COVER SHEET

Title: **An Ultrasonic Guided Wave Sensor for Gas Accumulation Detection in Nuclear Emergency Core Cooling Systems**

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ABSTRACT

This paper presents an ultrasonic guided wave based inspection methodology for detecting gas accumulation in the subject nuclear cooling pipe system to (1) perform in-situ measurement of the gas accumulation in order to determine if regulatory action is needed, and (2) permit verification that the subject systems are in compliance with the regulatory requirements. This approach is highlighted by a novel sensing technique using ultrasonic guided waves to perform long range long term in-situ inspection in combination with an advanced cross time-frequency analysis technique for an intelligent processing of the sensory data.

Keywords: embedded piezoelectric wafer sensors, ultrasonic wave, gas accumulation, cross time-frequency analysis, nuclear cooling pipe.

INTRODUCTION

Gas accumulation in the emergency core cooling systems including decay heat removal (DHR), and containment spray can cause water hammer, gas binding in pumps, and inadvertent relief valve actuation that may critically damage pumps, valves, piping, and supports and may lead to loss of system operability. Thus, the U.S. Nuclear Regulatory Commission (NRC) has issued a generic letter to address their concern about gas accumulation in cooling systems and temporal technical guidelines. However, there is no system wide method to determine the existence and location of gas voids and to quantify their volume accurately. Currently, some common methods to determine gas quantity are to measure the volume of gas released through vents or to determine the gas volume by ultrasonic testing (UT), but performances of existing techniques are not satisfactory to warrant reliable and safe operations of cooling systems in nuclear power plant.

The presented technique is a nondestructive reflectometry technique, which is based on the radar principle. This reflectometry method will utilize a relatively low energy ultrasonic pulse in order to transmit the pulse down a waveguide, and any impedance discontinuity generates a reflection that one can detect; the impedance discontinuity can be located and characterized from the reflected signal. In this application, the pipeline filled with cooling fluid corresponds to the waveguide, and the gas accumulation causes the impedance discontinuity as illustrated in the Figure 1. Like other reflectometry techniques, the amplitude of the reflected waveform can be used to measure the discontinuity, while the time delay of the reflected wave can be used to locate it. Particularly, the phase difference between the measured reflected signal and the reference signal will be related to the quantity of impedance discontinuity, which reflects the volume of gas accumulation in the pipes. The gas accumulation detector, piezoelectric wafer sensors, will be used to generate and/or receive propagating guided wave in the pipe structures. Due to the multiple mode and dispersive natures of guided wave, the analysis of guided wave detection is complicated. We will use cross time-frequency analysis to relate the wave signatures directly with the size of gas accumulation in the fluid. Cross time-frequency analysis is capable of preserving the time- and frequency- varying phase difference while traditional time-frequency distribution cannot. Simple controlled proof-of-concept small scale tests have been conducted to evaluate the efficiency of the presented ultrasonic detection method.

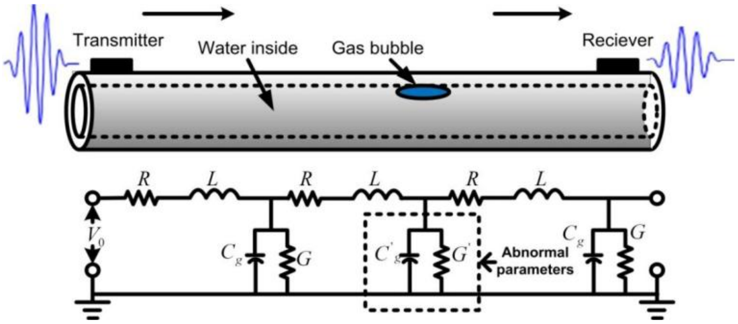
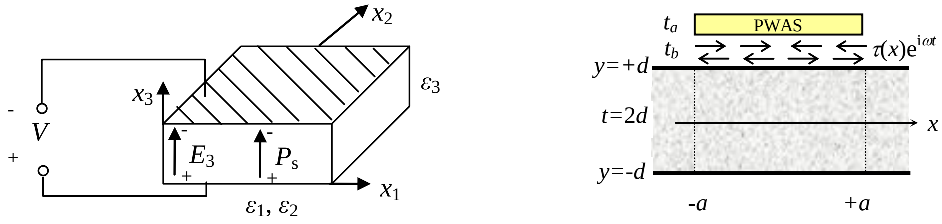


