U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI | Advanced Sensors and Instrumentation

High Temperature Embedded-Integrated Sensors

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

October 24 – 27, 2022

Research Assistant: Mr. Nicholas Garcia

North Carolina State University, Mechanical & Aerospace Engineering Dept.

Principal Investigator: Dr. Xiaoning Jiang | Program Manager: Daniel Nichols

Project Overview

Research Scope:

- High temperature non-invasive sensing including
  - Liquid level sensing
  - Vibration sensing
  - NDT, stress sensing
  - Corrosion resistant coatings
  - Wireless relay of sensor data

In this presentation we will primarily discuss:

- Mechanical vibration sensing/accelerometer
  - HT resistant Aluminum Nitride (AlN) receiver
  - Detects the mechanical vibrations of a steel vessel
  - Commercial sensor provides comparison (68 mV/g)
  - Test AlN response between 150 Hz – 350 Hz at 50 °C – 200 °C
- Photoacoustic high temperature transducer
  - Liquid metal layer (~150 um) absorbs laser light and transmits ultrasound (US) in steel
  - Fields metal high boiling point and coeff. of volumetric thermal expansion make it useful
  - Surface is highly reflective, but addition of carbon nanoparticles strengthens ultrasound
  - Resilient at high temperatures and able to recover lost strength after cooling

Project Overview

- **Participants (2022)**

Xiaoning Jiang, **PI**, NC State University (NCSU) (Tasks 1, 2 & 3), **Mohamed Bourham**, Co-PI, NCSU (Tasks 2 & 3), **Mo-Yuen Chow**, Co-PI, NCSU (Tasks 2 & 3)

Sean Kerrigan, PhD student, NCSU (Tasks 2 & 3), **Nicholas Garcia,** PhD student, NCSU (Tasks 2 & 3)**, Geet Khatri,** PhD student, NCSU (Tasks 2 & 3).

Schedule

Year	Task	Role	Responsibility	Note
1 & 2	HiTEIS design and development	HiTEIS development	X. Jiang	NCSU
		Sensor material radiation resistance	L. Winfrey	PSU
2, 3 & 4	HiTEIS Integration and characterization	Wireless communication system	M. Y. Chow	NCSU
		HiTEIS integration & characterization	X. Jiang & M. Bourham	NCSU
2, 3, 4, & 5	Development of embedded sensors and laser ultrasound	Laser ultrasound transducer development	X. Jiang	NCSU
		Sensor radiation/corrosion resistance	M. Bourham	NCSU
		Wireless communication for embedded sensors	M. Y. Chow	NCSU

Technology Impact

- Structural Health Monitoring (SHM)
  - HiTEIS would operate in the reactor compartment on appropriate parts of reactor structure.
  - Improved methods of detecting structural characteristics in a non-invasive rather than an invasive manner.
  - New methods of high temperature ultrasound transmission.
  - Monitoring of parameters such as liquid level, structural integrity, vibration/acceleration, stress, and others.
- High temperature non-destructive testing (NDT)
  - Small ultrasound transducer that may be placed in harsh environments to monitor component integrity.
- Stakeholders include but not limited to:
  - Dept of Energy, reactor plant contractors, reactor plant operators, and the general public.
- Accurate, non-invasive sensing may result in more efficient and safer maintenance evolutions for reactor servicing planners and crews.

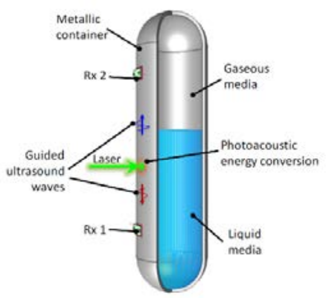
Results and Accomplishments

❑ Liquid level sensing

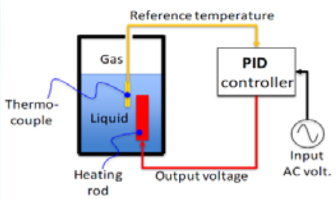
- AlN high temp sensors
- Steel vessel (2.4 mm thick wall)
- Filled with HT fluid to some level between the sensors
- Exterior laser US
- No direct sensor contact with fluid
- Heater and PID control temperature 50 – 200 °C
- US energy partially absorbed by the fluid media

