Transformational Nuclear Material Sensor System Design Optimization Using Multiphysics Simulation

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Abstract

The timely detection of special nuclear materials (SNMs) in combating nuclear terrorism is a Top 10 R&D Priority for the 21st Century – according to the 2008 National Academy Report. We have found that by inducing fluids into tensioned (yes, sub-zero pressure) metastable states, neutrons (the tell-tale signs of SNMs) can be detected with unparalleled efficiency compared to conventional systems. Of the ways to induce tensioned states in fluids, a laser-cavity like resonance-mode oscillatory acoustic field creation offers unique benefits.

Three different types of acoustic system designs are in development based on guidance from a multiphysics modeling framework. Each system includes a resonance chamber, a piezoelectric oscillator, and drive electronics. The current iteration of design includes a borosilicate glass vessel with a reflector placed in the top of the chamber. A piezoelectric disk at the bottom of the vessel drives the detector.

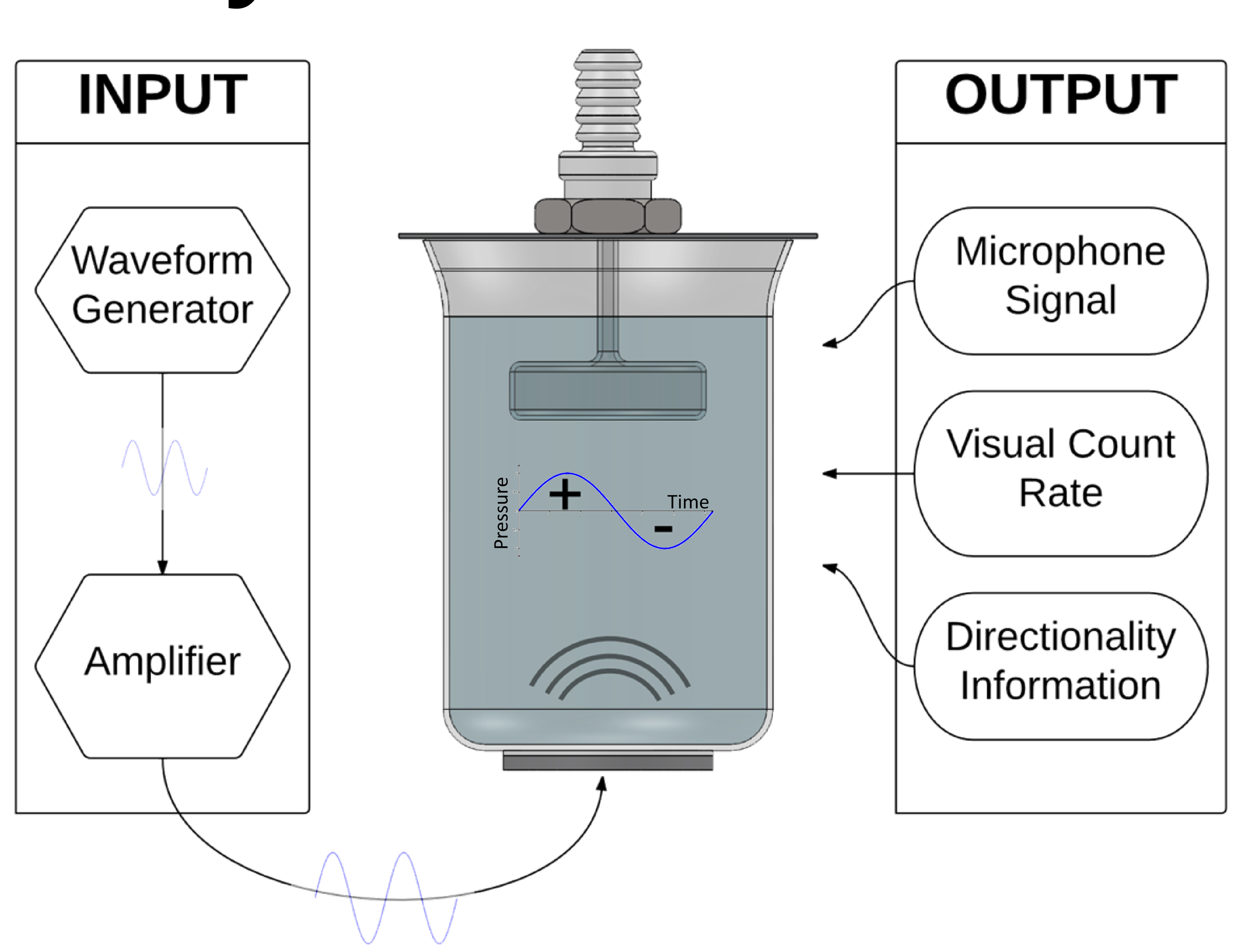
Each of the multiple designs must be optimized for several criteria. In general, the highest volume of negative pressure is desired in the system to maximize intrinsic efficiency. Also, the structural rigidity and dynamic stress-strain response must fit within design requirements.

