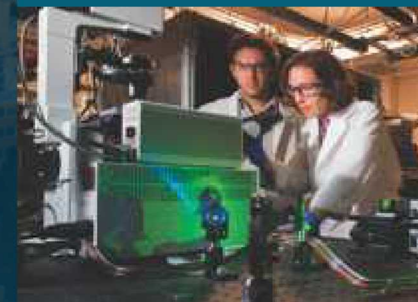
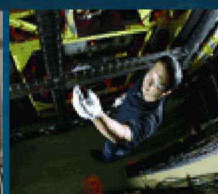
SAND2018-12398C

Cavitation Modeling in NESM using Sierra-SD





PRESENTED BY

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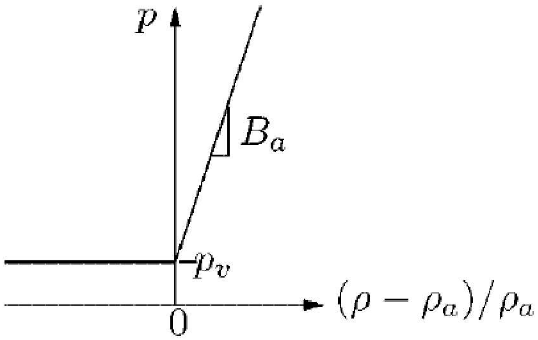
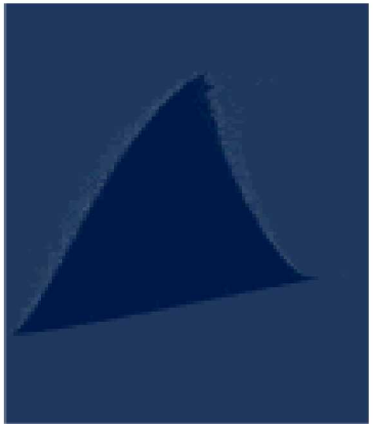
Problem Statement

- Simulate moderate cavitation that occurs due to underwater explosions
  - No focus on free surface at this time; significant hydrostatic pressure exists
  - Capture evolution and collapse of cavitating region – secondary pressure pulse
  - Localized cavitation at moderate depths
  - Large scale simulations - scalability
- Modeling Approach
  - Cavitating acoustic finite elements (lower order elements)
    - Single acoustic fluid with bilinear pressure model
  - Velocity potential implementation of cavitation constraint
  - Implicit time stepping formulation





Cavitation Formulations In Literature

Displacement Potential Formulation:

$$\frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} - \nabla^2\psi = 0; \quad \nabla\psi = \underline{u}; \qquad \frac{\partial^2\psi}{\partial t^2} = \max(c^2\nabla^2\psi, p_o)$$

- Most widely used from 1970's by Newton to CAFE and CASE by Sprague and Geers
- Explicit implementation with verification to Bleich-Sandler problem
- One fluid, cut-off cavitation formulation

Pressure Potential Formulation:

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \nabla^2 p = 0; \quad p = \frac{\partial^2\psi}{\partial t^2}$$

- Uses a pseudo- or auxiliary pressure to evolve the state of the acoustic material
- Developed by Nimmagadda and Cipolla and implemented in Abaqus

Velocity Potential Wave Equation

$$\frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} - \nabla^2\phi = 0; \quad \phi = \frac{\partial\psi}{\partial t}; \quad \nabla\phi = \frac{\partial \underline{u}}{\partial t} = \underline{v}$$

- Valid for both implicit and explicit time stepping
- This is the formulation used in NESM/Sierra-SD
- Compatible with the NESM implementation of Navy UNDEX acoustic scattering loads
- Compatible with monolithic structural acoustic coupling in Sierra-SD
- Implementation uses auxillary or pseudo-velocity potential similar to Nimmagadda and Cipolla
- Not used elsewhere – Newton gives smoothness arguments against this and the pressure potential cavitation formulation

Velocity Potential with Cavitation Constraint

Constrained wave equation with a displacement potential

$$\frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} - \nabla^2\psi = 0; \qquad \frac{\partial^2\psi}{\partial t^2} = \max(c^2\nabla^2\psi, p_o)$$

Constrained wave equation with velocity potential

$$\frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} - \nabla^2\phi = 0;$$

$$\frac{\partial\phi}{\partial t} = \max(c^2\nabla^2\psi, p_o) = \max\left[c^2\nabla^2\int\phi\,dt, p_o\right]$$

The bilinear pressure constraint makes ϕ a heaviside function. The order of operations on ϕ are important; Laplacian cannot be brought inside integral.

Difficult to apply constraints to $\int\phi\,dt$; use change of variables $c^2\nabla^2\int\phi\,dt$ = $\frac{\partial\bar{\phi}}{\partial t}$

$$\frac{\partial\phi}{\partial t} = \max\left(\frac{\partial\bar{\phi}}{\partial t}, p_o\right)$$

$$\frac{1}{c^2}\frac{\partial^2\bar{\phi}}{\partial t^2} - \nabla^2\phi = 0;$$

Implicit Time-stepping with Explicit Cavitation Constraint

$$\frac{\partial^2 \bar{\phi}}{\partial t^2} = c^2 \nabla^2 \phi \ ; \qquad \frac{\partial \phi}{\partial t} = \max\left(\frac{\partial \bar{\phi}}{\partial t}, p_o\right)$$

$$\left.\frac{\partial \bar{\phi}}{\partial t}\right|_{n+1} = \left.\frac{\partial \bar{\phi}}{\partial t}\right|_{n} + \int_{t_n}^{t_{n+1}} c^2 \nabla^2 \phi dt$$

$$\left.\frac{\partial \phi}{\partial t}\right|_{n+1} = \max\left(\left.\frac{\partial \bar{\phi}}{\partial t}\right|_{n+1}, p_o\right)$$

Explicit Cavitation Constraint being applied over time-step, no nonlinear solve. Cavitation evolution is typically slower than the wave speed

$$\phi_{n+1} = \phi_n + \int_{t_n}^{t_{n+1}} \frac{\partial \phi}{\partial t} dt$$

Implementation

- Nodal constraints on the first time-derivative
- Explicit time stepping – straight forward application of constraint
- Implicit time stepping requires interlacing of contraint within time-step
- Subtle detail: Construct to store the time derivative of the auxiliary variable, $\frac{\partial \bar{\phi}}{\partial t}$

