

High temperatures health monitoring of the condensed water height in steam pipe systems

Shyh-Shiuh Lih, Yoseph Bar-Cohen, Hyeong Jae Lee, Mircea Badescu, Xiaoqi Bao,
Stewart Sherrit, Nobuyuki Takano, Patrick Ostlund, and Julian Blosiu

Jet Propulsion Laboratory/California Institute of Technology, MS 67-119, 4800 Oak Grove Drive,
Pasadena, CA 91109-8099, 818-354-0784, lih@jpl.nasa.gov, Web: <http://ndea.jpl.nasa.gov>

ABSTRACT

Ultrasonic probes were designed, fabricated and tested for high temperature health monitoring system. The goal of this work was to develop the health monitoring system that can determine the height level of the condensed water through the pipe wall at high temperature up to 250 °C while accounting for the effects of surface perturbation. Among different ultrasonic probe designs, 2.25 MHz probes with air backed configuration provide satisfactory results in terms of sensitivity, receiving reflections from the target through the pipe wall. A series of tests were performed using the air-backed probes under irregular conditions, such as surface perturbation and surface disturbance at elevated temperature, to qualify the developed ultrasonic system. The results demonstrate that the fabricated air-backed probes combined with advanced signal processing techniques offer the capability of health monitoring of steam pipe under various operating conditions.

Keywords: High Temperatures (HT), HT piezoelectric transducers, Fluid height monitoring, health monitoring, monitoring steam condensation, Sensors

1. INTRODUCTION

Health monitoring systems are used for many applications and the focus of this paper is on steam pipes. Generally, steam pipes are used in various major cities in the world. The system that is operated in Manhattan, New York City is managed as a district heating system carrying steam from central power stations under the streets to support heating, cooling, or supply power to high rise buildings and businesses. Health monitoring of such systems is critical to assure their safe operation. Excessive rise in the level of condensed water inside a steam pipe is a source of concern due to the possible excitation of water hammer effects that may lead to serious consequences including damaged vents, traps, regulators and piping. The water hammer effect is caused by accumulation of condensed water that is trapped in horizontal portions of the steam pipes. In order to prevent this from occurring, an effective health monitoring system is required, where the system needs to be able to make height measurements while accounting for the effects of water flow and cavitation, and to have the ability to track the condensation of water through the steam pipe walls in real-time. In addition, the sensor needs to be operated at the harsh environments encountered in manholes, i.e., with elevated temperatures as high as 250 °C and high humidity [Bar-Cohen et al. 2010, 2011].

Making nondestructive measurements of the water height level inside a pipe, without modifications to the pipe, may be feasible using ultrasonic methods, such as ultrasonic pitch-catch and pulse-echo methods. A piezoelectric material is a key component in these ultrasonic systems, acting as both ultrasonic transmitter and receiver and its thickness determines the operational frequency of the transducer. The performance of ultrasonic transducer depends on the the properties of a piezoelectric material, such as electromechanical coupling and dielectric permittivity. In general, high-coupling piezoelectric transducer allow effective energy conversion between electrical and mechanical energy, improving overall transducer performance, such as transducer efficiency, sensitivity and bandwidth [Jaffe et al., 1971, Berlincourt, 1971, Newnham, 2005]. The dielectric permittivity of piezoelectric material is also an important consideration for the design of a transducer. In order to obtain the maximum transmit and receive sensitivity, the electrical impedance of the transducer should be close to the 50 Ohm electronics.

For use of the piezoelectric transducers at high temperature, however, other aspects need to be considered along with piezoelectric properties, such as phase transition, thermal aging, thermal expansion, electrical resistivity, chemical stability (decomposition and defect creation), and the stability of properties at elevated temperatures. Among them,

property degradation and phase transitions at elevated temperatures are the critical limitations as the transducer are permanently depolarized at a certain temperature, known as Curie temperature, and cannot be used for transducer applications. In practice, the operating temperature must be substantially lower than the Curie point in order to minimize thermal aging and property degradation. The piezoelectric materials that possess high Curie points $>500\text{ }^{\circ}\text{C}$ are available, such as tungsten bronze, bismuth layer (BLSF) or double perovskite layer (PLS) structures, LiNbO_3 and Quartz. However, the issues associated with these materials are the transducer properties are considerably lower than conventional piezoelectric material, such as lead zirconate titanate (PZT) [Damjanovic, 1998, Zhang et al., 2005, Ka'zys et al., 2008, Turner et al., 1994]. In fact, the health monitoring system working at high temperature $>200\text{ }^{\circ}\text{C}$ requires high performance ultrasonic transducers as the steam pipes involve several issues, such as the effect of the pipe curvature that caused wave losses and increased attenuation at high temperatures. These effects greatly reduce the signal-to-noise ratio, preventing the ultrasound wave from propagating through material mediums in steam pipe systems.

