BENCHMARKING AND EXPLORING PARAMETER SPACE OF THE 2-PHASE BUBBLE TRACKING MODEL FOR LIQUID MERCURY TARGET

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Introduction

The spallation reaction at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory involves an intense proton pulse hitting a mercury target to produce the most intense pulsed neutron beams in the world for scientific and materials discovery [1]. A 2-phase material model that incorporates the Rayleigh-Plesset (R-P) model is expected to address this complex multi-physics dynamic problem by including helium bubble dynamics in with the liquid mercury. We refer to this 2-phase material model as the R-P model. Here we present:

- A benchmarking study comparing the measured strains in the SNS target vessel with the simulation results of the solid mechanics simulation framework.
- An investigation of the effect of the model bubble parameters, including the bubble size distribution and the discretization into bubble families, on vessel's strain response.
- An investigation of the effect of other physical model parameters, such as the mercury's bulk modulus, viscosity, and surface tension on vessel's strain response.

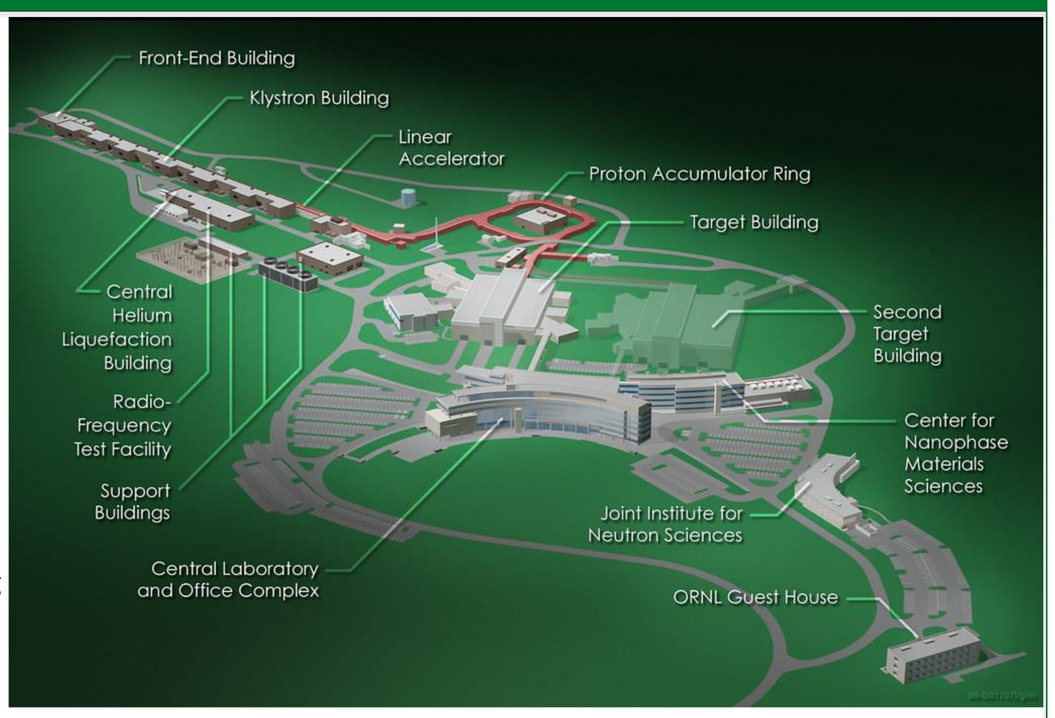
Methods

Rayleigh-Plesset equation [2]:

$$R\ddot{R} = -\frac{3}{2}\dot{R}^2+\frac{1}{\rho_{L0}}[p_{b0}(\frac{R_0}{R})^{3\gamma}-4\mu\frac{\dot{R}}{R}-\frac{2\sigma}{R}-p_{b0}-p]$$