Newmark-Beta Time stepping as implemented in Sierra-SD

(1) Given ϕ_n , $\dot{\phi}_n$ and $\ddot{\phi}_n$, use Newmark-Beta implicit time stepping to solve wave equation for ϕ_{n+1} , $\dot{\phi}_{n+1}$ and $\ddot{\phi}_{n+1}$. Only $\dot{\phi}_{n+1}$ will be modified by cavitation

(2) Given $\ddot{\phi}_n$ and $\bar{\dot{\phi}}_n$ from previous time-step and using $\ddot{\phi}_{n+1}$ from step (1), use Newmark-Beta equation for velocity to update $\bar{\dot{\phi}}_{n+1}$

$$\bar{\dot{\phi}}_{n+1} = \bar{\dot{\phi}}_n + \Delta t\left[(1-\gamma)\ddot{\phi}_n + \gamma\ddot{\phi}_{n+1}\right]$$

(3) Solve for $\dot{\phi}_{n+1}$ by using $\bar{\dot{\phi}}_{n+1}$ in the cavitation constraint

$$\dot{\phi}_{n+1} = \max\left[\bar{\dot{\phi}}_{n+1}, p_o\right]$$

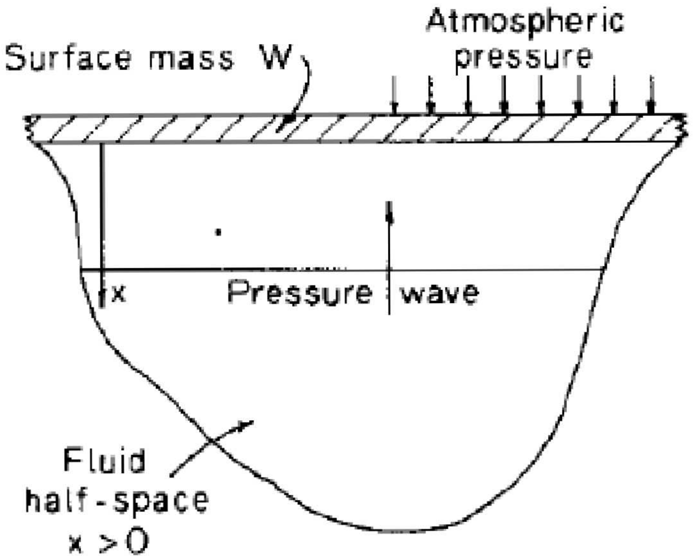
(4) Advance time-step and repeat

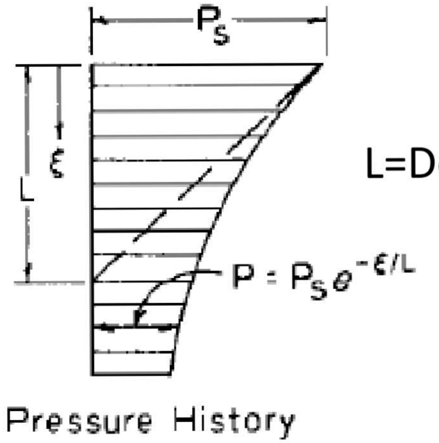
Note:

$\bar{\dot{\phi}}$ is the only auxiliary term being computed and its time evolution is tracked in step (2).

When cavitation occurs, only $\dot{\phi}$ is changed in the current time step.