❑ Results

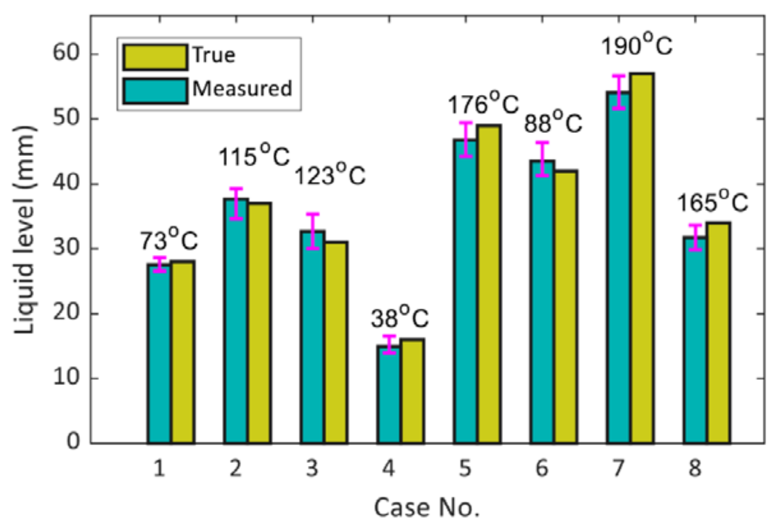
- Linear level vs. temp relationship at room temp
- Nonlinear relationship between temperature and level at high temperature
- Repeatability within 4.2 mm
- %error of within 4.5%



Vessel and sensors



Experimental diagram



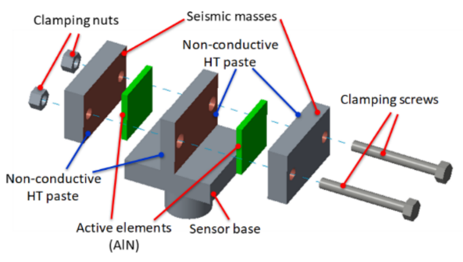
Results of liquid level sensing

❑ Vibration sensing

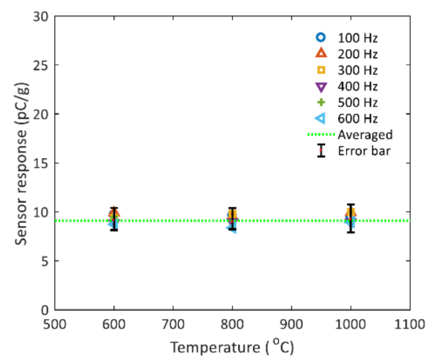
- Steel base with two seismic masses
- Screws and nuts for mechanical clamping
- Two AlN HT resistant piezoelectric sensors
- Sensing range up to 600 Hz
- Two experimental configurations

❑ Results

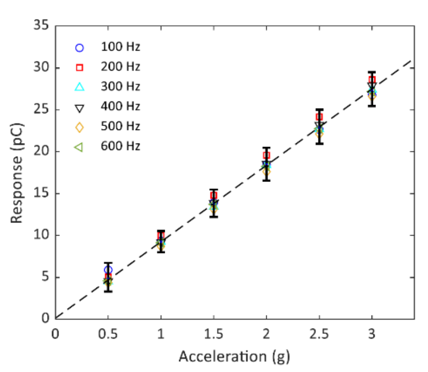
- AlN performance consistent in high radiation flux
- Sensitivity of 9.3 pC/g
- Consistent over HT at 100 Hz – 600 Hz
- Linear relationship between sensor response and acceleration



Sensor assembly (exploded view)