Figure 1 Transmission line model of the ultrasonic gas accumulation detection system

SENSING WITH PIEZOELECTRIC THIN WAFERS

Piezoelectric Wafer Sensors

Piezoelectric wafer active sensor (PWAS) functions as an active sensing device or network using piezoelectric principles and provides a tensorial relation between mechanical and electrical variables [1]. They can be permanently attached to the structure to monitor condition at will and can operate in propagating wave mode or electromechanical impedance mode. For a piezoelectric wafer as depicted in Figure 2a, an electric field, E_3, is applied parallel to the spontaneous polarization, P_s. If polarization P_s is aligned with the x_3 axis, then the application of field E_3 is created by applying a voltage, V, between the bottom and top electrodes. The situation of $E_3//P_s$ results in a vertical (thickness-wise) expansion $\varepsilon_3 = d_{33}E_3$ and a lateral (in plane) contractions $\varepsilon_1 = d_{31}E_3$ and $\varepsilon_2 = d_{32}E_3$ (d_{ij}: piezoelectric coupling coefficients). The strains experienced by PWAS are direct strains and such an arrangement can be used to produce thickness-wise and in-plane vibration of PWAS.



(a) (b)

Figure 2 (a) Induced strain response of PWAS; (b) interaction between the PWAS and the structure

The transmission of actuation and sensing between the PWAS and the host structure is achieved through the bonding adhesive layer. The adhesive layer (Figure 2b) acts as a shear layer, in which the mechanical effects are transmitted through shear effects. Using 1-D plane-strain analysis [2] for static morphing and the quasi-static low frequency vibrations, it has been found that the shear transfer process is concentrated towards the PWAS ends at large values of the shear-lag parameter. Shear-lag analysis indicates that at an infinitely large shear-lag parameter value, all the load transfer can be assumed to take place at the PWAS actuator ends. This leads to the concept of ideal bonding, also known as the pin-force model, in which all the load transfer takes place over an infinitesimal region at the PWAS ends, and the induced-strain action is assumed to consist of a pair of concentrated forces applied at the ends.

Electromechanical Impedance Spectroscopy

The principles of electro-mechanical (E/M) impedance method are illustrated in Figure 3. The drive-point impedance presented by the structure to the active sensor can be expressed as the frequency dependent variable $Z_{\mathrm{str}}(\omega)=k_{\mathrm{str}}(\omega)/j\omega=k_{\mathrm{e}}(\omega)-\omega^2{}_{\mathrm{m}}(\omega)+j\omega c_{\mathrm{e}}(\omega)$. Through the mechanical coupling between PWAS and the host structure, on one hand, and through the E/M transduction inside the PWAS, on the other hand, the drive-point structural impedance is reflected directly in the electrical impedance, $Z(\omega)$, at the PWAS terminals

$$Z(\omega)=\left[j\omega c\left(1-\kappa_{31}^2\frac{\chi(\omega)}{1+\chi(\omega)}\right)\right]^{-1} \tag{2}$$

where C is the zero-load capacitance of the PWAS and κ_{31} is the E/M cross coupling coefficient of the PWAS ($\kappa_{31}=d_{31}/\sqrt{\bar{s}_{11}\bar{\varepsilon}_{33}}$), and $\chi(\omega)=k_{str}/k_{PWAS}$ with k_{PWAS} being the static stiffness of the PWAS. During a frequency sweep, the real part of the E/M impedance, $Z(\omega)$, follows the up and down variation as the structural impedance as it goes through the peaks and valleys of the structural resonances and anti-resonances [1]. The E/M impedance method is applied by scanning a predetermined frequency range in the high kHz band (up to 10 MHz) and recording the complex impedance spectrum. By comparing the real part of the impedance spectra taken at various times during the service life of a structure, meaningful information can be extracted pertinent to structural degradation and ongoing damage development.

