Computational Modeling of High-Temperature MEMS Sensor Array for Ultrasonics and Acoustic Emission in Structural Health Monitoring of High Temperature Advanced Reactor Pipes

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ABSTRACT

In recent years, development of advanced liquid metal thermal hydraulics enabling technologies has become increasingly important for commercial deployment of advanced reactors. One of the challenges is the need for reliable structural health monitoring (SHM) systems capable of detecting early signs of critical metallic structure failure in high-temperature environments. To address this need, we investigate a new type of piezoelectric microelectromechanical system (MEMS) sensor that can continuously operate at high temperatures. We study the use of a circumferential array of high-temperature piezoelectric MEMS sensors for deployment on a piping system of Argonne's Mechanisms Engineering Test Loop (METL) liquid sodium thermal hydraulic facility. The MEMS sensors consist of square silicon carbide wafer with 5 mm length and aluminum nitride as piezoelectric element. These materials were shown to be resilient to ionizing nuclear radiation in prior studies. The sensors are arranged in a circumferential array on the pipe surface to enable dual ultrasonics and acoustic emission sensing. To determine the optimal number of transducers needed to achieve the excitation of Lamb wave for ultrasonics testing, we created a Multiphysics numerical model to simulate the coupling between the sensors and the pipe. Overall, the results of the study demonstrated the potential of using high-temperature piezoelectric MEMS sensors for SHM in liquid metal reactors. By detecting critical structure failure in high-temperature environments, these sensors could help reduce the risk of forced reactor shutdown and minimize operation and maintenance costs.

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INTRODUCTION

Non-destructive evaluation (NDE) techniques have become increasingly important in the field of structural health monitoring (SHM), especially in industries such as aerospace and nuclear, where the reliability and safety of structures are of utmost importance [1]. Ultrasonics and acoustic emission are two commonly used NDE techniques that have demonstrated significant capabilities in detecting and characterizing material defects of piping systems. However, the use of these contact techniques in harsh working conditions, such as those encountered in the advanced liquid metal reactor technologies, poses significant challenges to their reliability and effectiveness [2, 3, 4].

The Mechanism Engineering Test Loop (METL) is used to test advanced technologies in a high-temperature sodium environment, where experiments are critical to the successful operation of sodium-cooled fast reactors. It presents specific challenges for NDE techniques to test the sodium filled piping system at up to 650°C [5]. Researchers have developed aluminum nitride (AlN) based MEMS sensors capable of withstanding high-temperature conditions. This material has been shown to be resilient to ionizing nuclear radiation in prior studies [6]. AlN is a piezoelectric material with excellent high-temperature stability, making it an ideal material for the fabrication of NDE sensors. Kim et al. conducted AlN single-crystal plate to detect photoacoustic Lamb waves generated by thermal expansion in high-temperature conditions up to 800°C with high sensitivity [7]. By combining the high-temperature piezoelectric response of AlN with the impressive mechanical and chemical properties of silicon carbide (SiC) as the structural layer, Esteves et al. developed such MEMS devices that could endure at 950°C and in situ testing up to 500°C [8].

The mechanical properties of a material being tested can be altered by high temperatures, which can result in changes in vibration performance and affect acoustic signals [9, 10, 11]. However, temperature is not the only factor to consider when analyzing wave propagation in complex piping systems. The internal fluid flowing through the pipes, as well as the presence of piping bends and elbows, can also have an impact on wave behavior. Sato et al. studied guided waves in fluid-filled pipes and observed differences in dispersion curves with and without fluid [12]. Baik et al. reported that the attenuation of sound in liquid-filled pipes increased with frequency, while the phase velocity and group velocity changed differently [13]. Additionally, guided waves passing through elbows experience wave focusing and mode conversions, which must be considered in the detection process [14]. Taken together, these findings suggest that wave propagation in piping systems is influenced by multiple factors, and a comprehensive understanding of these factors is essential for accurate defect detection and localization.

This paper aims to investigate the potential use of MEMS sensor arrays for dual sensing of ultrasonic and acoustic emission testing in METL pipes. The effects of high temperature, flowing sodium fluid, and pipe elbows on wave propagation and attenuation can be used to guide further experiments in the field of non-destructive testing of METL.