Sensor response over temperature range

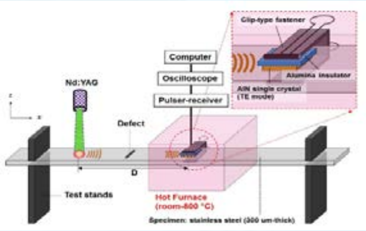


Sensor response over g-force range

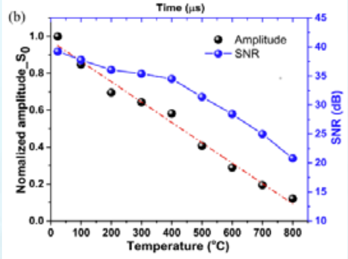
Results and Accomplishments

- **NDT Sensing**
  - Thin steel plate (300 μm)
  - AlN receiver was clamped to compensate for HT thermal expansion
  - Artificial defect, machined (500 μm wide, 20 mm long)
  - AlN sensor was heated using a furnace

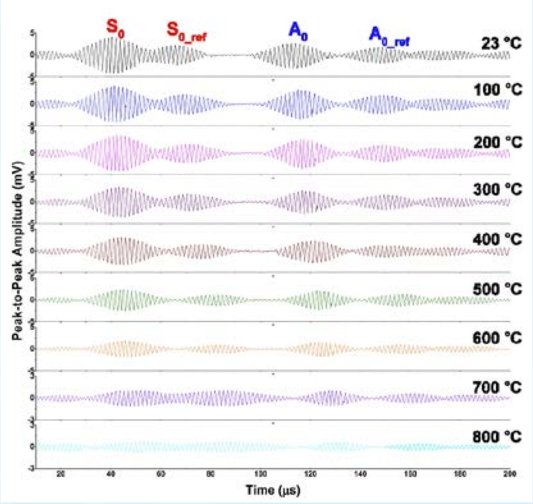
- **Results**
  - Thin plate allows activation of S0 and A0 lamb wave modes and excludes others
  - AlN sensor picked up laser ultrasound (LUS) up to 800 °C
  - SNR ratio drops from ~40 dB at RT to ~20 dB by 800 °C
  - ToF of waves increases w/r to spacing of laser and receiver



Experimental setup



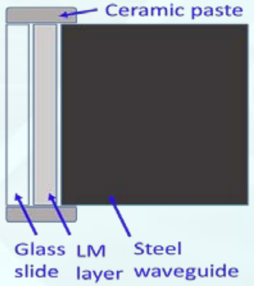
SNR analysis at high temp

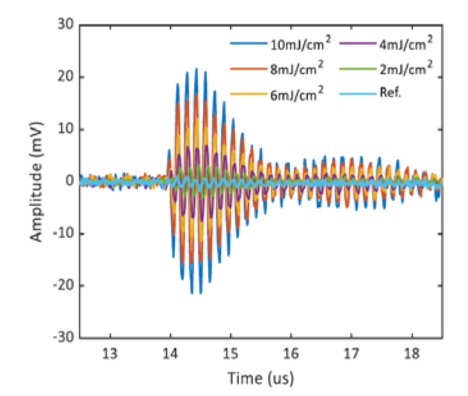


Wave packet NDT analysis

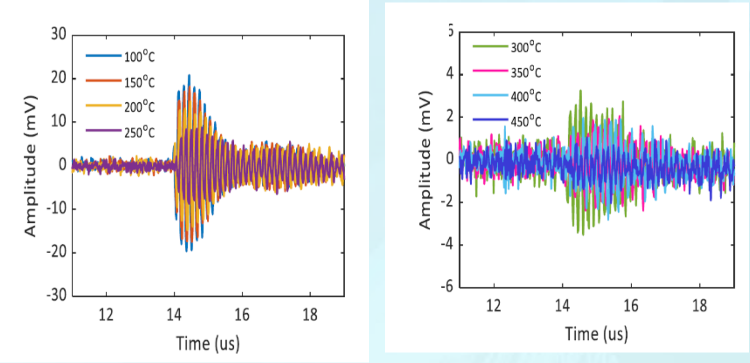
- **HT liquid metal transmitter**
  - Planar layer of Fields Metal under glass
  - Thermal expansion is suitable
  - Optical absorbance is low
  - Can be stimulated by laser fluence

- **Results**
  - Viable ultrasound up to 450 °C
  - HT resistant but degrades quickly
  - Center frequency of 6 MHz
  - Best amplitude at 10 mJ/cm^2 (~40 mV$_{pp}$)





