reflection. Here we are interested in the correct transmission of elastic waves through a non-reflecting boundary. Exact solutions [13] are in general only available for specific geometries e.g. straight and circular boundaries. Additionally they are non-local in space and time requiring the integral transforms and additional storage of field variables from previous time steps. In contrast there are local methods which, whilst not as accurate, are more generally applicable. Given the Lagrangian nature of SPH exact boundary conditions may be impractical and therefore we use a local, approximate, condition. Enquist and Majda [14] (see also [15]) derive the boundary condition,

\[
\frac{\partial u}{\partial t} = c_i \frac{\partial u}{\partial x_i},
\]

for elastic waves in 2 dimensions incident to the boundary \( x_i = 0 \). To apply (1) to SPH first we re-write for a general straight boundary

\[
\frac{\partial u}{\partial t} = c_i \left( \nabla u \cdot n \right) n,
\]

Then we differentiate (2) with respect to time, assuming that the boundary normal varies slowly in time and therefore \( n \approx 0 \),

\[
\frac{\partial v}{\partial t} = c_i \left( \nabla v \cdot n \right) n,
\]

finally substitute \( \frac{\partial v}{\partial t} = \frac{\partial v}{\partial t} \) into the total acceleration \( \frac{Dv}{Dt} \).

The boundary condition is applied independently for each particle; for particle \( i \) with boundary normal \( n \) the acceleration is

\[
a_i = c_i \left( n \cdot \nabla v \cdot n \right) n + c_i \left( t \cdot \nabla v \cdot n \right) t + v \cdot \nabla v.
\]

To identify boundary particles we calculate

\[
\mathbf{e}_i = \langle 1 \rangle = \sum \frac{m_i}{\rho_v} \nabla W(x_i, x_2, h),
\]
the error in the gradient of a constant function. If \( \left\| e_i \right\| > \varepsilon \) then particle \( i \) is designated as a boundary particle. We have found that setting \( \varepsilon = 0.75 \times \max_i \left\| e_i \right\| \) identifies boundary particles correctly in all examples considered here. To approximate the boundary normals we use

\[
n_i = -\frac{1}{\left\| e_i \right\|} e_i.
\]

The velocity gradient \( \nabla \mathbf{v} \) is approximated as in standard SPH;

\[
\langle \nabla \mathbf{v}_i \rangle = \sum_k \frac{m_k}{\rho_k} (\mathbf{v}_k - \mathbf{v}_i) \otimes \nabla W(x_i, x_k, h) \tag{5}
\]

One caution is that non-boundary particles should not ‘see’ the boundary i.e. all non-boundary particles should have a full compliment of neighbours. This can be achieved by designating all neighbours of ‘real’ boundary particles as boundary particles too for the purpose of calculating the acceleration or by choosing the smoothing length such that the minimum inter-particle separation is greater than the smoothing length. It might be expected that the boundary condition (4) would perform poorly due to the error associated with approximating derivatives near the boundary however this is not the case and using a more accurate 1st-order consistent approximation does not give a significant improvement.

B. Results

1) Non-reflecting boundary

The boundary condition (2) is theoretically only perfectly absorbing for an incident wave normal to the boundary. We expect that corners and waves arriving at an angle to the boundary to be reflected. To test the effectiveness of the boundary under these circumstances we use a square (100x100) of particles all with an initial velocity equal in magnitude and towards the centre of the block Fig. 1. As expected, Fig 2, the boundary condition reflects more strongly from the corner.

![Figure 1. Metal Square 2cm x 2cm (100x100 particles), contours of resultant velocity.](image)

![Figure 2. Reflection of shock wave from non-reflecting boundary near flat boundary (top) and the corner (bottom).](image)

Fig 3 compares the kinetic energy of the 1cm x 1cm centre square in the above simulations to the kinetic energy of an identical square with the boundary truncated. The reflected kinetic energy is clearly. With increasing magnitude of the initial velocity we find that the peak of this reflected kinetic energy is a greater percentage of the initial kinetic energy, Fig. 4.
2) Multi-scale SPH

One application of a NRBC is to allow selective use of high-resolution sub-domains. The domain is discretised by two sets of particles, a coarse set of larger more massive particles and a fine set of smaller particles. This fine set is used only where higher resolution is required. The coarser particles only interact with particles of the same size which include, near the interface, slave particles whose velocity is interpolated from the smaller particles using a normalised weighted average of the surrounding fine particles. These slave particles function as a boundary condition for the coarser domain. For the fine region a NRBC is used along the interface to absorb incident waves.

We compare the above method with basic SPH using a 1D bar with a NRBC applied to both ends see Fig 5. We plot the velocity histories of the particles (indicated in Fig 5) either side of the refinement. The smoothing length is four times greater and the particles correspondingly four times further apart on the coarse side. Fig. 6 compares basic SPH and the Multi-Resolution SPH method described above. Less oscillation and spurious reflection is observed.

<table>
<thead>
<tr>
<th>$v_0$ (cm/μs)</th>
<th>Peak percentage of kinetic energy reflected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.004</td>
<td>0.7</td>
</tr>
<tr>
<td>0.02</td>
<td>1</td>
</tr>
<tr>
<td>0.1</td>
<td>1.9</td>
</tr>
<tr>
<td>0.5</td>
<td>3.9</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 3. Effect of domain truncation on total kinetic energy of the 1cm x 1cm centre square. Expanded view inset.

Figure 4. 2) Multi-scale SPH

Figure 5. Bar impact: Red particles (on the left) given initial velocity of 10 m/s and the blue particles (on the right), -10m/s. NRBC applied to both ends.

We compare the above method with basic SPH using a 1D bar with a NRBC applied to both ends see Fig 5. We plot the velocity histories of the particles (indicated in Fig 5) either side of the refinement. The smoothing length is four times greater and the particles correspondingly four times further apart on the coarse side. Fig. 6 compares basic SPH and the Multi-Resolution SPH method described above. Less oscillation and spurious reflection is observed.

III. CONCLUSION

The paper describes ongoing work on development of local non-reflecting boundary algorithm and its application to SPH. Given the minimal computational effort required to apply and the theoretical limitation on the effectiveness - perfectly absorbing only for incident waves normal to a straight boundary - the results are promising. In practice when simulating a semi-infinite domain care should be taken in designing the discretisation and corners should certainly be avoided where possible.

As well as the usual application of NRBCs to domain truncation we apply the boundary condition to a simple 1 dimensional variable resolution impact problem. Here the method allows a shock wave to pass through the refinement boundary with visibly less reflection and oscillation.

IV. REFERENCES


methods", *Computational Mechanics*, vol. 20, no. 4, pp. 295.