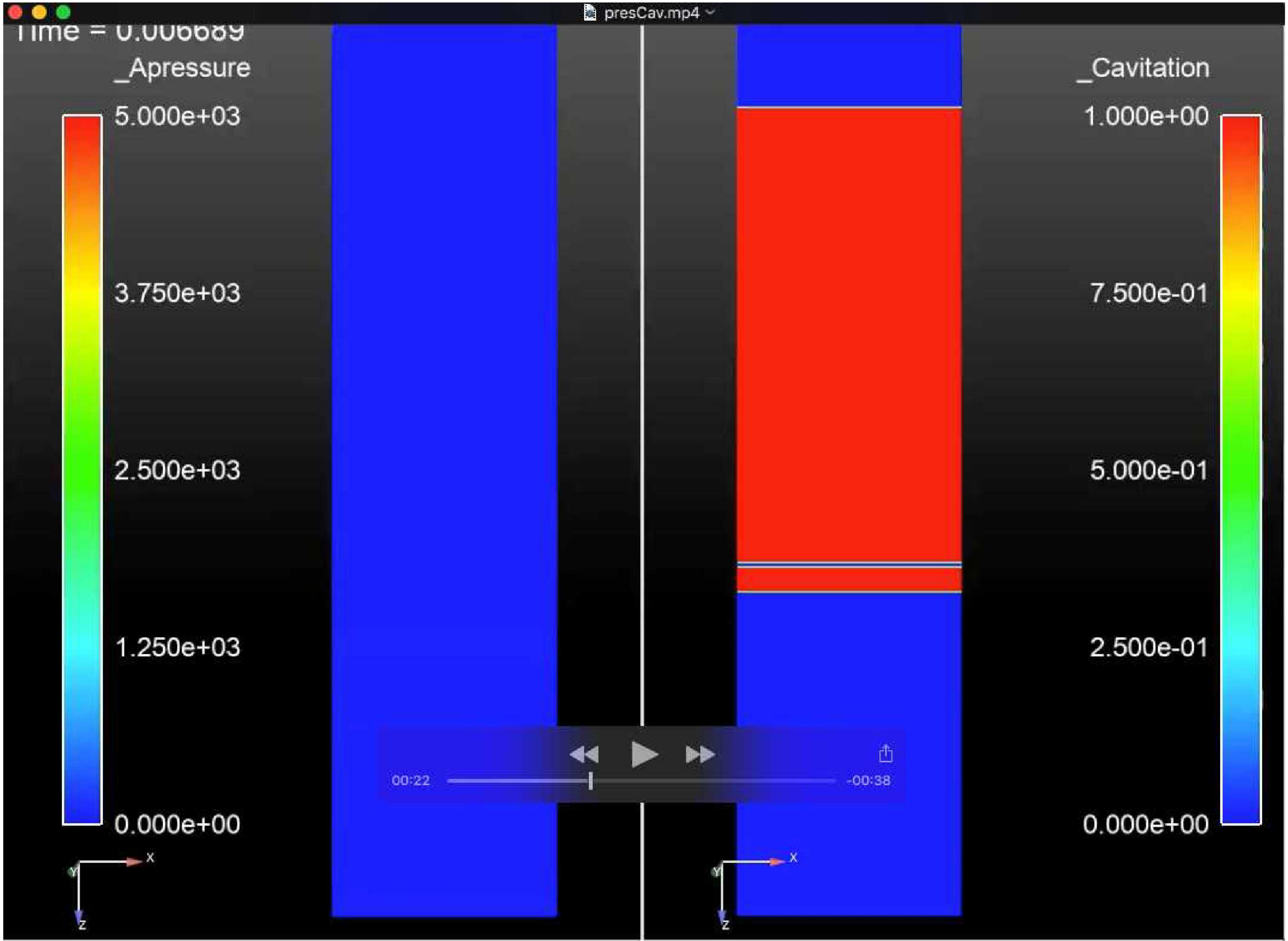
Bleich Sandler Problem Set-up





L=Decay Length = 4.74ft

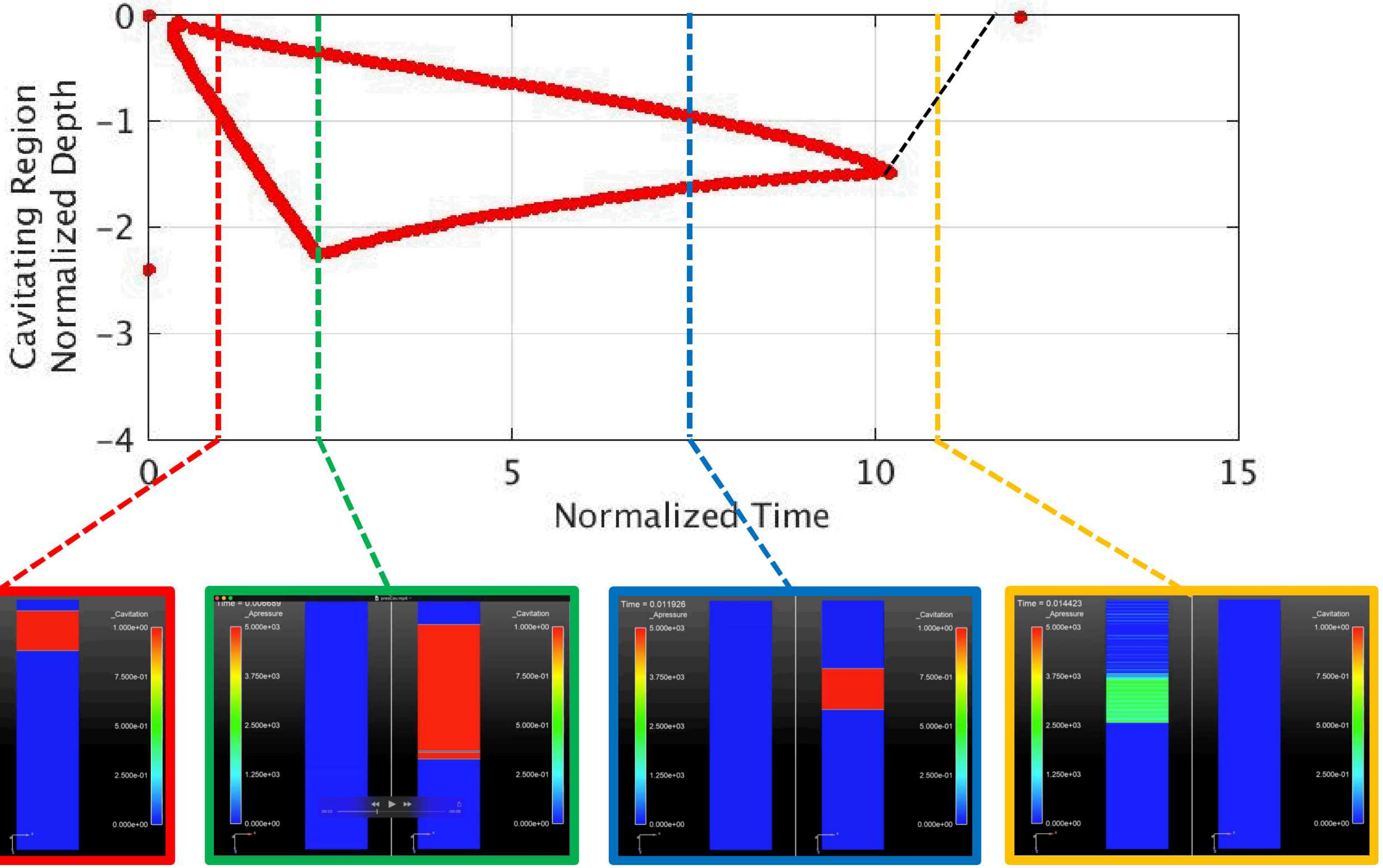
Bleich Sandler Example



Bleich Sandler - No Cavitation

$$\frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} - \nabla^2\phi = 0;$$