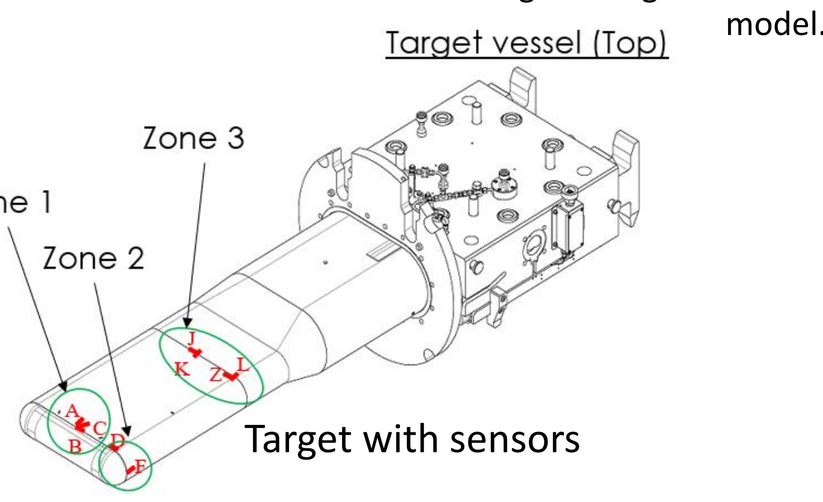
- R is the radius of the bubble,
- $\dot{R}$ is the time rate of change of the radius of the bubble,
- $\ddot{R}$ is the time rate of change of $\dot{R}$,
- ρ is the density of the fluid surrounding the bubble,
- μ is the kinematic viscosity of the surrounding fluid,
- γ is the adiabatic index of the bubble gas,
- σ is the surface tension of the fluid,
- p_{b0} is the initial pressure of the bubble,
- p is the real-time pressure in the surrounding fluid.

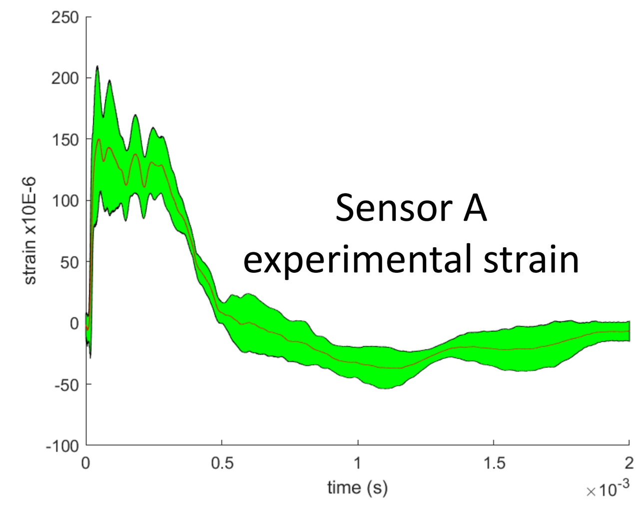
By simultaneously solving the coupled equations for an arbitrary number of bubble families and the surrounding compressible liquid to conserve pressure and strain, the time-varying bubble radii and their derivatives can be numerically solved.

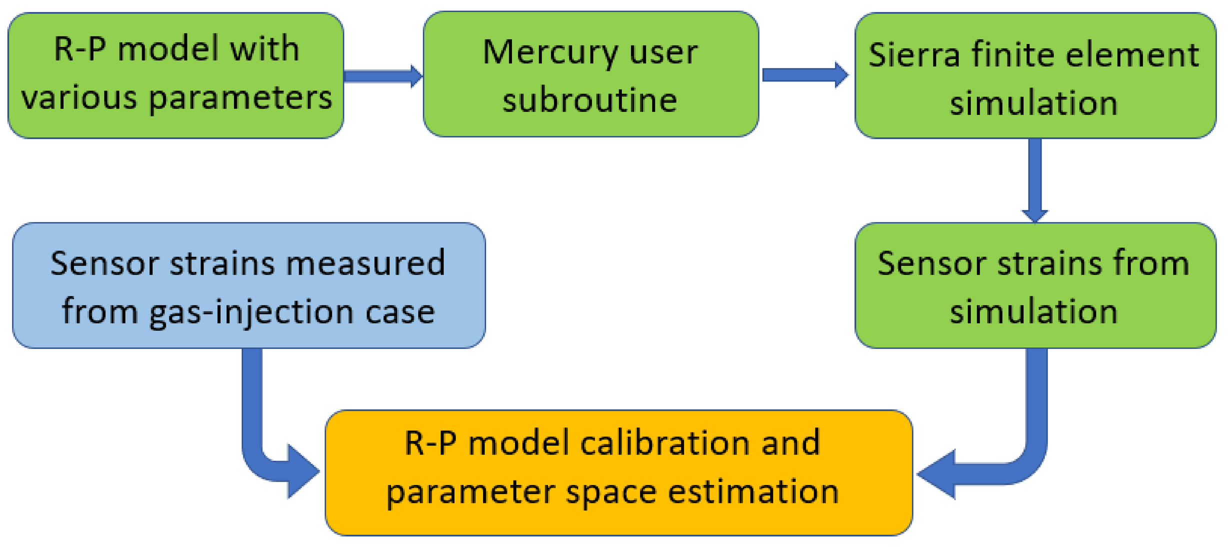


Experimental measurements:

The strong (23.3 kJ) but short (0.7 µs) proton pulses result in stress/strain waves propagating to the stainless-steel vessel, which can be measured through the attached sensors. Measurements of the sensor strains for 2 milliseconds after the pulse delivery under the same pulse power level (1.4 MW) but different loading cycles have been collected and processed as the baseline for validating the target model simulations. These experimental strains are used to ca model.





