2015

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Prototype ultrasonic NDT transducers for use in immersion in coolants for small modular reactors have shown low signal to noise ratio. The reasons for the limitations in performance at high temperature are under investigation, and include changes in component properties. This current work seeks to quantify the issue of thermal expansion and degradation of the piezoelectric material in a transducer using a finite element method. The computational model represents an experimental set up for an ultrasonic transducer in a pulse-echo mode immersed in a liquid sodium coolant. Effect on transmitted and received ultrasonic signal due to elevated temperature (~200°C) has been analysed.

Keywords
Ultrasonic, Transducers, High temperature, Finite element, Small modular reactors, Thermal

Disciplines
Structures and Materials

Comments
This article is from *Physics Procedia* 70 (2015): 433–436, doi:10.1016/j.phpro.2015.08.137. Posted with permission.

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Physics Procedia 70 (2015) 433 – 436

Physics Procedia

2015 International Congress on Ultrasonics, 2015 ICU Metz

Effect of Thermal Degradation on High Temperature Ultrasonic Transducer Performance in Small Modular Reactors

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Abstract

Prototype ultrasonic NDT transducers for use in immersion in coolants for small modular reactors have shown low signal to noise ratio. The reasons for the limitations in performance at high temperature are under investigation, and include changes in component properties. This current work seeks to quantify the issue of thermal expansion and degradation of the piezoelectric material in a transducer using a finite element method. The computational model represents an experimental set up for an ultrasonic transducer in a pulse-echo mode immersed in a liquid sodium coolant. Effect on transmitted and received ultrasonic signal due to elevated temperature (~200^{o}C) has been analysed.

*Keywords:*ultrasonic, transducers, high temperature,finite element, small modular reactors,thermal

1. Introduction

Generation IV fast nuclear reactors are under development to support sustainable development, economic competiveness and improve safety [1]. Past experience, specifically, with regard to long term maintenance experience from the Phoenix reactors (France) has underlined the need to provide effective and reliable inspection of components in any proposed advanced liquid metal cooled small modular, and other advanced reactors [2]. In the 1970s, the Hanford Engineering Development Laboratory (HEDL), Richland, Washington [3] developed high

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doi:10.1016/j.phpro.2015.08.137

temperature transducers using lead Zirconium titanate (PZT). Recent studies which sought to re-establish this capability have found that the new high temperature transducers developed could operate continuously at about 250°C for 8 hours, but had a limited signal to noise ratio [4]. It is unclear as to what causes the limits to performance. The current study focuses on a finite element analysis of the temperature effects on PZT-5A and de-bonding phenomenon caused by the thermal expansion at high temperatures.

2. Ultrasonic NDE Measurement system: a Temperature driven system

An ultrasonic NDE measurement system is basically a linear time-shift invariant system comprising of response functions. One such response function is for the conversion of an electric pulse into a mechanical motion which generates a wave. This is called direct piezoelectric effect that can be written as [5]:

$$S_i = S_{ij}{}^E T_j + d_{mi} E_m \quad (1)$$

$$D_m = d_{mi} T_i + \varepsilon_{mk}{}^T E_k \quad (2)$$

Where S^E is the mechanical strain under constant electric field E, d is the piezoelectric constant, and ε^T is the dielectric permittivity under constant mechanical stress, S is the total strain and D is dielectric displacement. Due to symmetry of poled piezoelectric ceramics, the complete material matrix reduces to the ten independent coefficients for PZT which includes five elastic, three piezoelectric and two dielectric constants. [6, 7]. Temperature variation of these constants can result in variation in piezoelectric effect and thus it can affect the transmitted and received ultrasonic signals. Also, the rapid increase or decrease in the operating temperature produces thermal strain in the transducer components which increases the likelihood of de-bonding. Kažys et al. [8] have analysed the bonding techniques for high temperature transducers. The current study uses the linear thermal expansion coefficient data reported by Piezo-technologies (K350) [9] and Duralco 4703[10]. The liquid sodium coolant and PZT-5A temperature dependent properties used in the finite element model have been published in previous studies [6,11 12].

3. Finite Element Model:

The ultrasonic transducer pulse-echo experiment, shown in Fig 1, is simulated using a finite element method in COMSOL. The model is 2D axisymmetric and it uses the equation for the piezoelectric effect shown as equation (1) and (2) to the wave equation in a fluid. A maximum 10 elements per wavelength and a time step with CFL value of 0.18 is applied to achieve convergence of the solution of the partial differential wave equations. A detail description of the computational model has been provided previously [13].