In addition to ultrasonic probe issues, the ultrasonic measurements may involve issues associated with the interference of the multiple reflections with the pipe bottom wall and the pipe-probe interface; interference with turbulence in the condensed water; scattering from potential sediments in the bottom of the pipe inner surface along the path of the wave and the presence of multiple reflections inside the condensed water, which requires effective signal processing technique to distinguish the reflections from the top and the bottom surfaces of the condensed water. The objective of this research was to develop high temperature ultrasonic probes that can sustain and operate at high temperature environment for use of health monitoring in steam pipe system, and to test the validity of developed computer program that can determine the height from the ultrasonic measurements in real time while accounting for the effects of cavitation and wavy water surface.

2. THE PULSE-ECHO SYSTEM

For the monitoring of steam pipes, two techniques were considered: pitch-catch and pulse-echo method. Pitch-catch method involves sending waves in an angle and receiving the reflections at the same angle at the opposite side of the surface normal. For this purpose, two separate probes are used and the piezoelectric crystals that generate and receive the wave are mounted side-by-side at an angle to the surface of the water. When the wave impinges onto an interface (the pipe or the water) surface, refraction occurs at an angle that is determined by the related acoustic velocities. When the wave impinges in an angle over interface with solid material, shear and longitudinal modes are generated. In contrast, the pulse-echo uses the same probe for both transmitter and receiver of the sound waves. For the purpose of this test, the wave path should be normal to the interface surface. The value of the height is the time multiplied by the wave velocity divided by two (taking into account the wave path back and forth thru the water bulk). Of the two methods, pulse-echo provides greater flexibility in measuring the height since there is no reliance on receiving the reflection at a specific angle [Schmerr et al., 2007]. Thus, in this study, the pulse-echo method was chosen to investigate the ultrasonic distance measurements at high temperatures. An illustration of the proposed health monitoring system that is currently developed are demonstrated in Figure 1, which shows the harsh environment and possible issues for health monitoring in steam pipe systems, such as high humidity, high temperature, and long cables effects, surface perturbation effects, the corrosion stability after long term use and etc. Although these issues are being considered, the work discussed here is mainly focused on the development and evaluation of the high temperature ultrasonic probes. Other issues related to the health monitoring system would be the subject of future publications.

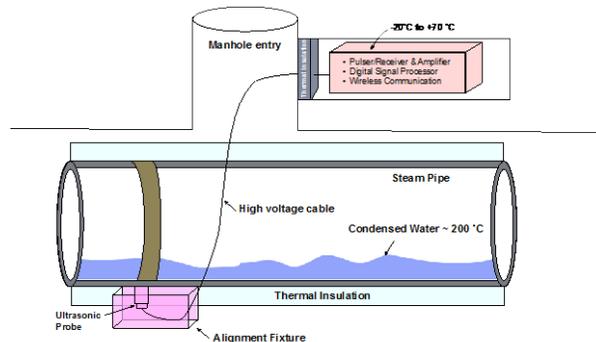


Figure 1: Illustration of the health monitoring system and the pulse echo method of measuring the condensed water height using time-of-flight of reflected ultrasonic waves.

2.1 High Temperature Probe

Given the criticality of the HT probe and the difficulties that were encountered in finding producers, the probes were made in-house. The general configuration of an ultrasonic probe is schematically shown in Figure 2. A primary consideration in the development of high temperature ultrasonic probe is the selection of the piezoelectric material. This choice determines the transducer performance including the electromechanical efficiency and thermal stability. The ideal material is the one possess high electromechanical coupling factor, which is generally proportional to piezoelectric coefficient, with high Curie temperature; however, there is a tradeoff between piezoelectric related properties and Curie temperature, e.g., the materials with high Curie temperature suffer from low piezoelectric related properties [Zhang et al., 2012, Zhang et al., 2011]. From this work, modified Navy type II, known as PZT5A, was selected because this material family offers a combination of high piezoelectric properties with high Curie temperature, allowing for ultrasonic probe with broad bandwidth and higher sensitivity over a broad temperature range. A study was conducted to determine the materials suitable for high temperature environment. Based on the preliminary results, 2.25 MHz, modified type II, EC-64 and TRS203, yield satisfactory probe bandwidth and sensitivity with high thermal stability up to 250 °C. (EC-64 is made by ITT Exelis - Acoustic Systems, Salt Lake City, UT, and TRS203 is made by TRS technologies Inc., State College, PA). The room temperature properties of these materials are listed in Table 1. It is worth noting that although both ceramics showed similar transducer performance below 250°C, TRS 203 ceramics posses higher transition temperature compared to conventional type II cermaics, as demonstrated in Figure 3.