LM fluence test of transducer

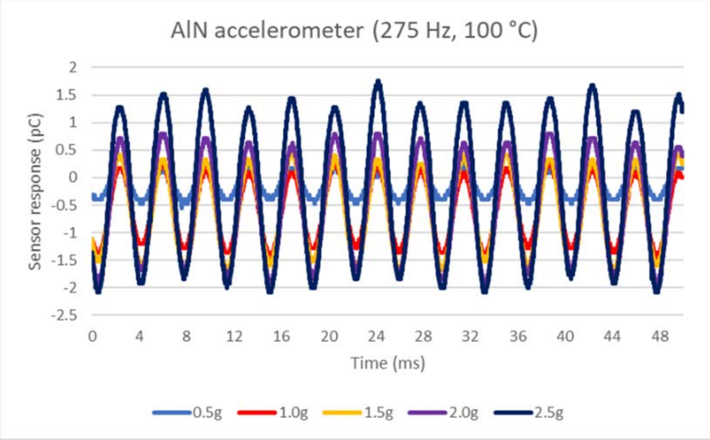


LM heating test of transducer

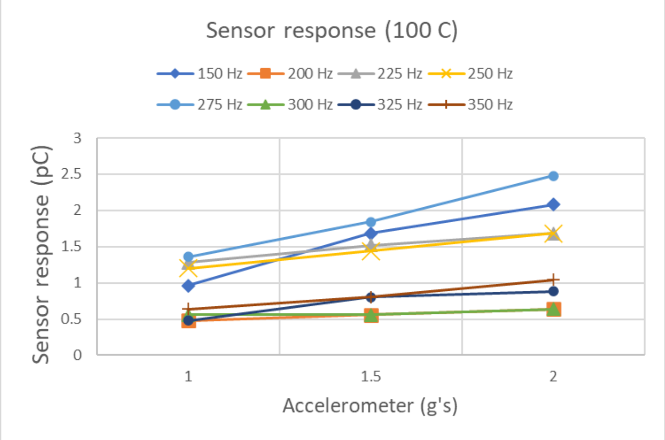
Results and Accomplishments

- **Vibration sensing on mockup**
  - Single AlN sensor mounted on mockup vessel
  - Commercial sensor operates in tandem on the shaker to measure g-forces
  - Heated fluid in vessel allows for HT testing
  - Function generator varies frequency from 150 – 350 Hz
  - PID controller and immersion heater

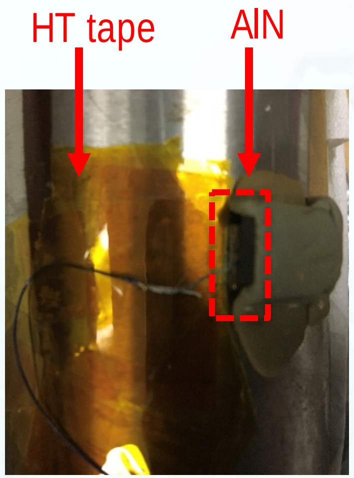
- **Results**
  - HT test up to 200 °C
  - Tested AlN response in multiple cases and temperatures
  - Sensitivity is lower while mounted directly on vessel
  - Best response at 100 °C
  - Continuing to process data

