Water Flow Simulation Using Smoothed Particle Hydrodynamics (SPH)

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Michael Harris

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Motivation

• Is rainbird water throw going to wet the vehicle?
• Answer it by smoothed particle hydrodynamics (SPH) modeling

SSS Flow Test 39A, May 2004
VOF Simulations

• 2 simulations using a 2-D structured mesh of rainbird nozzle mounted 12’ above the deck based on OpenFOAM multiphase flow solver.
• Simulation 1 - “corner rainbird” case: Water injection at 112,500 gpm.
• Simulation 2 - “center rainbird” case: Water injection at 55,250 gpm.
• Both simulations were run up to 5 seconds.
55,250 GPM
55,250 GPM
112,500 GPM
112,500 GPM
Recommendation

- 3-D VOF
- Smoothed Particle Hydrodynamics
SPH Formulation

- SPH is a meshfree method with nodal collocation, spatial discretization, and kernel approximation.

- Starting with the conservation equation of mass and momentum:

\[
\frac{D\rho}{Dt} = -\rho \nabla \cdot \vec{v}
\]

\[
\frac{D\vec{v}}{Dt} = -\frac{1}{\rho} \nabla P + \nu \nabla^2 \vec{v} + \vec{g}
\]

written in compact matrix form:

\[
A(f(r)) = \nabla \sigma + \vec{F}, \quad \forall r \in \Omega
\]

\[
B(f(r)) = \vec{f}, \quad \forall r \in \Gamma
\]

- Let \( f^h(r) \) is an approximation of \( f(r) \):

\[
f(r) \approx f^h(r) = \sum_{i=1}^{n} N_i(r)f_i
\]

where \( f_i = f(r_i) \) is nodal value of \( f(r) \) at specified particle \( r_i \).

\( N_i(r) \) is the shape function used to interpolate field \( f(r) \) from \( f_i \).
SPH Formulation

• For any test function $v$ in the domain $\Omega$ and boundary $\Gamma$,

$$\int_\Omega v^T A(f(r)) d\Omega + \int_\Gamma v^T B(f(r)) d\Gamma = 0$$

• Test function $v$ can be constructed by some basis function $\Phi_i$

$$v = \sum_{i=1}^r b_i \Phi_i \quad \text{and} \quad \bar{v} = \sum_{i=1}^r b_i \bar{\Phi}_i$$

leading to the final weighted residual function

$$\int_\Omega \Phi^T A(f^h(r)) d\Omega + \int_\Gamma \bar{\Phi}^T B(f^h(r)) d\Gamma = 0$$
SPH Formulation

• Point collocation discretized the weighted residual function based on Dirac delta function
  \[ \delta(r) = \begin{cases} 
  0, & r \neq 0 \\
  1, & r = 0 
\end{cases} \]

• Dirac delta function has some useful properties:
  \[ \int_{\Omega} \delta(r)dr = 1 \quad \int_{-\infty}^{\infty} \delta(r-r')f(r')dr' = f(r) \]

• For a boundary value problem,
  \[ A(f(r)) = 0, \quad \forall r \in \Omega \]
  \[ B(f(r)) = 0, \quad \forall r \in \Gamma \]

• Use the delta function \( \delta(r_i-r) \) as test function, we can derive a set of collocation eqs:
  \[ A(f^h(r_i)) = 0, \quad i = 1,2,\ldots,r_1 \]
  \[ B(f^h(r_j)) = 0, \quad j = 1,2,\ldots,r_2 \]

where \( r_1 \) and \( r_2 \) are particles in \( \Omega \) and \( \Gamma \), respectively
SPH Formulation

• In a Kernel approximation, the $\delta$ function can be replaced by a smoothing function $w(r-r', h)$, which is an even function and satisfies the following conditions:

$$\int_{\Omega} w(r-r', h) dr' = 1 \quad \lim_{h \to 0} w(r-r', h) = \delta(r-r') \quad w(r-r', h) = 0 \text{ when } |r-r'| > kh$$

where $k$ defines the compact support of the smoothing function, and $f(r)$ can be approximated as

$$f^h(r) = \int_{\Omega} f(r') w(r-r', h) dr'$$

• The integral form can be discretized by particle approximation:

$$f^h(x) = \sum_{i=1}^{n} w_i(r) \Delta V_i f_i = \sum_{i=1}^{n} N_i(r) f_i$$

where $w_i(r) = w(r-r_i)$, and $\Delta V_i$ is the volume of particle $r_i$. 