Normalized Time= t*c/decay Length
Normalized Depth = depth/decay Length



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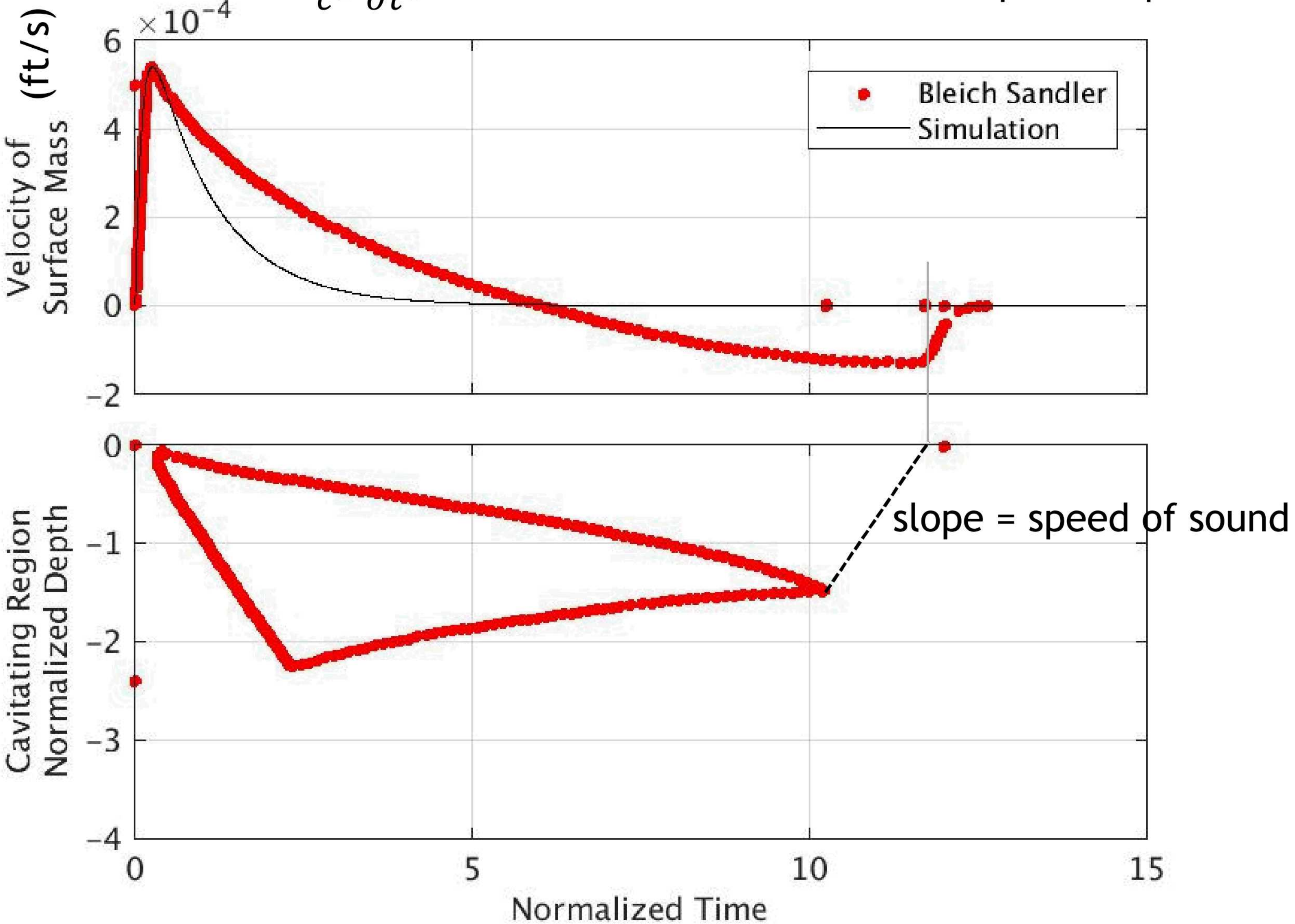
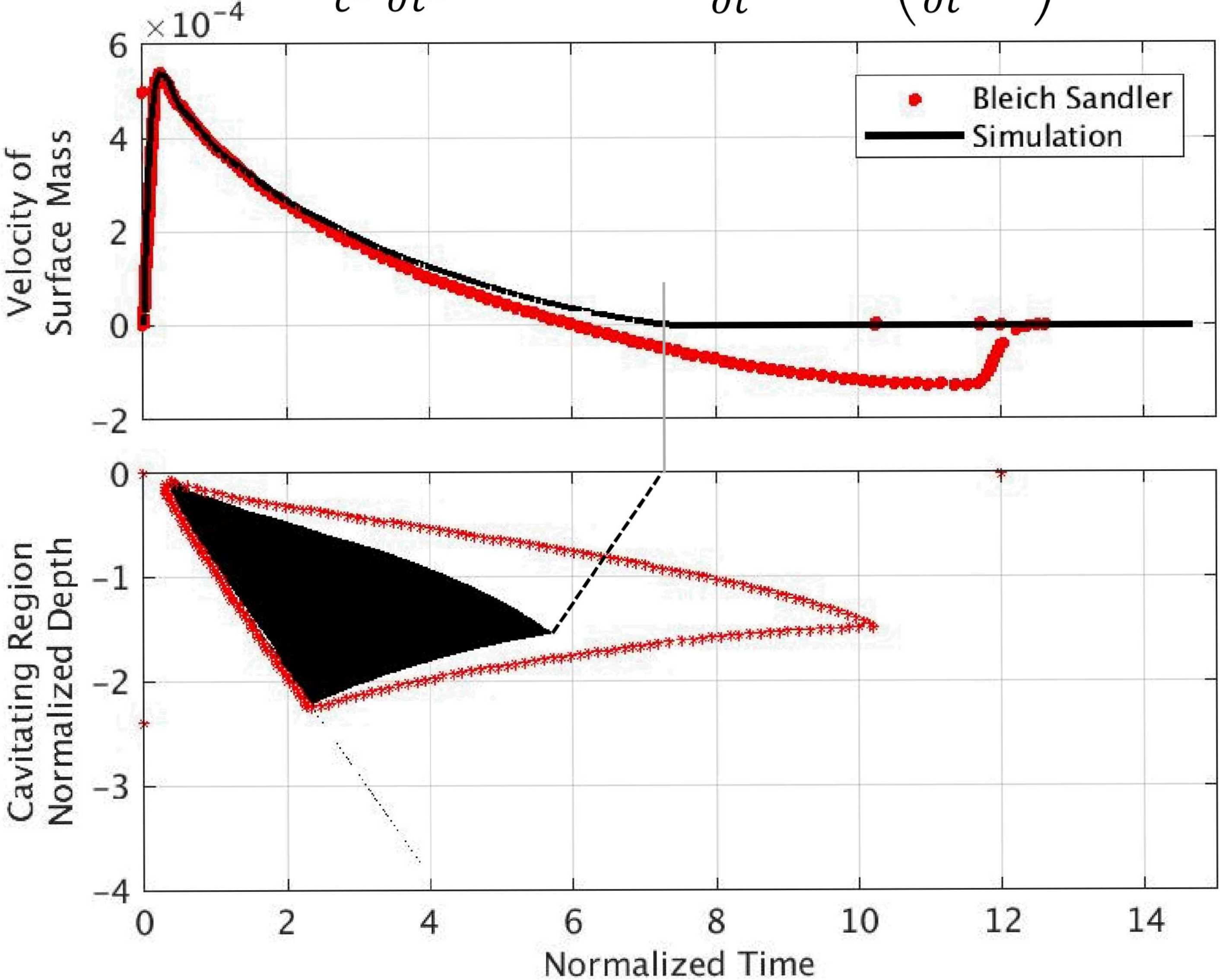