A multiphysics simulation platform for these chambers has been created which takes into account structural dynamics, electromagnetics, acoustics, and fluid-structure interactions. This multiphysics platform has been benchmarked in several ways: matching of Piezoelectric Transducer power and neutron induced cavitation count rate with location in frequency space of simulated resonances and matching of laser power threshold for laser induced cavitation with simulated resonance pressure profile. Each experimentally found resonance matched simulation data to within 9% and a specified resonance profile matched laser induced cavitation mapped profile to within 1σ error.

Motivation

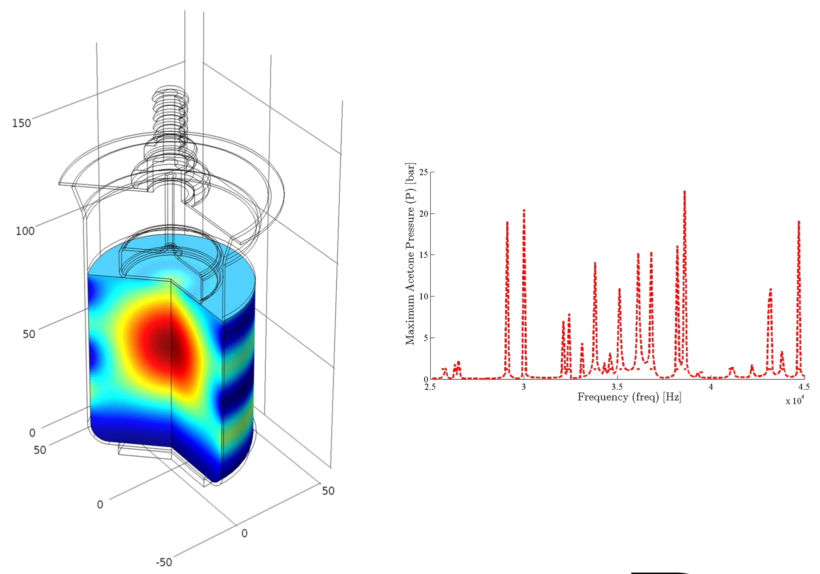
Parameter	Conventional Detector	TMFD System
Intrinsic efficiency	~0% (MeV neutrons) ~90% (0.01 eV neutrons) (3cmx30cm tube)	~90% (MeV neutrons) ~90% (0.01 eV neutrons) (10cmx10cm volume)
On-Off times	Minutes, saturation during pulsed interrogation	Microseconds, adaptable for pulsed systems
Gamma blindness?	Limited; Saturation in high gamma fields	Yes; No gamma saturation issues
Neutron Directionality?	No with single systems; Yes if arrays are used	Yes (to within 10°) with single system
Can system detect neutrons and alphas?	No; neutron spectroscopy requires Bonner spheres and spectrum unfolding	Yes. Same system can be adapted to detect neutrons, and alphas with spectroscopy
Cost	High (~$5k-$10k for single tube systems)	Low-to-Modest ($50-$1k+)

System Structure



Methodology and Analysis

Out of the wide range of variables in the chamber setup, the reflector submersion, transducer voltage and transducer frequency were studied. For each physical model case, frequencies were swept from 25 kHz to 45 kHz to try and identify the resonant frequency creating the most desirable pressure profile. Transducer Bias at $1\ V$, $15\ V$, $75\ V$, and an experimentally defined nonlinear voltage sweep were run for each of these frequencies. The maximum pressure created within the fluid was charted. At each of these peaks, the centerline pressure profile within the chamber was plotted. To benchmark these results, several different methods were used:



Optimal Profile

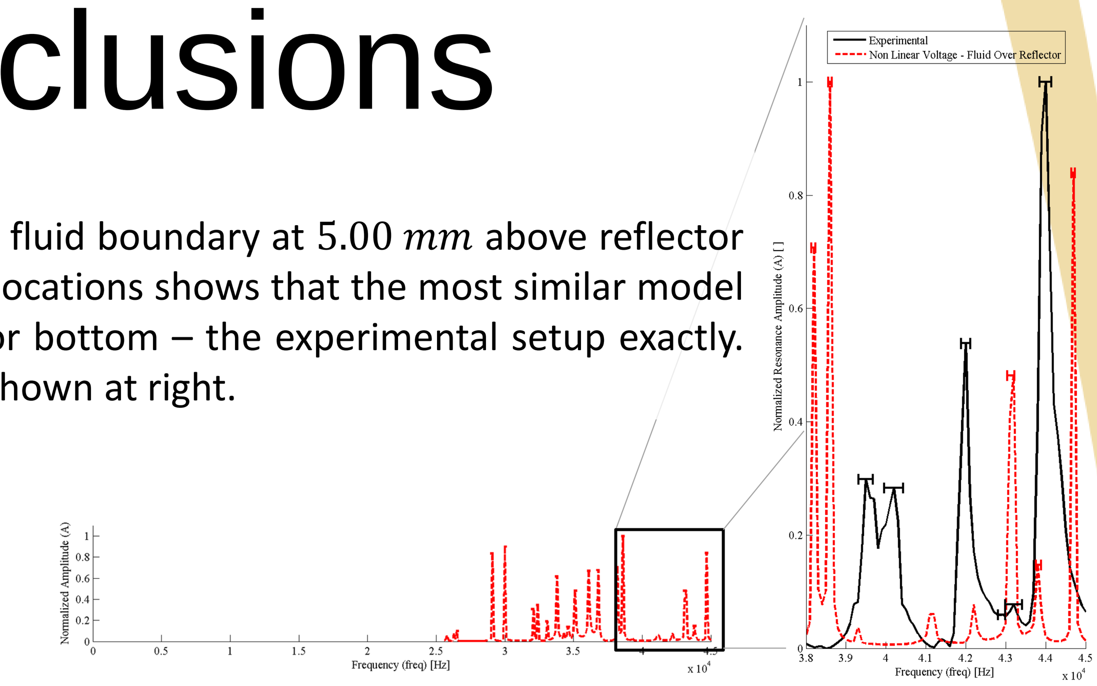
- Power matching – based on the hypothesis that the true power input of the transducer system will increase dramatically at resonances. A waveform generator was used to set input voltage and frequency to an amplifier, whose output signal was limited in power, causing reduction of voltage at resonances. The phase angle, VRMS, and ARMS of the system were measured for each frequency.
- Laser pressure profile mapping – profiling is done using energy deposition from a laser to generate cavitations. A $337.1\ nm$, $7.2\ mW$ $30Hz$ laser was focused on regions of suspected high negative pressure. Visual verification of cavitation was used for this mapping.
- Neutron Mapping - Incident neutrons will cause cavitation on high negative pressure fields, effectively indicating when a resonance is reached. A Plutonium-Beryllium neutron source (~4.5 MeV neutrons) is used to indicate areas of pressure below $\sim -3.5\ bar$. This is driven with a waveform at $7\ V$ and passed through a $20\times$ amplifier to sweep through frequencies.