SPH Formulation

• In SPH, finite volume of particle is related to mass of particle through density
  \[ m_i = \rho_i \Delta V_i \]

• The approximate function can be written as
  \[ f^h(r) = \sum_{i=1}^{n} w_i(r) \Delta V_i f_i = \sum_{i=1}^{n} w_i(r) \frac{m_i}{\rho_i} f_i \]

• The approximate solution of particle \( i \) is
  \[ f^h(r_i) = \sum_{j=1}^{n} w_{ij} \frac{m_j}{\rho_j} f(r_j) \]

where \( w_{ij} = w(r_i - r_j, h) \), thus the density of particle \( i \) becomes:

\[ \rho_i = \sum_{j=1}^{n} w_{ij} m_j \]

• The above equation shows particle density is based on smoothing the surrounding particle masses, therefore the name “smoothed particle”. 
Floating
Multi-GPU SPH

GPUs: 64 x M2090 (BSC)
MPI: Dynamic balancing
Algorithm: Verlet & Wendland
Particles: 1,015 Millions
Steps: 237,342
Runtime: 91.9 hours
Physical time: 12 seconds
Computational Resource

• Current Beast:
  • Dual Quadro 6000, 6 GB, 448 CUDA GPU
  • 256 GB RAM
  • Dual Intel Xeon E5-2690
  • 512 GB SSD, 3 TB SATA (Win7)
  • 256 GB SSD, 2 TB SATA (Debian Linux)

• Upgrade Beast:
  • Tesla K40 (12 GB GDDR5, 2880 CUDA cores) for computations (4.29 Tflops)
  • Quadro K6000 (12 GB GDDR5, 2880 CUDA cores) for graphic rendering (2560x1600)
  • 1 TB SSD Drives
Approach

• Import full ML CAD Model
• Run multiple rainbirds with variable flowrates and timing sequence
• Activate vehicle motion with velocity/acceleration profile extracted from MSFC trajectory analysis
Water Tank & Rainbird
Rainbird
SPH Rainbird
SPH Rainbird

Time: 0.000000 sec
SPH Rainbird

Time: 5.000000 sec

Vel (m/s)
SPH Rainbird

Time: 5.000000 sec

Vel (m/s)

23.1

20

10

1.01e-005
Test case 1

Time: 0.000000
a=15m/s²

Vel Magnitude
13.9
12.5
10
7.5
5
2.5
0.00186
Test case 2

Time: 0.000000
Vpiston=4m/s
Test case 3

Time: 0.000000

\( V_{\text{piston}} = 1 \text{ m/s} \)
SPH Rainbird
Verification

- Traj Plots CSE with bypass (from Nick Moss’ Rainbird Water Throws)
  - North Corner Rainbirds: 28,381 GPM
  - South Rainbirds: 56,762 GPM
Verification

- Traj Plots CSE with bypass (from Nick Moss’ Rainbird Water Throws)
  - North Corner Rainbirds: 6.01m – 7.433m
  - South Rainbirds: 7.0m – 8.7m
Verification

North Corner (28,381GPM)
Time: 2.5 sec

South Rainbird (56,762GPM)
Time: 2.5 sec
Verification

North Corner (28,381 GPM)
Time: 0 sec
Verification

South Rainbird (56,762 GPM)
Time: 0 sec

V (m/s)
Verification

North Corner (28,381GPM)
Time: 2.5 sec

South Rainbird (56,762GPM)
Time: 2.5 sec
Verification

North Corner (28,381 GPM)
Time: 0 sec

V (m/s)
Verification

South Rainbird (56,762 GPM)
Time: 0 sec
Verification

- Flow time = 3.5s
- Total time = 6.5s

Time: 0 sec

- 44,084 GPM
- 51,786 GPM
- 69,982 GPM
- 44,084 GPM
Verification

- Flow time = 3.5s
- Total time = 6.5s
Water volume flow was based on a maximum nominal rainbird flow during T-10 to T+20sec.
Full Simulations