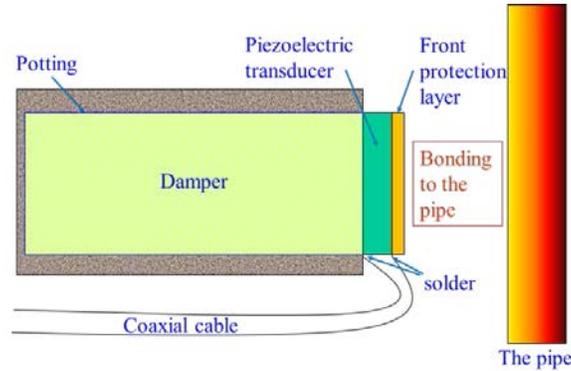


Figure 2: A schematic diagram illustrating the probe components (not to scale).

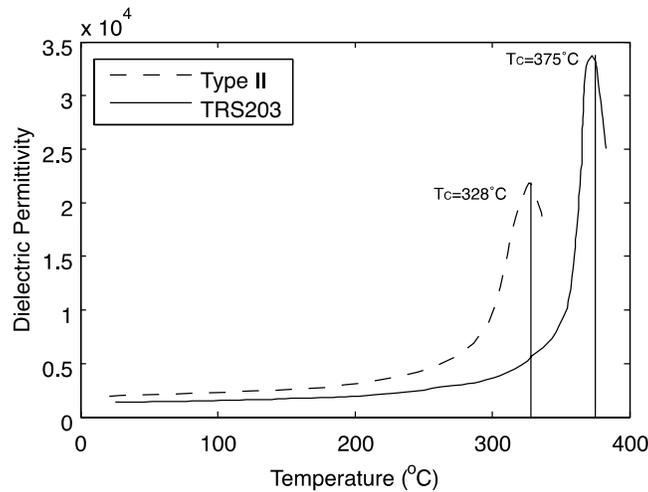


Figure 3: Temperature dependent dielectric properties of conventional Type II and TRS203 ceramics. The data was obtained from TRS Technologies Inc.

Table 1: Dielectric and electromechanical properties of EC-64 and TRS203 piezoelectric materials.

Transducer	T_c (°C)	ρ (g/cc)	c (m/s)	k_t	$\epsilon_{33}^T / \epsilon_0$	$\tan\delta$	c_{33}^D (GPa)
EC-64	350	7800	4452	0.45	1116	0.02	154
TRS203	375	7810	4547	0.45	1411	0.013	161

On the back of the piezoelectric transducer, a thick and high impedance layer, referred to as backing, was attached. The purpose of this backing is to reduce the duration of the ringing in order to be able resolve shallow water depths and have high resolution; however, the consequence is that it lowers the probe sensitivity. Therefore, the appropriate selection of backing layer is a key factor for successful and efficient design of ultrasound probes. Three different types of backing were used in this study: (A) high impedance polymer (mixture of 20 % of tungsten particles and 80% of high temperature epoxy, Duralco 4460, Cotronics Corp., Brooklyn, NY), (B) low impedance polymer (Duralco 4460), (C) no backing (air backing). The general properties of Duralco 4460 are listed in Table 2.

Table 2: Material properties of Duralco 4460.

Sample	T_m (°C)	ρ (g/cc)	c (m/s)	α (*10 ⁵ °C)	η (cps)
Duralco4460	600	1100	2200	5.4	600

NOTE: T_m is the maximum usage temperature, ρ is density, c is longitudinal sound velocity, α is thermal expansion, and η is viscosity.