Thermal expansion simulation is performed using ABAQUS. A solid coupling bonding technique [8] has been used to simulate bonding between the materials. The bonding agent is modelled to maintain contact between the transducer components. The computed deformation due to de-bonding is converted into an equivalent acoustic model using an air gap for the corresponding deformation (20 microns). Hence, the de-bonding process here is basically treated as a special case of a lightly damped ultrasonic transducer in the acoustic model.

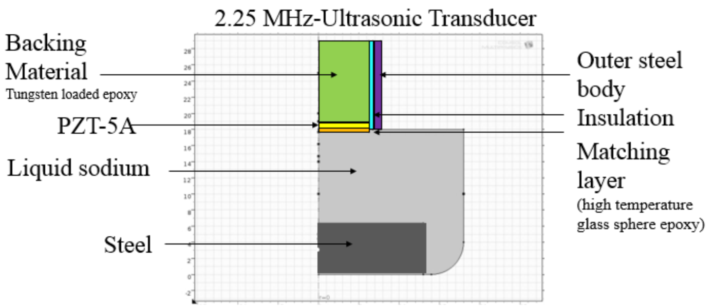

Figure 1-Finite element Model

4. Preliminary Results

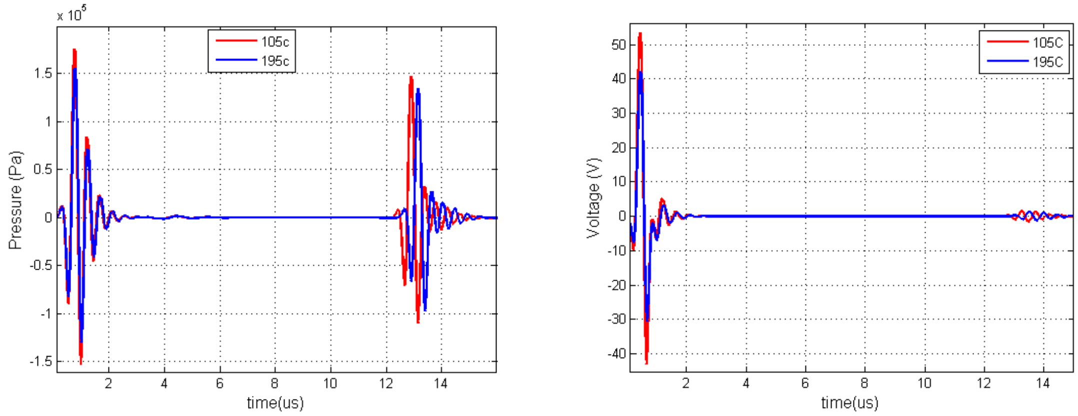

Figure 2-Pulse echo response- a) Pressure amplitude at 105° and 195°C b) Voltage across the piezo electric material at 105° and 195°C

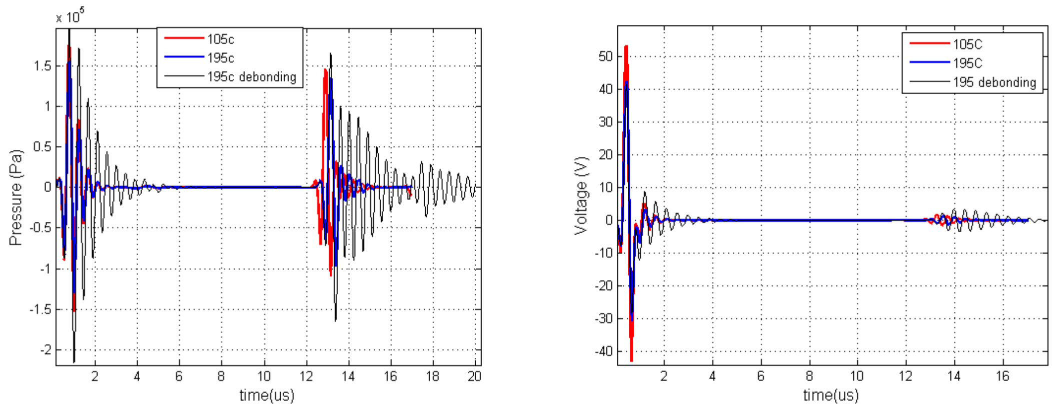

Figure 3- Signal without and with de-bonding a) Pressure Amplitude b) Voltage across the piezo electric element

5. Discussion

As the simulated temperature for the liquid sodium coolant is increased from 105°C to 195°C, the pressure amplitude decreases by about 1dB and voltage measured across PZT-5A decreases by about 2dB as shown in figure-2 a) and b). This loss in the amplitude does not seem to be significant. As stated earlier, there are ten temperature dependent coefficients for PZT-5A which includes five elastic, three piezoelectric and two dielectric constants. The losses in amplitude of the simulated signal occur if only two of the piezoelectric and two dielectric constant are varied as a function of temperature, which was discussed in a previous study [14]. From the current study it appears that the temperature dependent variation in elastic constants also play an important role in determining losses in the amplitude of the signal as evidence from equations (1) and (2).