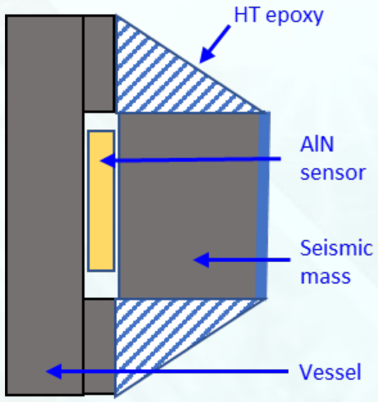


Sensor response at 275 Hz, 100 °C

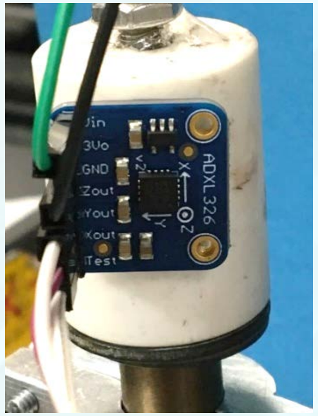


Sensor response across 150 – 350 Hz, 100 °C

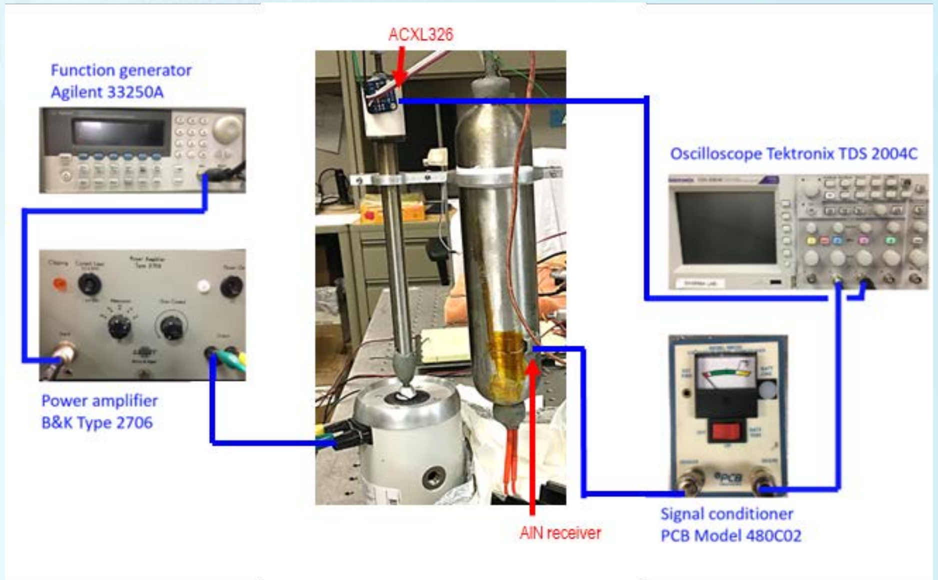




Cross section of AlN attachment



Commercial sensor attachment

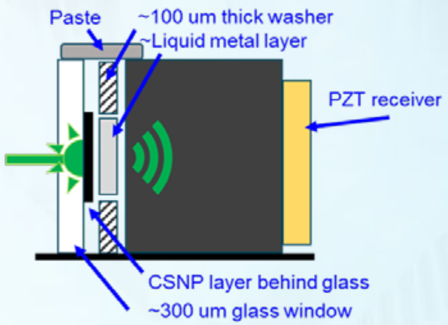


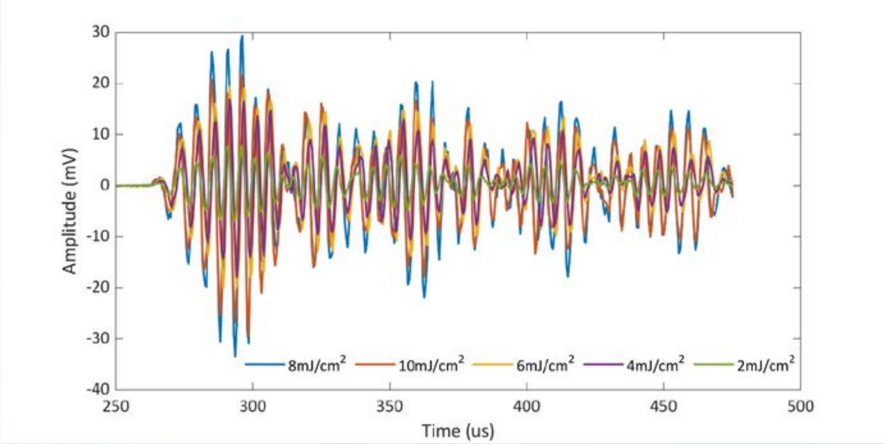
Experimental setup and component connections