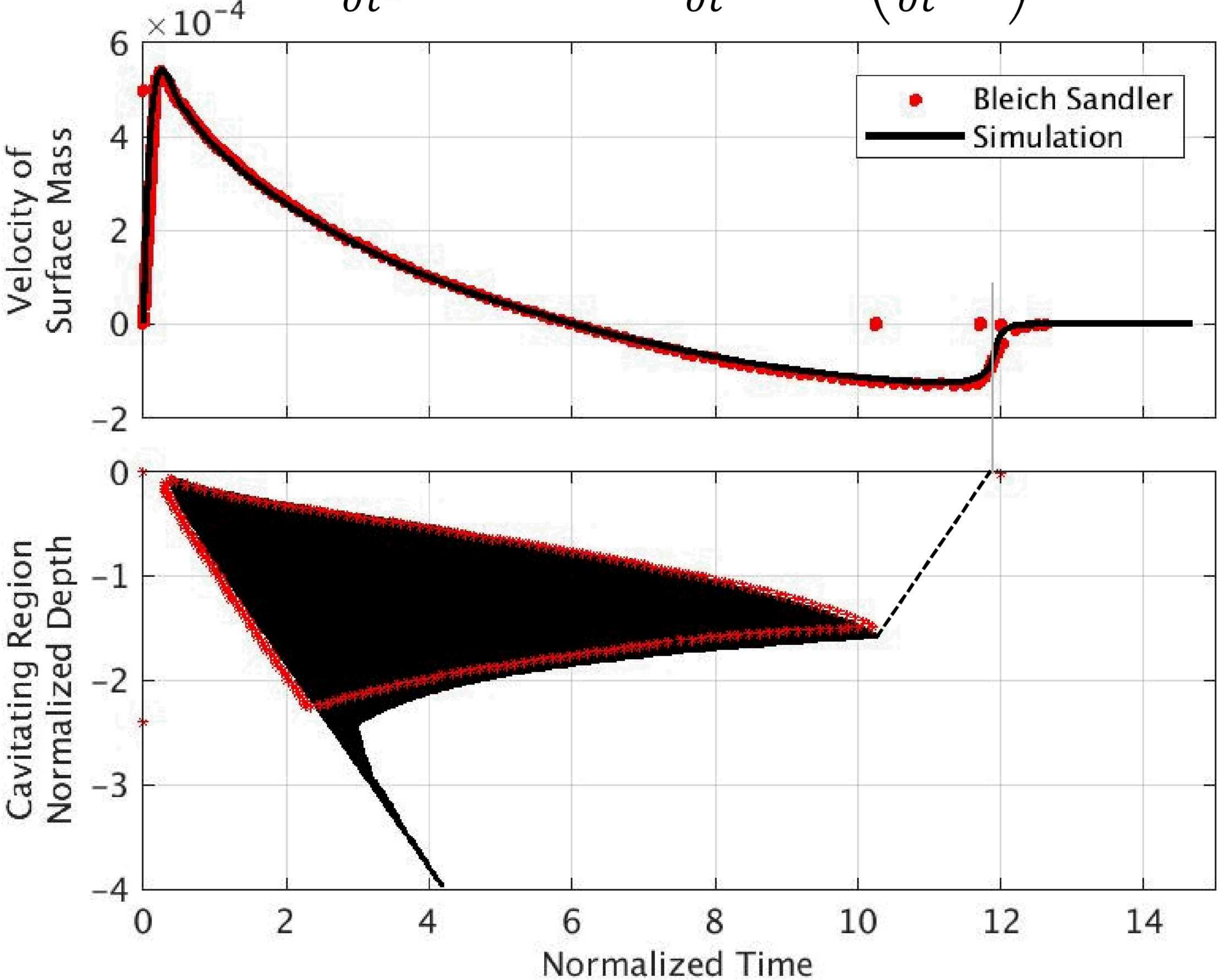
Bleich Sandler – Cavitation Constraint without Auxiliary Potential

$$\frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} - \nabla^2\phi = 0; \quad \frac{\partial\phi}{\partial t} = \max\left(\frac{\partial\phi}{\partial t}, p_o\right)$$



Bleich Sandler – 100 Elements per Length Scale (L = 4.74 feet)

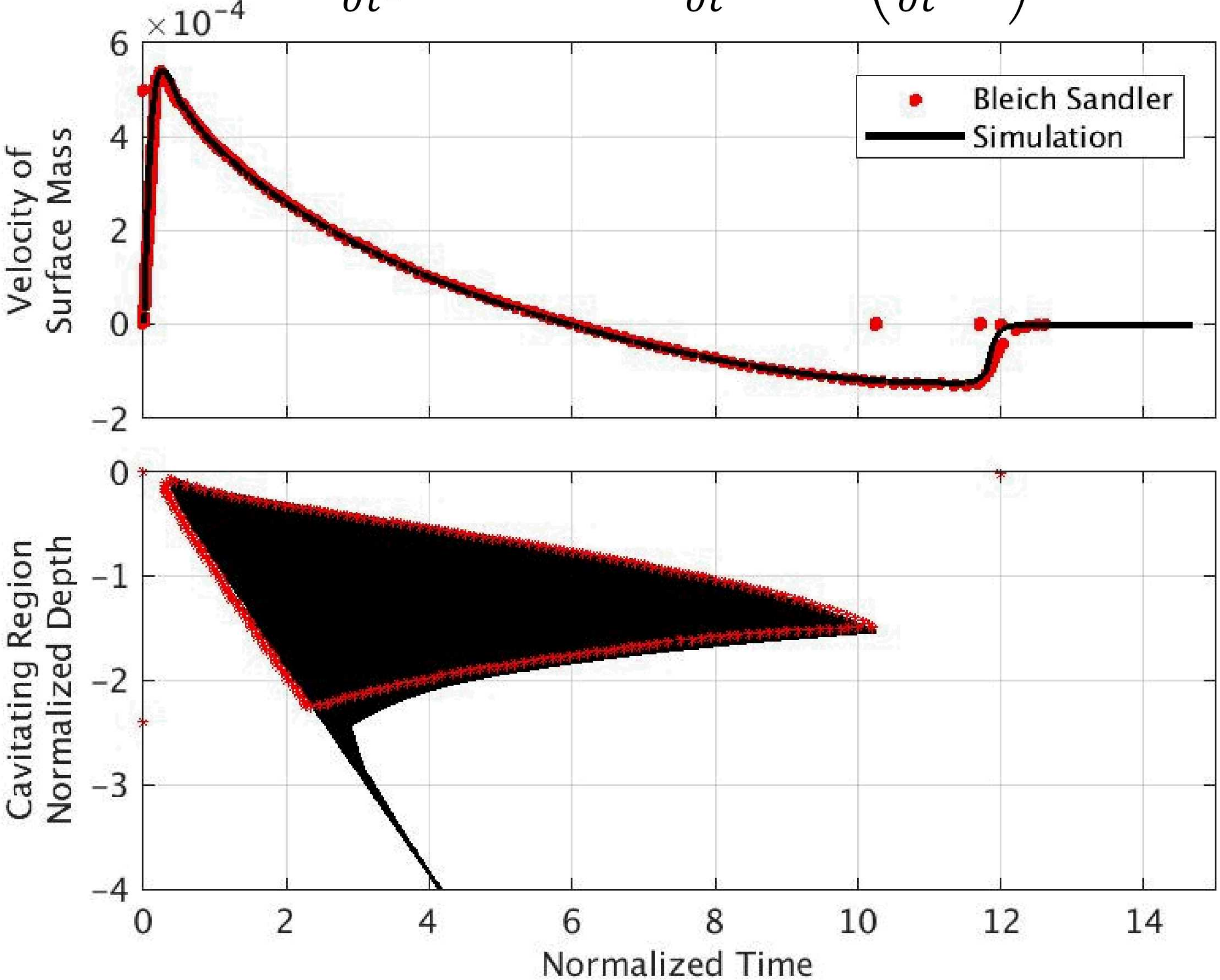
$$\frac{\partial^2 \bar{\phi}}{\partial t^2} - c^2 \nabla^2 \phi = 0; \ \frac{\partial \phi}{\partial t} = \max\left(\frac{\partial \bar{\phi}}{\partial t}, P_0\right)$$