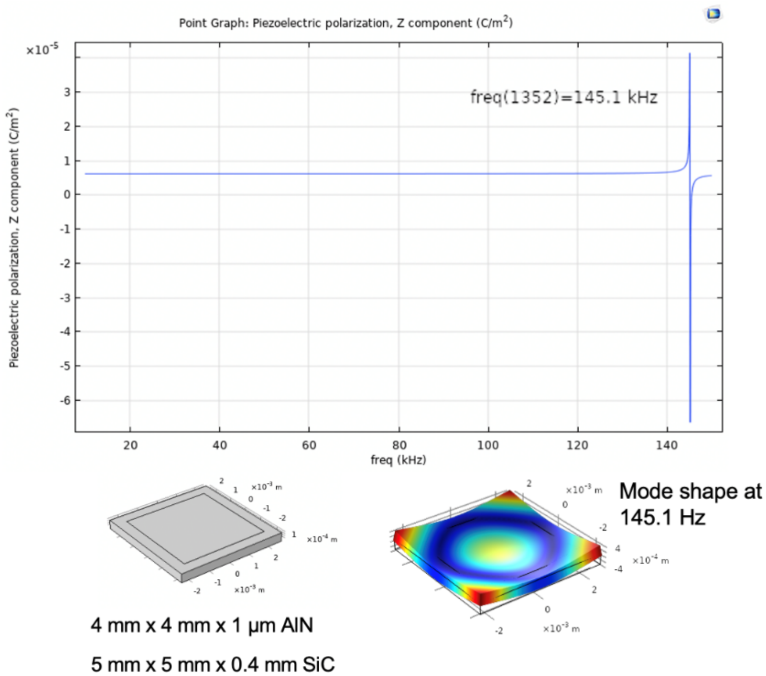

Figure 1. Sensor dimension and frequency response

NUMERICAL MODELS

The SCH 40S pipe in METL has an outer diameter of 3.34 cm (1.315 inch), with a thickness of 0.34 cm (0.133 inch), manufactured from 316 stainless steel. The AlN based MEMS sensor is designed as the AlN square film of 4 mm length and 1 μm thickness; SiC as the structural layer of 5 mm length and 0.4 mm thickness, coupled under the AlN as illustrated in Figure 1. The finite element-based numerical models are built using COMSOL Multiphysics to simulate wave propagation in the time domain. To ensure convergence based on wave frequency, optimized time step and mesh size are determined. Linear tetrahedral mesh elements are used as shape functions. Additionally, perfectly match layers (PML) were added to the two ends of all the geometries of the numerical models to absorb and reduce extra vibration and reflection.

Dual Ultrasonics and Acoustic Emission Sensing Using High-temperature MEMS Sensor Array

To verify the effectiveness of ultrasonic excitation, we modeled a sine wave with a frequency of 100 kHz and 5 cycles that was applied to the AlN layer perpendicular to the tangent plane of the pipe. As shown in Figure 2, the four-sensor configuration did not produce pure plane waves, whereas the eight-sensor configuration generated uniform displacement across the circumference, enabling the monitoring of the entire pipe circumference. When performing a single-channel measurement in METL, eight

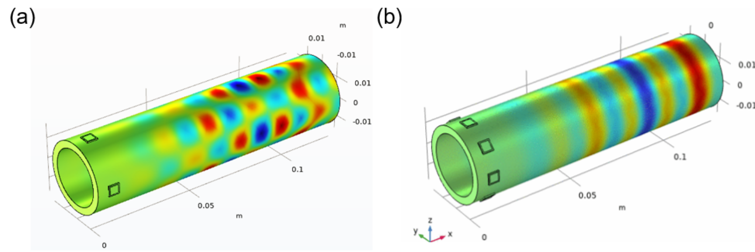

Figure 2. Numerical models determine the number of sensors at the pipe circumference to generate plane waves, (a) four sensors and (b) eight sensors.

sensors will be placed around the pipe circumference and connected in parallel. By using an eight-sensor array, Lamb wave packets were successfully generated, and axial displacement was extracted at the right end, as depicted in Figure 3(a).