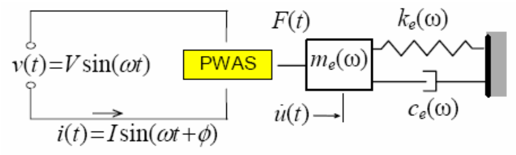


Figure 3 E/M coupling between PWAS and structure

Ultrasonic Guided Wave Propagation

For embedded NDE applications, PWAS can be used as embedded ultrasonic transducers acting as either actuators to excite guided waves or as sensors to receive the structural response in the pitch-catch mode (as illustrated in Figure 4). PWAS couple their in-plane motion with the particle motion of Lamb waves on the material surface while the in-plane motion is excited by the applied oscillatory voltage through the d_{31} coefficient.

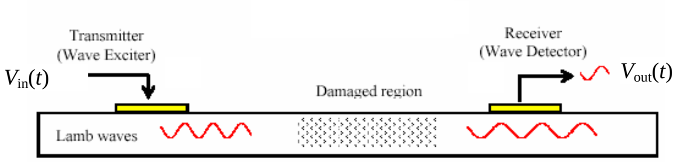


Figure 4 PWAS embedded NDE in pitch-catch mode as actuator and sensor

For Lamb waves, there are at least two Lamb modes, A0 and S0, existing simultaneously, where the product of the wave frequency and structure thickness falls in the range of 0~1 MHz-mm. The process of Lamb wave tuning attempts to modify the excitation parameters in such a way as to excite a certain mode for detecting a specified type or instance of damage. With wedge-coupled conventional ultrasonic transducers, guided wave tuning is performed by varying the frequency and the wedge angle until a maximum response is recorded. The change in frequency modifies the wave speed of the dispersive guided wave, while the change of wedge angle modifies the wave conversion relationship in Snell's law. Certain combinations of wedge-angles and excitation frequencies were able to generate increasing response in certain guided-wave modes. An important characteristic of PWAS, which distinguishes them from conventional ultrasonic transducers, is their capability of exciting multiple guided wave modes at a single frequency. A comprehensive study of these prediction formulae in comparison with experimental results has been given by [1]. By carefully selecting PWAS length at either an odd or even multiple of the half wavelength, a complex pattern of strain maxima and minima emerges. Since several Lamb modes, each with its own different wavelength, coexist at the same time, a selected Lamb mode can be tuned by choosing the appropriate frequency and PWAS dimensions.

An example of PWAS tuning is presented in Figure 5 for a 7-mm square PWAS installed on a 1-mm aluminum alloy 2024-T3 plate. The experimental amplitude plot in Figure 5a shows that for the plate being studied, a S0 tuning frequency around 200 kHz can be identified, where the amplitude of the A0 mode is minimized while that of the S0 mode is still strong. Therefore, by choosing the excitation frequency, a single mode can be obtained for damage detection [3]. Theoretical prediction given in Figure 5b is consistent with the experimental results.

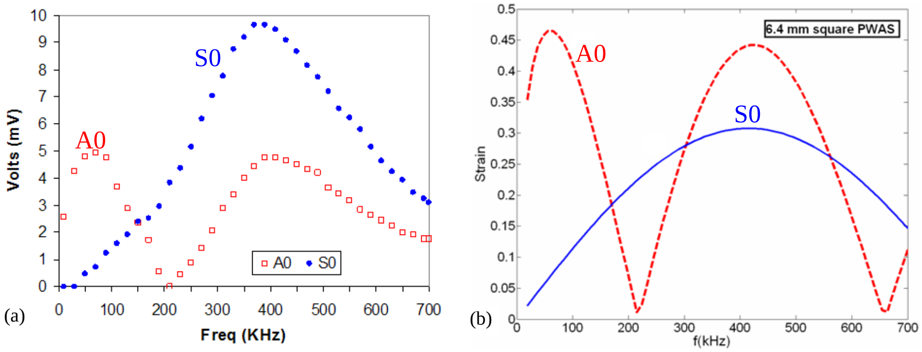
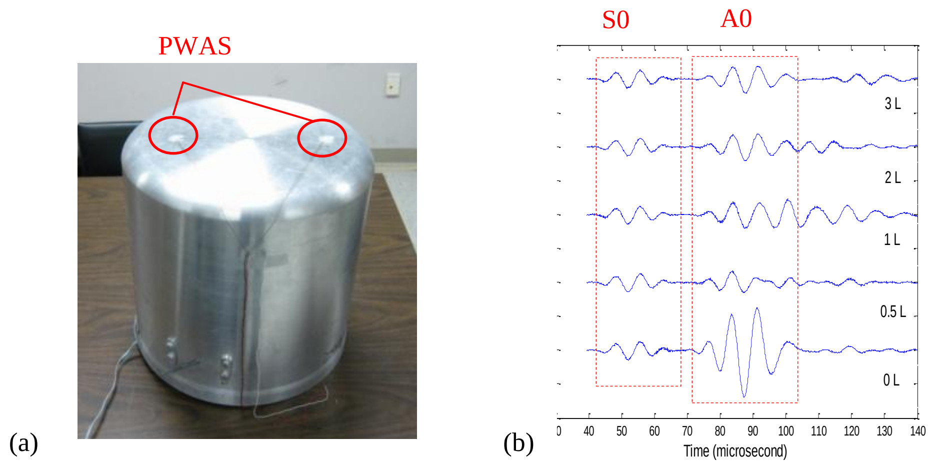