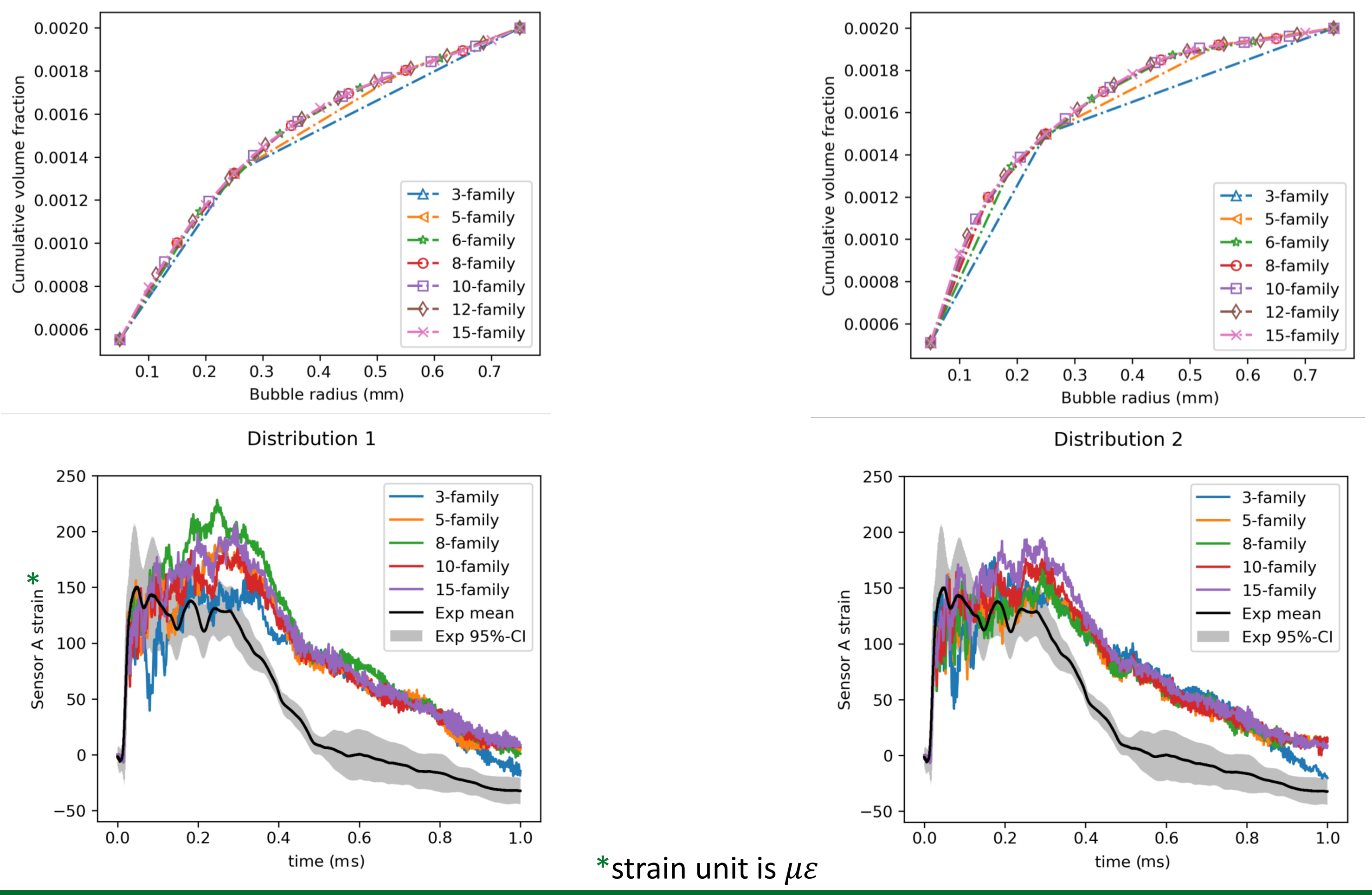


Calibration workflow

Results

- **Effect of bubble distribution**

Cases were run using the expected values for bulk modulus K = 2.86e+10 Pa, σ = 0.47 N/m, γ = 1.66, μ = 0.001 N·s/m^2, and gas volume fraction = 0.2% with varying bubble distributions and distribution discretization. A preliminary study shows that right-skewed distributions are more promising to capture the ground truth of the distribution of the bubble sizes. Results of Distribution 1 and Distribution 2 are compared.