On the front surface of a piezoelectric material, a thin layer is generally added to protect the transducer surface from the wear and corrosion when the probes are operating directly into high impedance load, such as steel pipe (~40 MRayl). However, when the probe is used in low impedance medium, such as water or tissue (~1.5 MRayl), the appropriate impedance and thickness of matching layer are required in order for efficient acoustic energy transfer between the probe and propagating medium. In general, the optimum impedance and thickness of the front layer can be obtained using the following equations:

$$Z_m = \sqrt{Z_t Z_p}, t_m = \frac{v_m}{4f_t} \quad (1)$$

where Z , f , t and v are acoustic impedance, operating frequency, thickness and sound velocity, respectively. The subscripts m , t , and p refer to matching layer, transducer layer and propagating medium, respectively.

Ultrasonic probe was assembled with the piezoelectric transducer attached to to the corrosion resistant stainless steel housing using an insulating commercial alumina adhesive paste (Resbond 989-FS, Cotronics Corporation of Brooklyn, NY, USA). This ceramic adhesive can provide high bond strength and excellent high temperature electrical, moisture, chemical and solvent resistance up to 1650 °C. The transducer was then electrically connected to a RG188 coaxial cable that can sustain temperatures much higher than 250 °C. (CB-188LN-100, CD International Technology, Inc., Santa Clara, CA). For soldering the wires, an Ersine multi core high temperature solder (Ersin Multicore 366 Solder, Westbury, NY) that has melting point of about 400 °C was used. The rear face of the housing was covered with aluminum using high temperature epoxy (Duralco 4460). The photo of fabricated ultrasonic probes is shown in Figure 4, whose design was used for high temperature ultrasonic testing.



Figure 4: Photograph of the produced thickness mode high temperature piezoelectric probe.

2.2 Evaluation of Ultrasonic Probe

The performance of the fabricated ultrasonic probes was investigated using conventional pulse-echo response measurements, in which the fabricated transducers were placed in aluminum plate and excited by a Panametrics pulser/receiver (model 5052PR, Panametrics Inc., Waltham, MA). The pulse echo responses of the transducers were recorded by receiving the reflected echo using a Tektronics model TDS2034B oscilloscope. Figure 5 shows the time domain pulse-echo waveforms and normalized frequency spectrum for prepared ultrasonic probe A, B and C. Because of a heavy backing ($Z_b=10$ MRayl), the probe A shows less ringing compared to other probes B and C, leading to high-transducer bandwidth, being on the order of 29.3 %. The short pulse of a heavy backed probe is because a heavy backing layer dampens the piezoelectric transducer to shorten the pulse length and ring down. However, it should be noted that the signal amplitude of probe A is significantly lower than a light backed (B) and air backed probes (C) because a large amount of power is lost in the backing layer. As expected, probe C exhibited highest signal amplitudes, being on the order of $0.54 V_{pp}$, which is one order of magnitude higher than that of probe A, whose signal amplitude is around $0.05 V_{pp}$. However, the pulse length and the bandwidth of the probe were increased and decreased, respectively. The measured properties made from three different ultrasonic probes are summarized in Table 3.

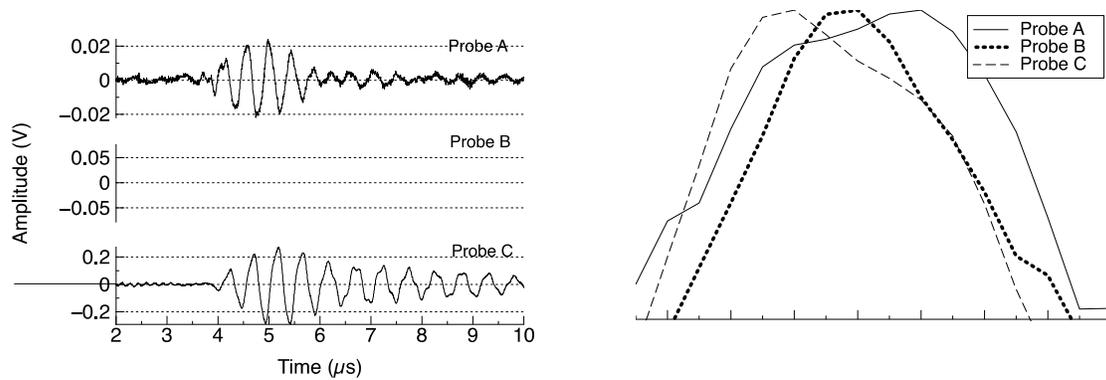


Figure 5: Time-domain (up) and frequency-domain (down) pulse-echo responses from a steel reflector in air, using probe A, probe B, and probe C.