Element Size
h=0.0474 ft
=0.015m

Bleich Sandler – 200 Elements per Length Scale

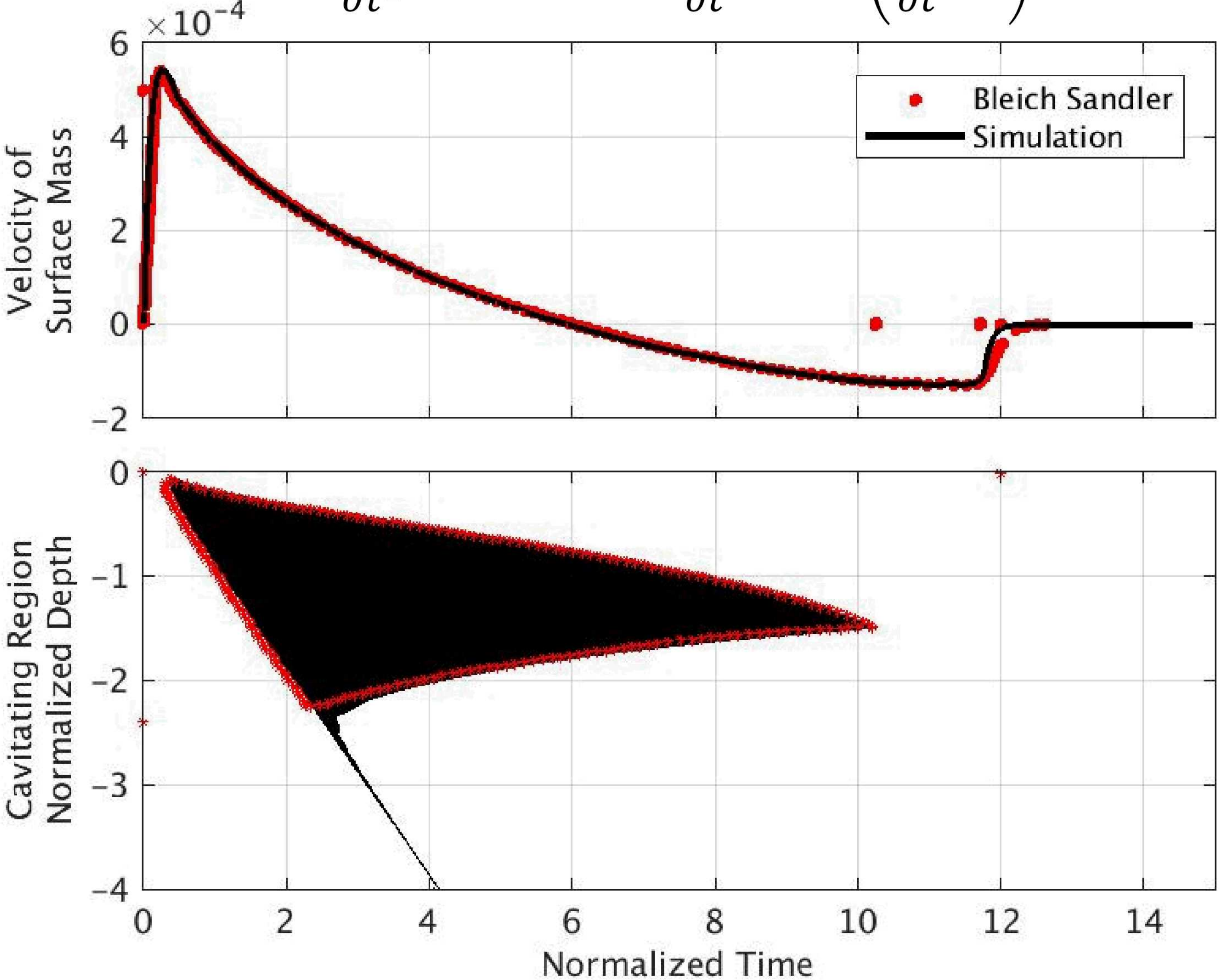
$$\frac{\partial^2 \bar{\phi}}{\partial t^2} - c^2 \nabla^2 \phi = 0; \; \frac{\partial \phi}{\partial t} = \max\left(\frac{\partial \bar{\phi}}{\partial t}, P_0\right)$$



Element Size
h=0.0237 ft
=0.0072m

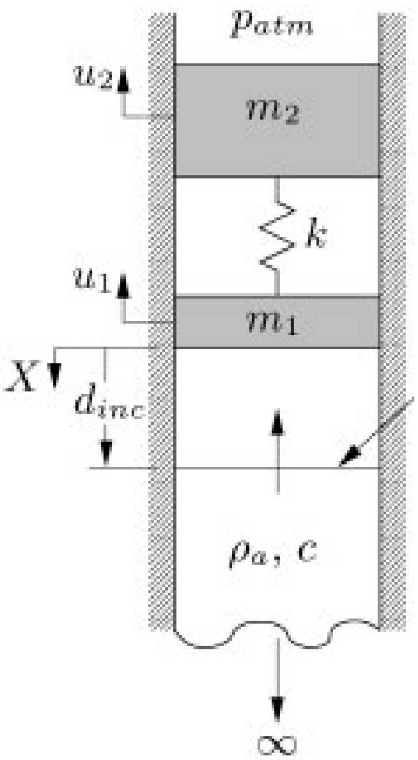
Bleich Sandler – 400 Elements per Length Scale

$$\frac{\partial^2 \bar{\phi}}{\partial t^2} - c^2 \nabla^2 \phi = 0; \ \frac{\partial \phi}{\partial t} = \max\left(\frac{\partial \bar{\phi}}{\partial t}, P_0\right)$$