Time: 1.200000 sec

Velocity (m/s)
Full Simulations

Time: 0.00000 sec

Velocity (m/s)

0  2.5  5  7.5  10
Next Iteration

• Correct rainbird flow timing and volume flow rates; make it variable based on Nominal or Abort operation to reduce conservatism.
• Correct vehicle motion; add correct velocity or acceleration profile
• Add geometry complexity to include TSM, ML deck roughness, and exhaust hole features
## Nominal RB Flows and SLS Motion

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### Nominal RB Flows and SLS Motion

#### Nominal RB Flows Based on 3.5-m Water Tank

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<th>SE/SW</th>
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#### Time (sec) | vel (m/s) | NE | NC | NW | SE/SW | NE/NW | NC | SE/SW |
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#### Time (sec) | vel (m/s) | NE | NC | NW | SE/SW | NE/NW | NC | SE/SW |
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#### Time (sec) | vel (m/s) | NE | NC | NW | SE/SW | NE/NW | NC | SE/SW |
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<td>0.5355</td>
<td>0.5355</td>
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</tr>
</tbody>
</table>

#### Time (sec) | vel (m/s) | NE | NC | NW | SE/SW | NE/NW | NC | SE/SW |
<table>
<thead>
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</tr>
</tbody>
</table>
Full Simulations

Time: 1.25 sec
Full Simulations

Time: 1.25 sec
ML Geometry
Correct Flow Ramp-up

South Rainbird
Time: -5 sec

Peak Flow = 56,762 GPM
Correct Flow Ramp-up

South Rainbird
Time: -5 sec

Peak Flow = 56,762 GPM
Double Jet

Spray Patterns


**Type 1, 50,000 GPM**
Nozzle span angle = 100°, Jet fan angle = 80°

(Not Shown)

**Type 2, 40,000 GPM**
Nozzle span angle = 190°, Jet fan angle = 150°

- 1:2.8 scale ratio
- Dissimilar pipe transition
Jet Spray Patterns
No SLS (-5s to 6.6s)

Time: -5 sec

Vel (m/s)
With SLS (-5s to 9s)

Time: -5 sec
Abort Simulation

Simulation window

Individual Rainbird Flows (ABORT)
Abort Simulation

Simulation window

TOTAL POST LIFTOFF FLOW (ABORT)
Region of Interest
Abort Simulation

Time: -5
Abort Simulation

Time: -5
Geometry Issues
Water Depth

Time: 3
Water Depth

Time: 5
Water Depth

Time: 5
Water Depth

Time: 5
Water Depth

Time: 5
• New GPU cards were installed and performing as expected
• Cameras will get minimal impact
• Water puddle is as deep as 0.3m = 12”
• TSM gap could result in shallow water depth
Updates

• Quadro K600 outperformed Tesla K40c
• Fix TSM gap
• Incorporate design of water barrier for HBOI
• Install camera locations
Abort Simulation (fixed TSM)
Abort Simulation (fixed TSM)
No TSM Gap

Time: 5

- Water puddle as deep as 0.4m = 16” near the TSM and on the South side
Fixed TSM

Time: 5
Fixed TSM

Time: 5
Fixed TSM

Time: 5
Fixed TSM
Forward Plan

• Build a multi-GPU cluster and equip the Beast with the best resources
• Recruit doctoral student and post doc through Graduate STEM Fellowship to conduct research in meshfree method
• Collaborate with UCF (A. Kassab), University of Cincinnati (G.R. Liu) and University of Manchester Research Group (A. Crespo)
References


• B.D. Rogers, “Developing smoothed particle hydrodynamics (SPH) on CUDA – work by the SPHysics group,” School of Mechanical, Aerospace and Civil Engineering (MACE), University of Manchester, UK.

Websites

• Free open-source SPHysics code: [http://wiki.manchester.ac.uk/sphysic](http://wiki.manchester.ac.uk/sphysic)

• GPU-SPHysics: a GPU-based SPH model for free-surface flows [http://www.ce.jhu.edu/dalrymple/GPU](http://www.ce.jhu.edu/dalrymple/GPU)

• SPHERIC = SPH European Research Interest Community: [http://wiki.manchester.ac.uk/spheric](http://wiki.manchester.ac.uk/spheric)