Table 3: Measured acoustic performance for various ultrasonic probes. Z_b is backing material and F_c is center frequency BW is -6dB bandwidth and V_{pp} is peak-to-peak voltage. $M=10^6$.

	Probe A	Probe B	Probe C
Z_b (Rayl)	10M	2M	400
F_c (Mhz)	2.4	2.2	2
BW (5)	29.3	16.9	23.18
V_{pp}	0.048	0.15	0.544

3. HEALTH MONITORING OF STEAM PIPE

Successful operation for health monitoring system relies on the accurate determination of the time-of-flight (TOF), which is the time that ultrasound travels from the transmitter to the receiver after being reflected from the target. Assuming that the ultrasound speed c in propagating medium is a constant, the particular traveling distance can be determined using the equation of $\frac{1}{2} \cdot c \cdot \text{times TOF}$. ~~The process of acquiring the time of flight (TOF) data was done separately by manually uploading the data onto the computer using the downloaded data from the digital scope.~~ To automate the data acquisition and analysis that determines the target height directly by the computer, a LabView (National Instrument Corp., Austin, TX) computer program ~~was written~~, which consists of windowing, tracking and filtering the reflected signals was developed. Figure 6 shows the front panel of the developed LabVIEW program, which ~~used shows~~ various signal processing data analysis methods, such as autocorrelation function [Bracewell et al., 1978,

Cutard et al., 1994, Hertzog et al., 2004], Hilbert envelope [Boashash, 1992, Oruklu et al., 2009, Chen et al., 2005], and Fourier transform of Hilbert envelope [to calculate the in-situ water height](#). Note that the [signal data](#) processing algorithm automatically selects a suitable method depending on the target conditions in order to improve the accuracy of target height. The detail of this algorithm is the subject of another separated [paper](#).

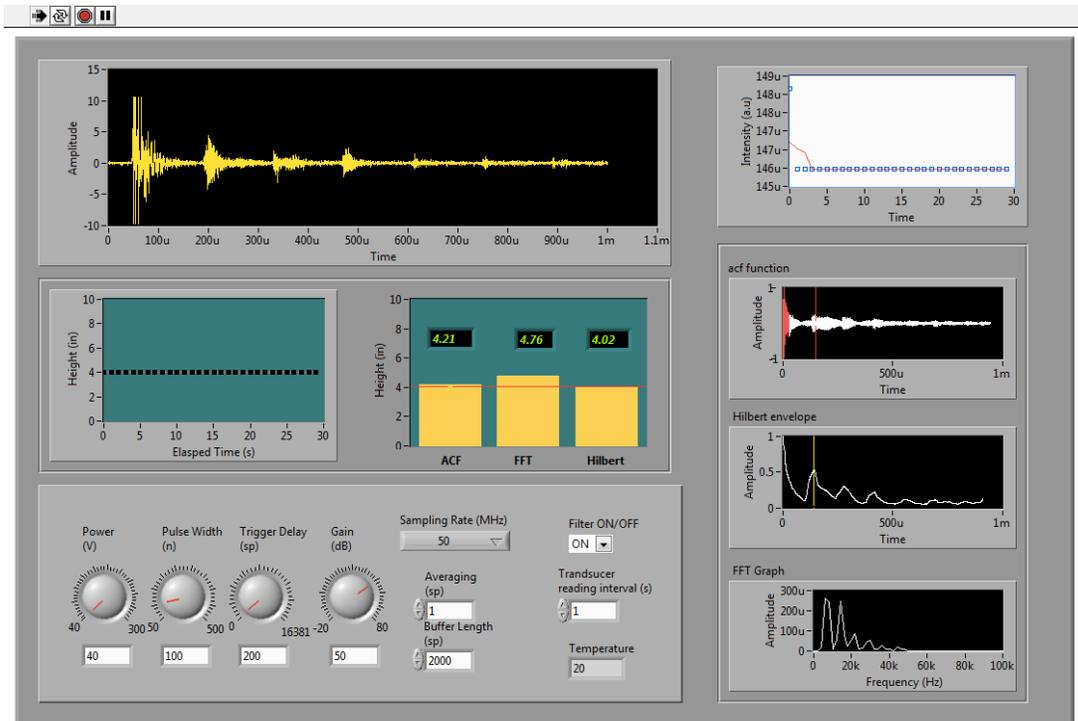


Figure 6: The front panel of LabVIEW program. Signal processing algorithms were implemented into the program.