Results and Accomplishments

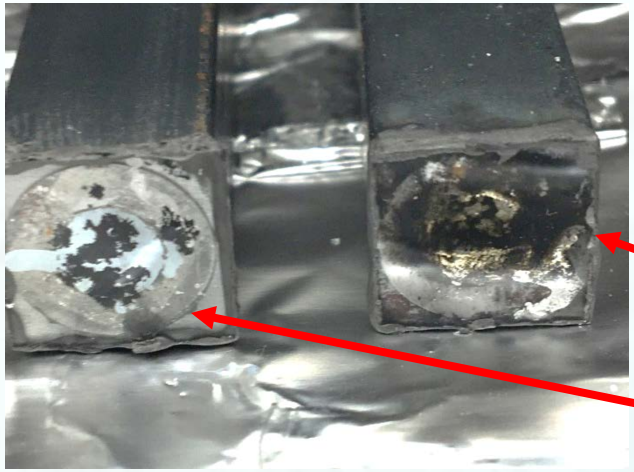
Liquid Metal Laser Ultrasound
- LM layer ~143 um thick
- Carbon nanoparticles enhance low frequency ultrasound
- Ref case is ~10 mJ/cm^2
- Nanoparticles are difficult to distribute
  - Clusters
  - Particle layer
  - Glass deposit

Results
- Transducer lasts for weeks and multiple tests
- Transducer recovers signal strength by cooling
- Heat test 100 – 300 °C at 40 dB gain
- Fluence test from 2 – 10 mJ/cm^2
- Strong improvement over reference case



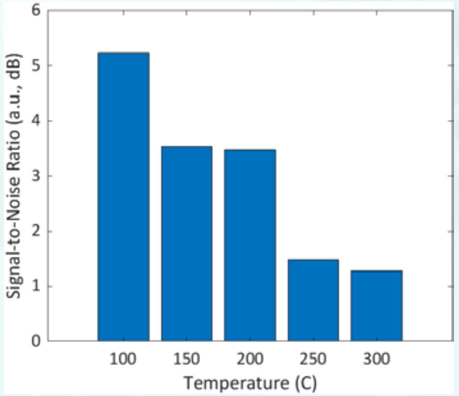


Fluence test results (2 mJ/cm^2 through 10 mJ/cm^2)

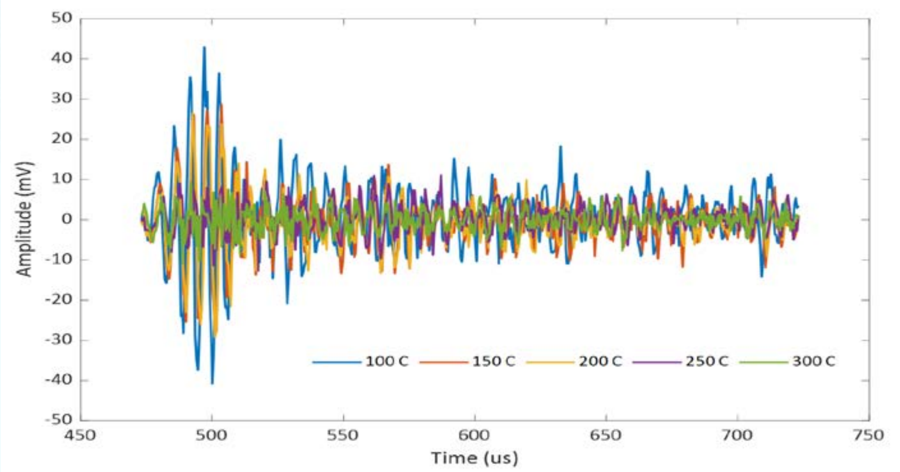


Fabricated on July 13th and used in multiple tests.

Newly fabricated transducer.



Signal-to-Noise Ratio graph



Heat test results (100 °C through 300 °C)

Concluding Remarks

- This project has investigated high temperature sensing through:
  - Non-invasive liquid level sensing, with reported 4.5% error.
  - High temperature NDT using ToF of S0 and A0 wave packets.
  - Application of AlN as a HT resistant piezoelectric transmitter/receiver, consistent sensitivity (9 pC/g) in high temperature and high radiation conditions.
  - Application of AlN as a HT resistant accelerometer/vibrometer.
  - Potential use of liquid metal as a sensitive HT resistant transmitter.
  - Improved durability of liquid metallic transducer by addition of carbon nanoparticles and retaining ring. Distribution of carbon particles is challenging and investigation continues to determine which is the best method.