Figure 5 Lamb wave mode tuning on a 1-mm thick aluminum alloy 2024-T3 using 7-mm PWAS. (a) Experimental wave amplitude within 0~700 kHz; (b) predicted strain curves [3]

Initial Tests

Initial tests have been conducted to show the sensitivity of selected Lamb waves to water permeation. An aluminum bucket is used as the test specimen and water container. Two PWAS, one as transmitter and the other as receiver, are installed on the bottom of the bucket as shown in Figure 6a. Lamb waves are excited at 120 kHz using a 3-count Hanning window smoothed sine signal. Wave propagation and reception tests are performed without water (baseline), with 0.5 liter, 1 liter, 2 liter, and 3 liter water respectively. The results are shown in Figure 6b. It can be seen that A0 mode shows greater sensitivity to the water permeation and increment.



(a) (b)

Figure 6 Test on Lamb wave sensitivity to water permeation. (a) test specimen; (b) Lamb wave at 120 kHz without water (baseline), with 0.5 liter, 1 liter, 2 liter, and 3 liter water respectively

PHASE DIFFERENCE DETECTION

Cross Time-Frequency Analysis (CTFA)

Time-frequency analysis provides an effective tool for non-stationary signal analysis by a time and frequency localized signal representation. Various methods have been applied to a variety of applications; and Cohen's class generalizes various types of the time-frequency distributions in terms of a kernel [4]. The main objectives of the various types of time-frequency distributions are to obtain time-frequency localized energy distribution with high resolution and to overcome interference effects within the limits of the uncertainty principle.

The limitation of Cohen's class in our application is that the traditional definition of the time-frequency distribution within Cohen's class concerns a non-stationary signal and generation of the time-varying energy spectrum. Thus, another critical feature of the signal, the phase difference, is not available in the real-valued time-frequency distribution function. Phase is meaningful when considering the relative phase difference between the signals to represent propagation of a signal. In particular, phase difference spectrum can reveal the dispersion phenomena and direction of propagation in wave propagation analysis. The cross power spectrum in frequency domain is usually used in the case of stationary signals. For non-stationary signals such as Lamb waves in the corrosion application, it is necessary to use time-frequency analysis in order to measure the relative phase difference in the time and frequency domains. In this research, we proposed the cross time-frequency distribution function to preserve the phase difference aspects of two signals [5][6].