To test the feasibility of the pulse-echo method for health monitoring in steam pipe, the ultrasonic probe was placed on the bottom of steam pipe. A high temperature chamber (Blue M 6680, Signal Test, Inc. San Diego, CA) was used in order to simulate the condition of 250 °C. Because of size limitation of the chamber, the pipe was cut half along its length and part of half pipe was used for high temperature testing. The pictures of the pipes are given in Figure 7. The pipe was filled with silicon oil (Clearco DPDM-400 Diphenyl-Dimethyl Silicone, Clearco Products Co., Inc. Bensalem, PA), which is able to sustain the temperatures from -20 °C to 250 °C. Note that the silicon oil was used as a substitute for condensed water in order to avoid safety issues related to steam and high pressure. The pulse echo responses of the probes were monitored and recorded by receiving the reflected echo using a LabVIEW-controlled computer. Since the oil has low heat conduction, where the thermal conductivity of the oil is 3.2×10^{-4} cal/cm/s/°C, a thermocouple was inserted into the oil and tracked the temperature as it has risen. The height of the silicon oil was measured while tracking the temperature of the chamber.

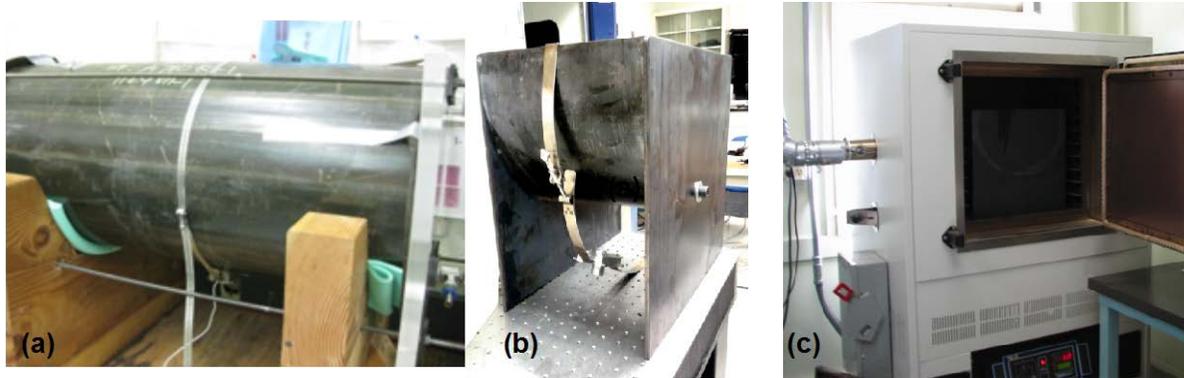


Figure 7: Photographs of steam full (a) and half (b) pipes. (c) is the photo of high temperature chamber (Model 6680). The pipes were made of A53B steel alloy having 40.6 cm (16 inch) diameter, 0.95 cm (3/8 inch) thick wall and 91 cm (3 ft) long with two end walls that simulate the steam pipe.

Various ultrasonic probes were tested to determine the optimum probe design. It was found that the reflected signals from the probe A and B were too low to allow for good height measurement accuracy. This is caused by a non-flat surface of the pipe, resulting in a large amount of energy loss through a pipe wall. In addition, the silicon oil has much higher sound of attenuation compared to water, where the room temperature attenuation (cm^{-1}) of water and silicon oil were reported to be $23 \times 10^{-17} f^2$ and $2 \times 10^{-12} f^{1.7}$, respectively [Schroeder et al., 2007]. In contrast, the air-backed probe showed the capability of transmitting and receiving signal through a pipe wall at high temperature due to their much higher sensitivities compared to others. The results of pulse-echo response using air-back probe at different temperatures are demonstrated in Figure 8.

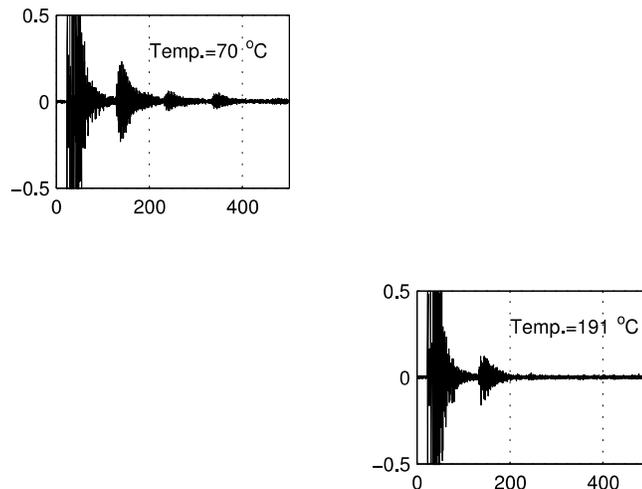


Figure 8 : Pulse-echo responses using air-backed probe from the half steam pipe that contains silicon oil at various temperatures.