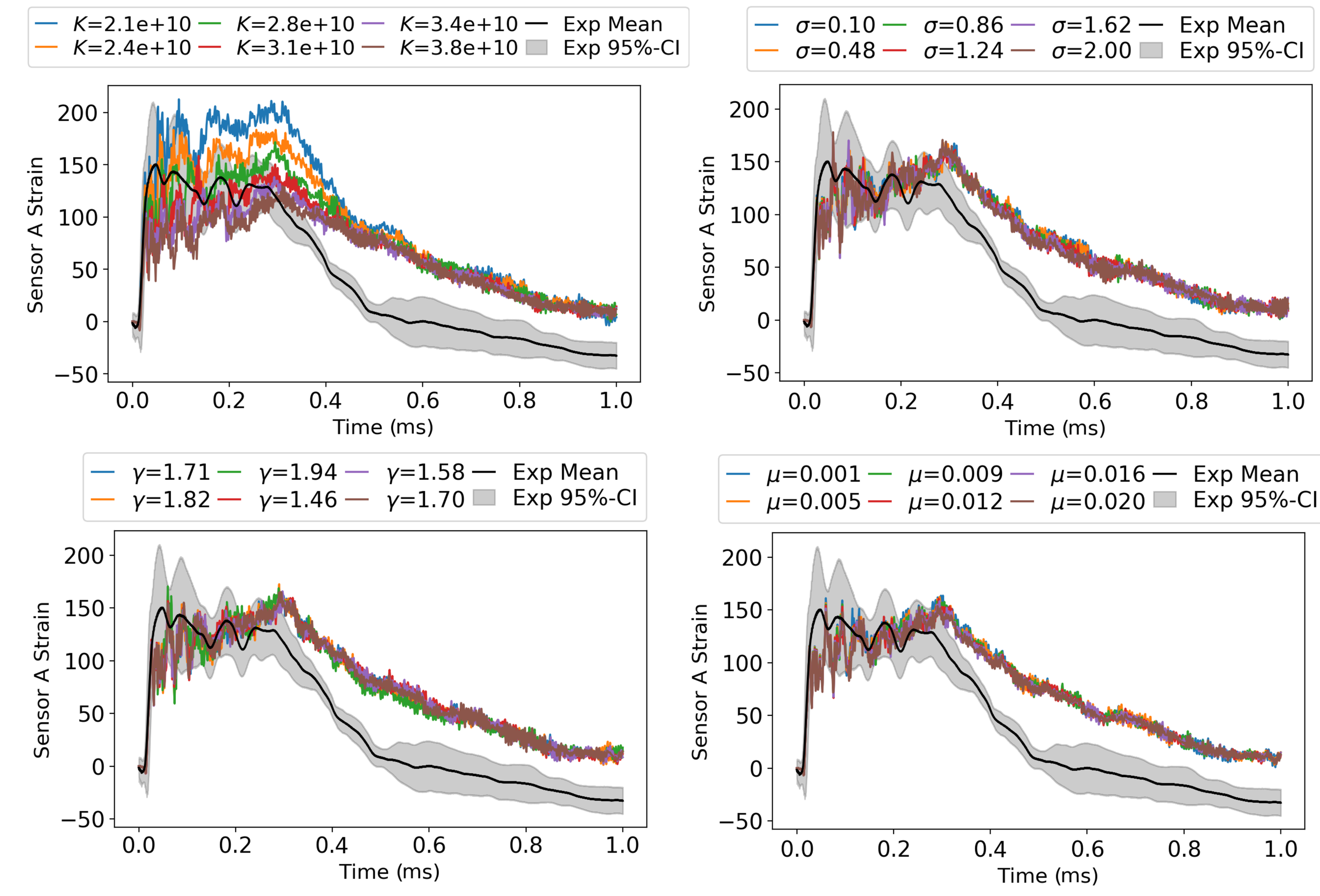


*strain unit is $\mu\varepsilon$

Results-Continued

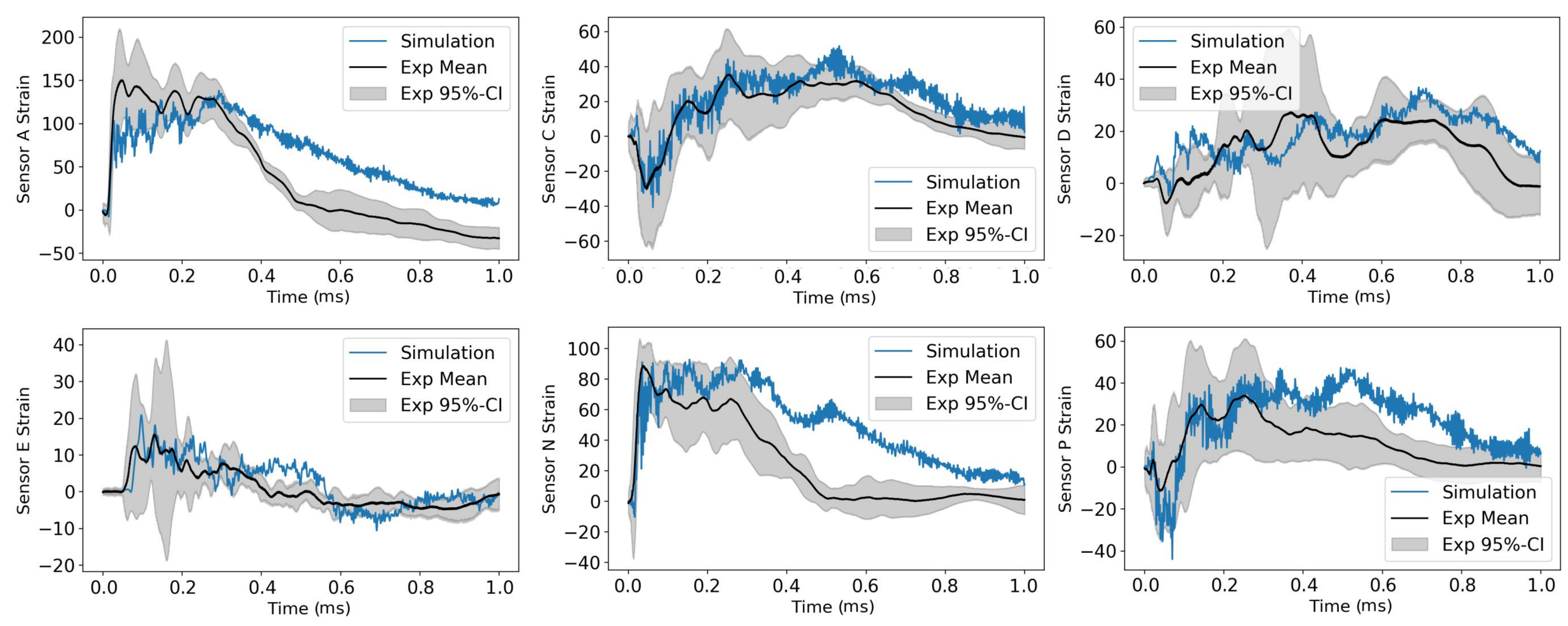
- **Effect of physical model parameters**

Other cases were run to investigate the sensitivity of the four physical parameters K, σ, γ, μ on the strain response in the R-P model. The bubble distribution was fixed to Distribution 1.



- **Best Case Results**

Out of more than 150 simulation cases, the simulation that best matches the measured data is plotted below and corresponds to K = 3.45e+10 Pa, σ = 0.47 N/m, γ = 1.66, μ = 0.0015 N·s/m^2, and the 8 bubble families using Distribution 1. The best simulation captures strains at sensors C, D, and E quite well, and the early part of the strain for sensors A, N, and P.



Conclusions

From this benchmarking study of the simulation for the liquid mercury target at the SNS using the proposed 2-phase mercury model that includes bubble dynamics, we found that:

- Preliminary results indicate that 8-10 bubble families with a monotonic right-skewed distribution seem to provide the best agreement with the experimentally measured target strain response with helium gas injection.
- The bulk modulus seems to have more impact on the simulated strain than surface tension, viscosity, or adiabatic index.
- Although our simulations seem to provide good agreement at the beginning of the pulse, a consistent overestimation was seen toward the end of the pulse for some sensors. We expect the tail strain discrepancy to be reduced in the future by exploring a wider parameter space.

References

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