A type of cross time-frequency distributions has been suggested by Williams [5] via the Hilbert transform. For a pair of complex analytic signal $x_1(t)$ and $x_2(t)$, the cross Wigner distribution is expressed in terms of the ambiguity functions as

$$W_{x_1,x_2}(t,\omega)=\frac{1}{2\pi}\int x_1(t+\tau/2)x_2^*(t-\tau/2)e^{-j\omega\tau}d\tau \tag{1}$$

From the cross Wigner distribution, other types of generalized cross time-frequency distribution functions, $J_{x_1,x_2}(t,\omega;\phi)$, can be obtained in terms of a kernel as

$$J_{x_1,x_2}(t,\omega;\phi)=\frac{1}{4\pi^2}\iint W_{x_1x_2}(u,\xi)\Phi(t-u,\omega-\xi)dud\xi \tag{2}$$

where $\phi(t,\omega)$ is the 2D Fourier transform of the kernel $\phi(\theta,\tau)$, i.e.

$$\phi(t,\omega)=\iint\phi(\theta,\tau)e^{-j(\theta t+\tau\omega)}d\theta d\tau \tag{3}$$

In this study, we will employ reduced interference distribution (RID) kernel that preserves time and frequency marginal properties. In particular, marginal properties are critical kernel requirements for appropriate measurement of time- and frequency- localized phase differences.

Phase difference measurement with CTFA

The CTFA was applied to two waveforms recorded between two PWAS installed on an aluminum plate before and after some material was removed as shown in Figure 7a. When cross time-frequency analysis is applied to the data set, study of the phase difference of the excitation frequency, 57 kHz, and specific time duration where A0 arrives can quantify the relationship of the material loss and phase difference. The phase difference between the two signals is a function of time. Figure 7b shows the time domain waveform of the baseline and the record 1. Figure 7c shows the corresponding phase of the cross time-frequency distribution between the two signals as a function of time *w.r.t.* 57 kHz which indicates the phase difference of the two signals changes with time. As observed from the figure, the phase difference is essentially a constant during the A0 wave packet existence as 0.73 radian.

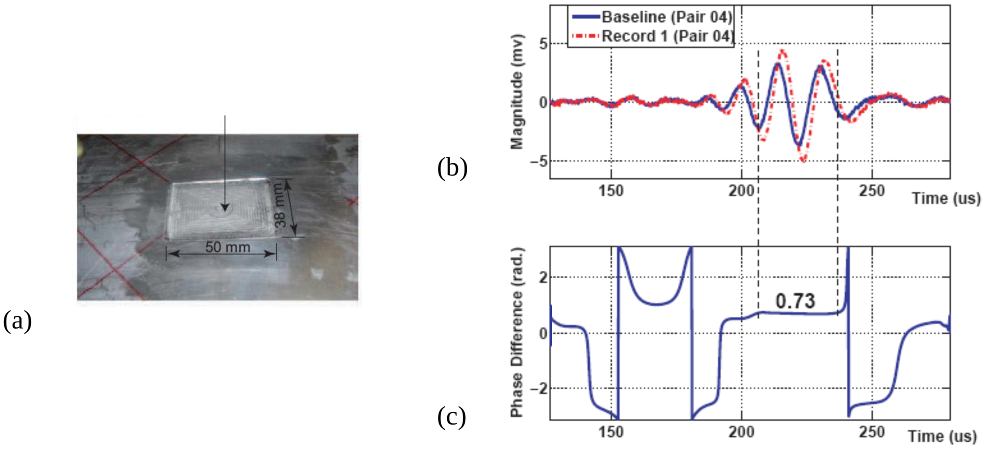


Figure 7 Phase of cross time-frequency distribution as function of time *w.r.t.* 57 kHz of pair 0-4 for record 1. (a) Specimen with material loss; (b) baseline and record 1 signals in time domain; (c) the phase difference obtained from CTFD. (The waveforms between the two vertical line is A0 wave packets.)

CONCLUSION

In this paper, we introduced the principle of PWAS, its application for guided Lamb wave generation and electromechanical impedance spectroscopy, and a cross time-frequency phase detection approach. The advantage of the proposed technique is that the gas accumulation inside a nuclear cooling pipe can be detected by a network of sensors mounted on the outer surface where other methods focus on surface and subsurface detection. The combination of wave propagation and electromechanical impedance spectroscopy enables the estimation of gas accumulation while the use of cross time-frequency analysis correlate the gas quantity to measured sensor data. We will further our study to initiate the relationship between the reflected wave characteristic and gas void volume. Ultimately, an overall in-depth solution for a timely detection, localization, and evaluation of the amount of gas accumulation in the pipe systems will be developed.

ACKNOWLEDGEMENT

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