One important consideration for health monitoring of steam pipe is the system needs to be able to make height measurements in real time while accounting for surface perturbation and cavitation effects as the surface of the condensed water in the manhole is not stationary due to various causes. In order to test the capability to handle surface and bulk interferences using the developed ultrasonic system, water height was monitored in real time while introducing bubbles into the path of the ultrasonic wave. The result is demonstrated in Figure 9, where the data was acquired while calculating a moving average curve. It was found that when the perturbation was introduced, there was water level fluctuation in the time window, the regions indicated by a double-headed arrow. The occurrence of statistical outliers observed in Figure 9 is because no reflection from the target surface occurs when the interface surface of the medium is

not normal to the wave path, resulting in over- or underestimation of height. The results demonstrate that the ultrasonic system offered good accuracy of the readings/measurement under simulated conditions.

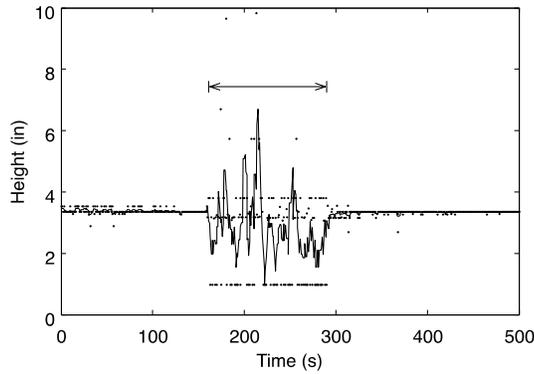


Figure 9: The height data obtained during surface rest and perturbation from bubbles, where the dot is the measured data while the line is the moving average curve. The height data during surface perturbation is indicated by a double-headed arrow.

For high temperature distance measurement, velocity recalibration is required as the material properties change with temperature [Canali et al., 1982]; generally, the sound velocity decreases and the material dimension expands as the temperature increases. In order to improve the accuracy, thermal effects need to be considered. Since the sound velocity of the oil at different temperatures are not available in the literature, the sound velocity of the silicon oil with temperature was estimated using the measured time-of-flight (TOF) and the pre-estimated height based on the thermal expansion coefficient of silicon oil and steel, which are $0.00073 \text{ cc/cc}^\circ\text{C}$ and $13 \text{ ppm}^\circ\text{C}$, respectively. The sound velocity in steel was assumed to decrease with 1 m/s per deg C . [Nowacki et al., 2009] Using the calculated velocity and curve fitting method, the sound velocity was obtained as a function of temperature. Figure 10 shows the change in oil height as a function of temperature with and without correction of sound velocity in steel and silicon oil. As expected, the height was increased with increasing temperature due to thermal expansion of the silicon oil, but note that the height was apparently overestimated without considering the temperature effect in sound velocity. Also note that the fluctuation in data point with temperature is due to the perturbations of the oil surface, which is caused by the air by the fan inside the high temperature chamber. The results demonstrate the suitability of developed probe and signal processing algorithms for the determination of the target height at high temperatures.

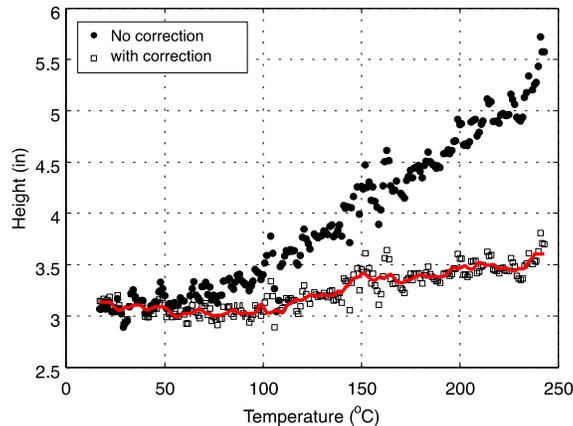


Figure 10: The determined height of silicon oil as a function of temperature using the developed software code. The red line is the moving-average of the determined data.