To verify the functionality of the MEMS array as receiver, a pencil lead break (PLB) signal was numerically introduced at the center of the pipe. The time dependence of the local surface deflection was modeled as PLB using the "cosine bell" function, with a maximum amplitude of 1 N, as described in Eq. 1 [15]. The function represents the PLB signal.

$$F(t)=\begin{cases} 0\ N,\ t\leq 0 \\ 0.5\text{-}0.5\times \cos\left(\dfrac{\pi\times t}{\tau}\right) N,\ 0<t\leq\tau \\ 1\ N,\ \tau\leq t\ (\tau=1\ \mu s) \end{cases} \tag{1}$$

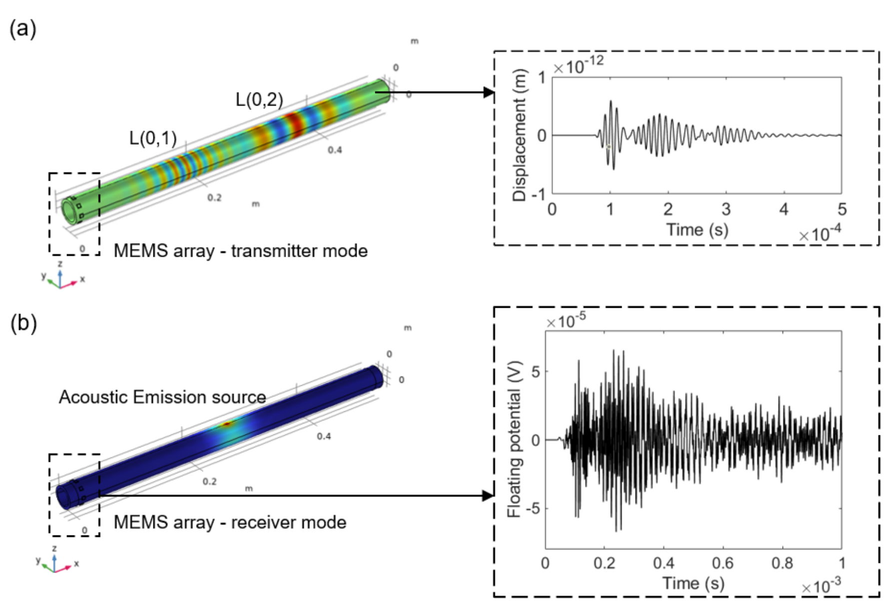

Figure 3. The dual functionality of MEMS array (a) the generation of pure Lamb wave modes with eight circular sensors positioned around the pipe circumference, (b) the simulation of acoustic emission signal, and acoustic emission signal detected by the MEMS array.

The output of the MEMS array in response to the PLB signal is presented in Figure 3(b). This demonstrates that MEMS sensor arrays can enable real-time, multi-parameter monitoring of wave propagation in piping systems. As a result, they offer a more efficient and comprehensive approach to both ultrasonic and acoustic emission testing.

Energy Leakage of the Ultrasonic Wave in Sodium-filled Pipe at High Temperature

The liquid sodium flowing through pipes can reach temperatures of 150°C to 650°C, which affects wave characteristics and attenuation. The numerical models used in this study consider two variables: the temperature-dependent properties of steel and liquid sodium. At room temperature (24°C), the mechanical properties of 316 stainless steel include a density of 7,950 kg/m^3, Young's modulus of 195 GPa, and Poisson's ratio of 0.26. At 650°C, these properties change to a density of 7,690 kg/m^3, Young's modulus of 148 GPa, and Poisson's ratio of 0.32. Liquid sodium at ambient pressure and 650°C has a density of 899 kg/m^3 and a speed of sound of 2,250 m/s. The numerical model of pipes filled with sodium was performed using the acoustic-structure interface to consider the interaction between solid and liquid, as shown in Figure 4(a). The excitation signal used in this study was a 100 kHz Hanning window signal with 5 cycles. Figure 4(b) shows the waveforms recorded at 0.6 m from the excitation. The temperature change causes a 12.6% reduction in signal amplitude, while the presence of sodium and temperature further decreases the amplitude by 15.3%. Consequently, to account for the signal decay resulting from temperature-dependent properties and leak of ultrasonic waves into sodium, a safety margin of approximately 30% should be added to the room temperature measurements.

