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
• 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
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:
  \[
  A(f^h(r_i)) = 0, \quad i = 1, 2, ..., r_1 \\
  B(f^h(r_j)) = 0, \quad j = 1, 2, ..., r_2
  \]

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 $r_i$. 
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

Press

1.82e+004

1e+4

-5.87e+003

0
Pump
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
SPH Rainbird
SPH Rainbird

Time: 0.000000 sec
SPH Rainbird

Time: 5.000000 sec

Vel (m/s)
Test case 1

Time: 0.000000
\[ a = 15 \text{m/s}^2 \]
Test case 2

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

Time: 0.000000
Vpiston=1 m/s

Velocity (m/s)
SPH Rainbird
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 (28,381 GPM)
Time: 2.5 sec

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

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

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

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

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

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

\[ V \text{ (m/s)} \]
Verification

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

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

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

Time: 0.000000 sec

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

V (m/s)

2.5  5  7.5  10  13
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: 0.000000 sec

Velocity (m/s)
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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### Ascent Elevation

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### TPS (time, elev, elev)

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### Nominal RB Flows and SLS Motion

#### Time (sec) vel (m/s)

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#### RB Flows Based on 3.5-m Water Tank
Full Simulations

Time: 1.25 sec

V (m/s)

2.5  5  7.5
Full Simulations

Time: 1.25 sec
Full Simulations

Time: 1.25 sec
ML Geometry
Correct Flow Ramp-up

Peak Flow = 56,762 GPM

South Rainbird
Time: -5 sec
Correct Flow Ramp-up

South Rainbird
Time: -5 sec

Peak Flow = 56,762GPM
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

Nozzle span angle = 190°
Jet fan angle ≈ 120°
66,543 GPM

Nozzle span angle = 180°
Jet fan angle ≈ 80°
56,652 GPM
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

GAP
Water Depth

Time: 3
Water Depth

Time: 5
Water Depth

Time: 5
Water Depth

Time: 5
Water Depth

Time: 5
Summary

• 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)

Time: -5
Abort Simulation (fixed TSM)

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
Fixed TSM

Time: 5
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)