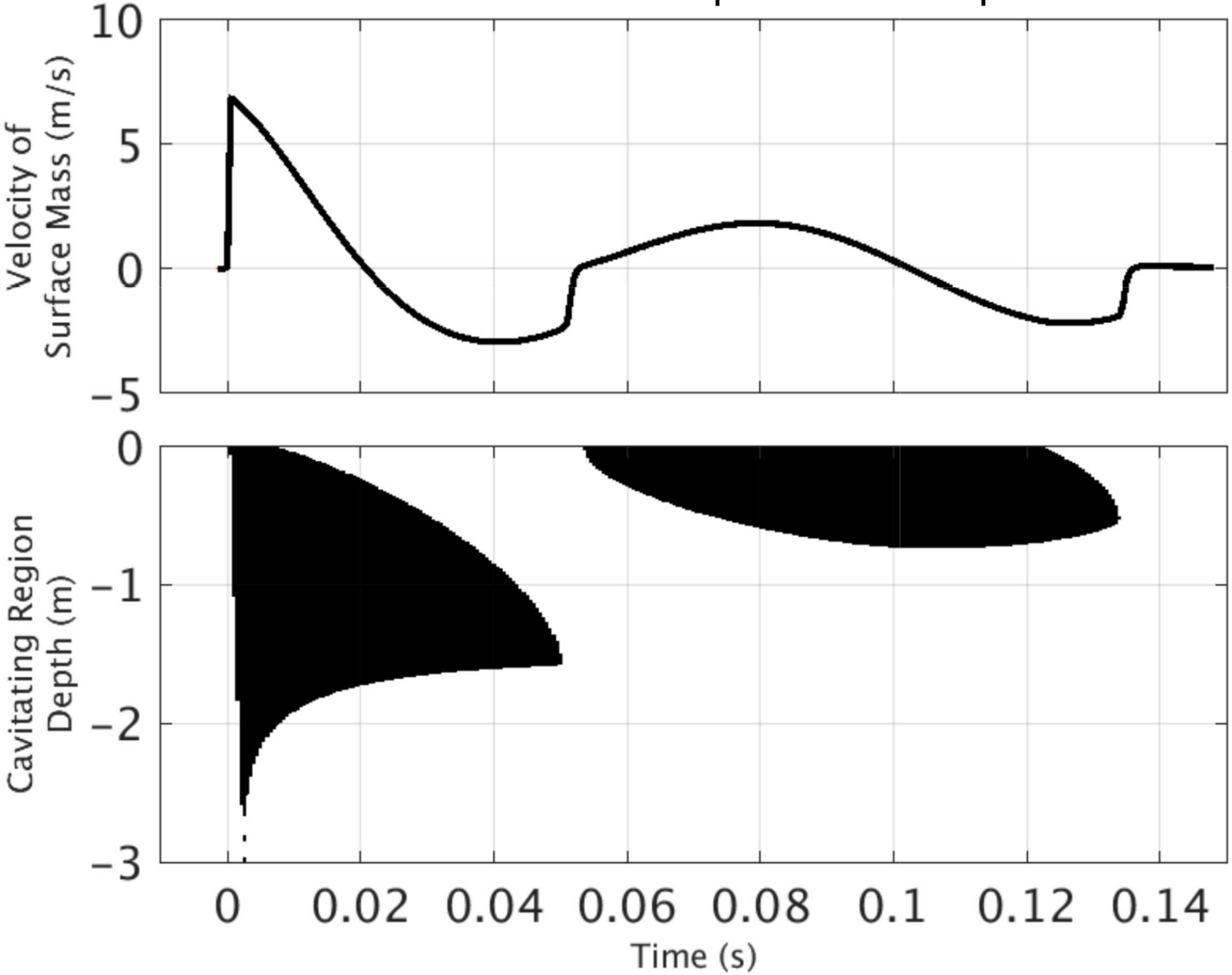


Element Size
h=0.0119 ft
=0.0036m

Sprague and Geers Spring Mass Variant of Bleich Sandler



Element Size, h=0.003m;
close to finest mesh in previous example



Submerged Cylindrical Shell – 2D Sprague and Geers Approximation

Carlos felippa 2d café model

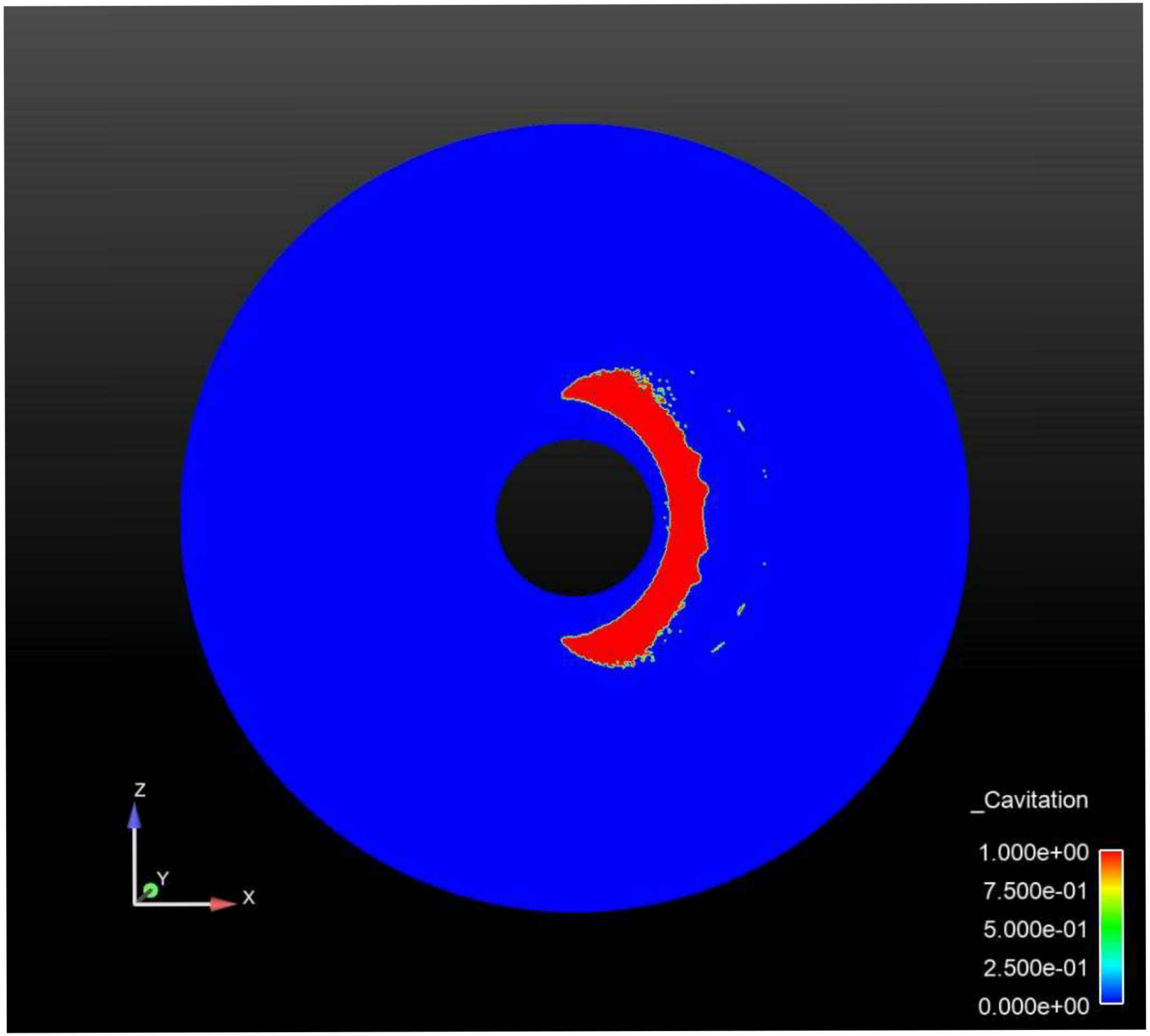
Steel Shell thickness=0.05m
Radius rc = 5m