Figure 3a) and b) compare the changes in the time domain waveforms due to temperature effects and due to temperature accompanied by de-bonding. It can be clearly seen that de-bonding serves as source of acoustic noise due to increased “ringing” in the signal. The de-bonding basically makes the transducer appear to be lightly damped which causes a reduction in the bandwidth. Further investigation is needed to quantify the effect of de-bonding on the signal to noise ratio.

6. Conclusions

It is demonstrated that the finite element method can be used as an analytical tool to quantify thermal degradation, when the temperature dependent material property data are available. From the current study it appears that, d_{33} is not the only property controlling the response of the ultrasonic transducer at high temperature. It appears to be a combination of all the ten mutually independent coefficients that contribute to the piezoelectric effect which is the source function for generation of a wave in fluid. Finite element modeling thus has helped to quantify this effect giving a simulated ultrasonic signal. Also, it can be seen that the de-bonding initiated due to thermal degradation of the bonding agent serves as a source of acoustic noise.

Acknowledgements:

This work is funded by the U.S. Department of Energy's office of Nuclear Energy under Nuclear Energy University programs (NEUP) under contract DE-NE0000676 and performed at the Centre for NDE, an NSF I/U CRC, at Iowa State University. The authors would like to acknowledge the assistance of Dr. Sabat (Department of Physics, Royal Military College of Canada, Kingston, Ontario K7K 7B4, Canada) who provided the experimental material property data for PZT (EC-65)

References

[1] OECD "*Technology roadmap update for generation IV nuclear energy systems*," OECD Nuclear Energy Agency for the Generation IV International Forum (2014). https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf

[2] CEA "*4th-generation sodium-cooled fast reactors The ASTRID Technological Demonstrator*," Direction de l'énergie nucléaire (nuclear energy division), Centre de Saclay, CEA (2012)

[3] Day, C. K., and Smith, R. W. (1973). *Under sodium viewing*, Report No. HEDL-SA—615, Hanford Engineering Development Lab., Richland, Washington. (USA).

[4] Griffin, J. W., Peters, T. J., Posakony, G. J., Chien, H. T., Bond, L. J., Denslow, K. M., Sheen, S. H. and Raptis, P. "Under-Sodium viewing: a review of ultrasonic imaging technology for liquid metal fast reactors," PNNL-18292, Pacific Northwest National Laboratory, Richland, WA (2009).

[5] Jaffe, B., Cook, Jr., W. R., and Jaffe, H. "Piezoelectric ceramics," *Academic Press*, London (1971).

[6] Sabat, R. G., Mukherjee, B. K., Ren, W., & Yang, G. (2007). Temperature dependence of the complete material coefficients matrix of soft and hard doped piezoelectric lead zirconate titanate ceramics. *Journal of Applied Physics*, *101*(6). doi:10.1063/1.2560441

[7] Jordan, T. L. and Ounaies, Z. 2001 Piezoelectric ceramics characterization. NASA/CR-2001-211225 *ICASE Report No* 2001-28

[8] Kazys, R., Voleisis, A. and Voleisiene, B. "High Temperature Ultrasonic Transducers: Review," Ultragarsas (Ultrasound), 63, 7–17 (2008).

[9] Piezo Technologies (http://www.piezotechnologies.com/)

[10] Cotronics Corporation (http://www.cotronics.com/vo/cotr/ea_ultratemp.htm)

[11] Foust, O. J. *Sodium-NaK Engineering Handbook,* **1,** Gordon and Breach, Science Publisheers, Inc., New York (1972).

[12] Leibowitz, L., Chasanov, M. G. and Blomquist, R. "Speed of sound in liquid sodium to 1000 C," Journal of Applied Physics, 42(5), pp. 2135-2137 (1971).

[13] Bilgunde, P. N., & Bond, L. J. (2015). A 2D finite element simulation of liquid coupled ultrasonic NDT system. In *41ST ANNUAL REVIEW OF PROGRESS IN QUANTITATIVE NONDESTRUCTIVE EVALUATION: Volume 34* (Vol. 1650, pp. 1543–1552). AIP Publishing. doi:10.1063/1.4914773

[14] Bilgunde, P. N. and Bond, L. J., "Analysis of High Temperature Ultrasonic Transducer Performance in Small Modular Reactors," Proc., NPIC & HMIT 2015 Conference, February 23–26, 2015, Charlotte, North Carolina, American Nuclear Society [in press] (2015).