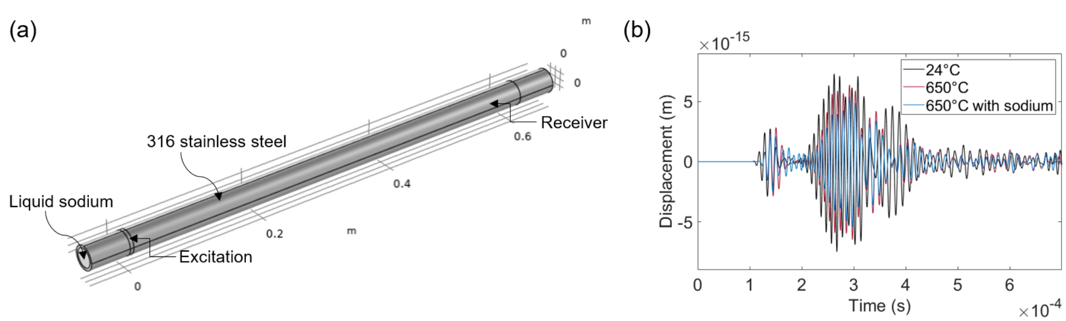

Figure 4. Influence of temperature and liquid sodium on wave propagation, (a) numerical models, and waveforms received 0.6 m away from the excitation, (a) hollow pipe at 24°C (b) hollow pipe at 650°C (c) pipe filled with liquid sodium at 650°C.

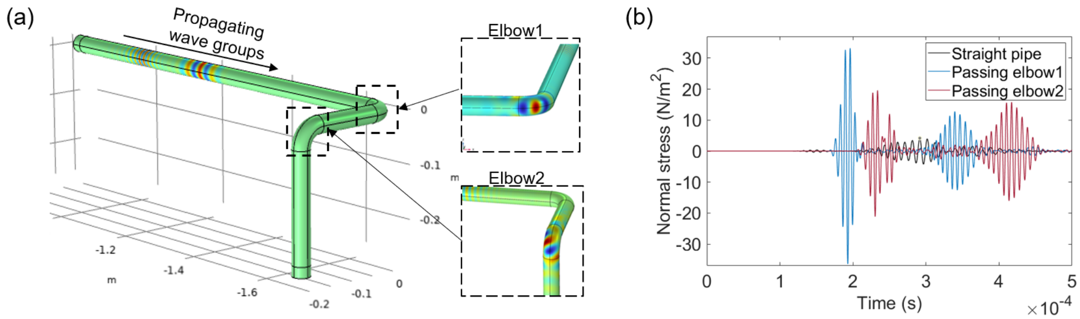

Figure 5. Influence of elbows on wave propagation, (a) wave propagating on the straight pipe and wave focusing when passing the elbow1 and elbow2; (b) comparison of time domain signals with respect to the influence of the existence of elbows.

Elbow Effect on Wave Propagation

To investigate the impact of piping turns and elbows on wave propagation, a twisted piping system was modeled, where a Hanning window excitation signal with 5 cycles at 100 kHz was applied at the left edge of the pipe. The resulting wave groups were allowed to propagate through the piping system. Figure 5(a) illustrates wave focusing on the outer side of two elbows. To further analyze wave propagation, time-domain signals were extracted at specific locations. As shown in Figure 5(b), signals were obtained at 1.5 m from the excitation, at the lower edge of elbow1, and at the lower edge of elbow 2. The amplitude of the signal increased nearly 8 times compared to the signal before passing elbow1, owing to wave focusing on the elbow. However, due to distortion and wave conversion occurring as the wave propagated through elbow 2, the amplitude reduced by 40%. Despite this, the amplitude at the lower edge of elbow 2 remained 4 times larger than that observed in the straight pipe. Overall, both the geometry of the pipe and the presence of elbows can create a waveguide with a natural amplifier in the piping system.

CONCLUSIONS

We developed COMSOL numerical models to study performance of circumferential sensor array of MEMS ultrasonic sensors made from AlN and SiC, with up to eight sensors employed depending on the pipe size. The materials of ultrasonic sensors are resilient to high temperature and ionizing nuclear radiation. The influence of temperature and flow of liquid sodium in the pipes on ultrasonic wave propagation, as well as the impact of elbows in the piping system are incorporated. Signal decay caused by temperature-dependent properties and leakage of ultrasonic waves into liquid sodium should be considered adding 30% margin for sensor arrangement. The piping elbows focus ultrasonic wave which avoids the energy leakage from mode conversion, with the relatively small diameter, making the piping system an efficient waveguide. As a result, the MEMS sensor array promises to provide an efficient approach to dual ultrasonic and acoustic emission nondestructive testing of high temperature pipes.

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