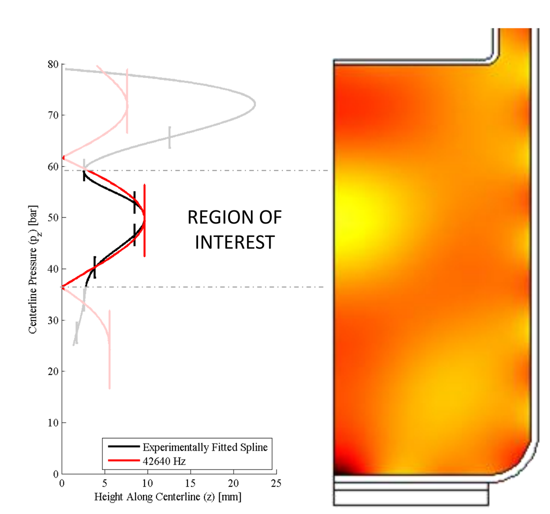
Results and Conclusions

Power Frequency Sweep Benchmarking

Through comparison of peaks in the frequency sweep, it can be shown that all models with fluid boundary at $5.00\ mm$ above reflector bottom exhibit a resonance that is not present in experimental data. Further analysis of peak locations shows that the most similar model to experimental is that with non linear PZT bias and fluid boundary $24.06\ mm$ above reflector bottom – the experimental setup exactly. These peaks are within $8.42\% \pm 0.60\%$ of experimental values: comparison of these peaks is shown at right.

Experimental Peak Frequencies	Variable Voltage - Fluid Over Reflector Peak Frequencies	Peak Offset	Peak Offset Percentage
39500 ± 183.35	38188 ± 47.66	-2711 ± 189.44	-5.13% ± 0.48%
40200 ± 238.21	38606 ± 46.76	-2012 ± 242.76	-8.42% ± 0.60%
42000 ± 113.24	43131 ± 85.04	231 ± 141.61	0.54% ± 0.33%
43200 ± 254.89	43821 ± 65.93	621 ± 263.28	1.43% ± 0.61%
44000 ± 151.78	44698 ± 44.52	698 ± 158.17	1.57% ± 0.36%





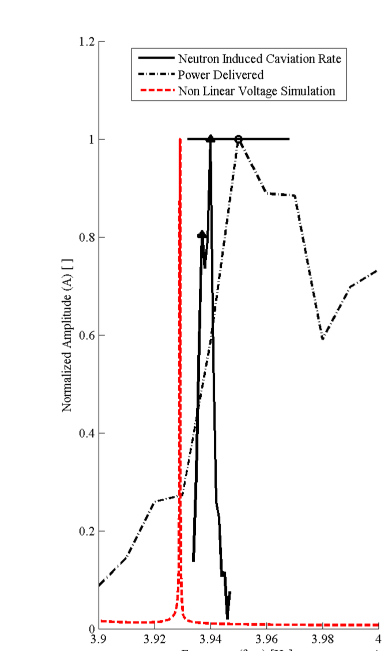
Laser Induced Cavitation Benchmarking

A ThermoScience UV laser was used to induce cavitation at specific locations throughout a chamber operating at resonance. A resonance controller board was used to sweep between $40\ kHz$ and $45\ kHz$. The threshold for cavitation was measured using the laser with varying levels of attenuation (burst energy varying from $\sim 3 - 35\ \mu J$); the maximum amount of attenuation still causing cavitation was assumed to be proportional to the pressure induced in the chamber. The resonance mode was found to be $42640\ Hz$ and the peaks between model and experimental match within 1σ error for 5 of 7 points.

Neutron Induced Cavitation Benchmarking

A Pu-Be neutron source was used to generate cavitations within the sensitive volume in a chamber at resonance. This source indicates regions where the true negative pressure was below the critical -3.5 bar. By sweeping the frequency around a defined resonance and comparing count rates, this peak could be compared against a model and the power matching data. The table below and chart at right shows this comparison. The model accurately predicts the experimental peak to within $0.53\% \pm 0.470\%$ and as accurately as within $0.20\% \pm 0.003\%$.

Power Matching Peak Frequency	Neutron Induced Cavitation Peak Frequency	Variable Voltage - Fluid Over Reflector Peak Frequency		Peak Offset	Peak Offset Percentage
39500 ± 183.35	39370 ± 11.3974	39291 ± 0.9509	**Minimum**	79 ± 11.437	0.20% ± 0.003%
			Maximum	209 ± 183.35	0.53% ± 0.470%



Future Work

- There is evidence to show that cavitations generated by a laser may show isobars within the chamber. Using micro to nano scale actuation and this fact, better pressure profiling may be achieved.
- Also, signal processing is in development to use audio count rate measurement.

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