4. CONCLUSIONS

The detection of defects and the characterization of materials properties without affecting the integrity of the material or structure require the use of nondestructive testing and evaluation methods. Increasingly, in-service monitoring methods are used to monitor the health of structures or determine various properties. The pulse-echo technique for health monitoring of steam pipes at 250 °C has been found quite effective. Among various probe designs, 2.25 MHz air-backed ultrasonic probe was found to have good performance in terms of resolution and sensitivity, which allows for the measurements of target height at high temperature. The fabricated ultrasonic probe and data analysis algorithm also demonstrated the capability for the analysis of the acquired reflected waves in real time under the surface anomalies of medium as well as high temperature condition. Further investigations on the real-world signal from the condensed water in steam pipe system will be carried out to confirm the validity of the developed system.

ACKNOWLEDGEMENT

Some of the research reported in this Chapter was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with National Aeronautics and Space Administration (NASA). The authors would like to thank Edward Ecock, Josephine Aromando, and David Y. Low for their support of this task and for the inputs, comments and helpful suggestions regarding the health monitoring of the height of condensed water in steam pipes.

REFERENCE

- Bar-Cohen Y., S. Lih, M. Badescu, X. Bao, S. Sherrit, S. Widholm and J. Blosiu, "In-service monitoring of steam pipe systems at high temperatures" *Proc. SPIE*, 1-6 (2010).
- Bar-Cohen Y., S. Lih, M. Badescu, X. Bao, S. Sherrit, S. Widholm, P. Ostlund, and J. Blosiu, "High temperature monitoring the height of condensed water in steam pipes," *Proc. SPIE*, 7-10 (2011).
- Berlincourt, D., "Ultrasonic Transducer Materials," (New York: Plenum, 1971) Chap. 2. Piezoelectric Crystals and Ceramics, pp. 63-124.
- Boashash, B., "Estimating and interpreting the instantaneous frequency of a signal- Part 1: Fundamentals," *Proc. IEEE* 80, 520-538 (1992).
- Bracewell R., *The Fourier Transform and its Applications* (McGraw-Hill, London, 1978).
- Canali, C., G. De Cicco, B. Morten, M. Prudenziati, and A. Taroni, "A temperature compensated ultrasonic sensor operating in air for distance and proximity measurements," *IEEE Trans. Ind. Electron.*, IE-29(4), 336-341, (1982).
- Chen, T.-I., P.-W. Que, Q. Zhang, and Q.-k. Liu, "Ultrasonic signal identification by empirical mode decomposition and Hilbert transform," *Rev. Sci. Instrum.*, 76, 085109 (2005).
- Cutard T., D. Fargeot, C. Gault, and M. Huger, "Time delay and phase shift measurements for ultrasonic pulses using autocorrelation methods," *J. Appl. Phys.*, 75, 1909-1913 (1994).
- Damjanovic, D., "Materials for high temperature piezoelectric transducers," *Curr. Opin. Solid State Mater. Sci.*, 3, 469-473 (1998).
- Hertzog P., and G. Jordaan, "Auto correlation on ultrasonic doppler signals for pregnancy determination in sheep," in *AFRICON, 2004. 7th AFRICON Conference in Africa*, 1, 173 -178, (2004).
- Jaffe, B., Cook, W. R., and H. Jaffe, *Piezoelectric Ceramics* (New York: Academic, 1971).
- Kažys, R., A. Voleišis, and B. Voleišienė, "High temperature ultrasonic transducers: review," *Ultragasarsas (Ultrasound)* 63, 7-17 (2008).
- Newnham, R. E., *Properties of materials: anisotropy, symmetry, structure* (Oxford University Press, USA, 2005).
- Nowacki K., and W. Kasprzyk, "The Sound Velocity in an Alloy Steel at High-Temperature Conditions," *Int. J. Thermophys.*, 31, 103-112 (2009).
- Oruklu, E., Y. Lu, and J. Saniie, "Hilbert transform pitfalls and solutions for ultrasonic NDE applications," *IEEE International Ultrasonics Symposium (IUS)*, 2004 -2007 (2009).
- Schmerr, L. and S. Song, *Ultrasonic nondestructive evaluation systems: models and measurements* (Springer Verlag, 2007).
- Zhang, S. J. and Yu, F. P., "Piezoelectric materials for high temperature sensors," *J. Am. Ceram. Soc.*, 94, 3153-3170 (2011)

Zhang, S. J. and Li, F. , “High performance ferroelectric relaxor-PbTiO₃ single crystals: status and perspective,” J. Appl. Phys., 111, 031301 (2012)