Dr. Xiaoning Jiang
Principal Investigator | Professor
Email: xjiang5@ncsu.edu
C (919)-515-5240
ORCiD: 0000-0003-3605-3801
Website: https://www.mae.ncsu.edu/jiang/

Concluding Remarks

Publications (to date):

1. T. Kim, J. Kim and X. Jiang, "AlN Ultrasound Sensor for Photoacoustic Lamb Wave Detection in a High-Temperature Environment," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 65, no. 8, pp. 1444-1451, Aug. 2018
2. J. Kim, H. Kim, W. -Y. Chang, W. Huang, X. Jiang and P. A. Dayton, "Candle-Soot Carbon Nanoparticles in Photoacoustics: Advantages and Challenges for Laser Ultrasound Transmitters," in *IEEE Nanotechnology Magazine*, vol. 13, no. 3, pp. 13-28, June 2019, doi: 10.1109/MNANO.2019.2904773.
3. T. Kim, W. Chang, H. Kim, and X. Jiang, "Narrow band photoacoustic lamb wave generation for nondestructive testing using candle soot nanoparticle patches", Appl. Phys. Lett. 115, 102902 (2019) https://doi.org/10.1063/1.5100292
4. H. Kim, W.-Y Chang, T. Kim, S. Huang, X. Jiang, "Stress measurement of a pressurized vessel using candle soot nanocomposite based photoacoustic excitation," Proc. SPIE 10971, Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XIII, 109710G (1 April 2019); https://doi.org/10.1117/12.2515211
5. B. Balagopal, S. Kerrigan, H. Kim, M. -Y. Chow, M. Bourham and X. Jiang, "A Smart Sensor Prototype for Vibration Sensing in Nuclear Power Plants,"*2019 IEEE 28th International Symposium on Industrial Electronics (ISIE)*, 2019, pp. 1127-1132, doi: 10.1109/ISIE.2019.8781139.
6. H. Kim, T. Kim, D. Morrow, and X. Jiang, "Stress Measurement of a Pressurized Vessel Using Ultrasonic Subsurface Longitudinal Wave With 1–3 Composite Transducers," in *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 67, no. 1, pp. 158-166, Jan. 2020, doi: 10.1109/TUFFC.2019.2941133.
7. H. Kim. ”Design, Prototyping, and Validation of Noninvasive Sensors for Nuclear Power Plant Applications” , 2020. Internet resource.
8. H. Kim, W. Y. Chang, T. Kim and X. Jiang, "Stress-Sensing Method via Laser-Generated Ultrasound Wave Using Candle Soot Nanoparticle Composite," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 67, no. 9, pp. 1867-1876, Sept. 2020
9. H. Kim, K. Kim, N. Garcia, T. Fang, and X. Jiang "Liquid metallic laser ultrasound transducer for high-temperature applications", Appl. Phys. Lett. 118, 183502 (2021)
10. H. Kim, S. Kerrigan, M. Bourham and X. Jiang, "AlN Single Crystal Accelerometer for Nuclear Power Plants," in IEEE Transactions on Industrial Electronics, vol. 68, no. 6, pp. 5346-5354, June 2021
11. T. Kim, H. Kim and X. Jiang, “Laser ultrasonic defect localization using an omni-arrayed candle soot nanoparticle patch” Published 7 September 2021, © 2021 Japanese Journal of Applied Physics, Volume 60, Number 10
12. **(Submitted for publication)** H. Kim et al, Non-invasive Liquid Level Sensing with Laser Generated Ultrasonic Waves. SSRN. Submitted for publication September, 2022.

Dr. Xiaoning Jiang

Principal Investigator | Professor

Email: xjiang5@ncsu.edu

C (919)-515-5240

ORCiD: 0000-0003-3605-3801

Website: https://www.mae.ncsu.edu/jiang/

Thank You