60kg HMX
12m standoff

Step Exponential Plane Wave
Scattering Approximation

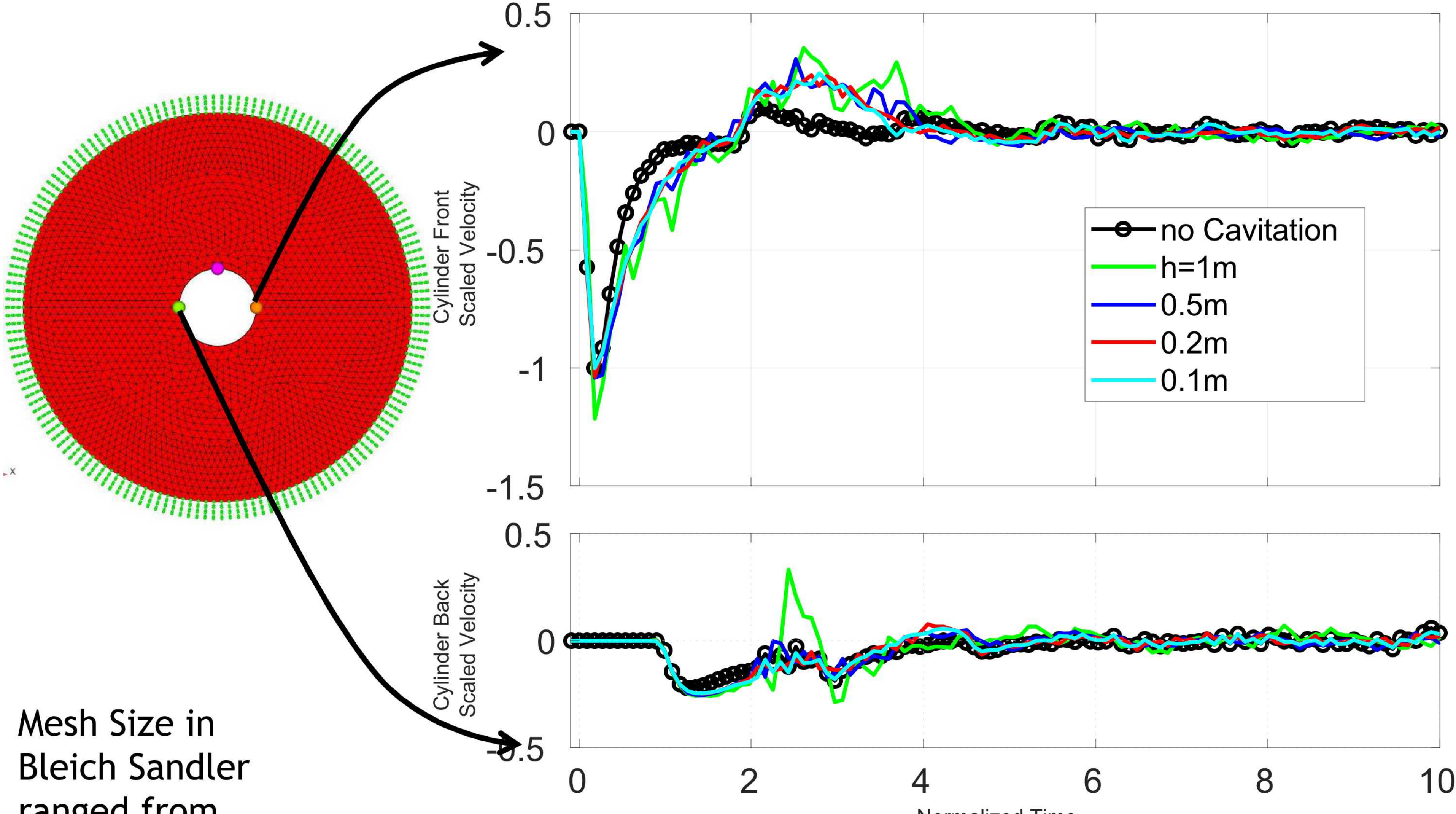
Acoustic domain radius, ra=25m
Green dots are infinite element
exterior boundary conditions
Uniform depth of 30m

Cavitation Movie



Velocity Response of Shell Structure

MOVIE With cavitation and pressure wave



Mesh Size in Bleich Sandler ranged from 0.015 – 0.003m

Normalize Time = t*c/rc

Comments and Future Developments

Comments:

- Sierra SD provides highly scalable cavitating acoustic capability
- Velocity Potential seems to ease frothing issues observed in displacement potential
- Uses numerical damping as opposed to explicit material damping
- Other Benefits of Sierra SD:
  - Infinite Element absorbing boundary conditions
  - Navy UNDEX loading
  - Monolithic Structural-Acoustics modeling
  - Coupling to other Sierra codes including Sierra Solid Mechanics

Future Improvements:

- Verification and validation with 3D Examples with Navy
- Cavitating Acoustic P-Elements (similar but not the same as CASE based on spectral elements). Slow convergence rates for lower order elements.