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Lossless and lossy modeling of ultrasonic imaging system for immersion applications: Simulation and experimentation☆

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ABSTRACT

The design, modeling, optimization, and development of the entire ultrasonic imaging system is a complex task which involves an understanding of acoustic physics of transducer, acoustic properties of propagating medium, transmission cables and analog front-end electronics for generating and receiving of ultrasonic signals. Such immersion systems are extensively utilized in non-destructive testing (NDT) application for flaw detection, dimensional measurements, material characterization and many more. This paper presents the one-dimensional simulation modeling of the entire ultrasonic imaging system. For validation purpose, a single channel real-time ultrasonic imaging system has been designed and developed for laboratory application which contains high voltage ultrasonic spike pulser, high voltage protection circuits, ultrasonic receiver amplifiers, co-axial cables and an ultrasonic transducer. Lossless and lossy (low-loss) simulations have been performed for ultrasonic transducer and propagation medium using the transmission line model. Effects of non-ideal, frequency-dependent and non-linear components in high voltage excitation circuit (pulser), the receiver circuit and the effects of cables are also considered for modeling and simulation. Validation results of the entire ultrasonic imaging system provide very close agreement with lossy simulated results.

1. Introduction

The immersion-based ultrasonic imaging systems are broadly utilized in many industrial fields such as detection of hydrogen-induced cracking (HIC) in steels in oil and gas industries [1]; scanning of side-drilled hole (SDH) and flat-bottomed hole (FBH) inside ingot; quality evaluation of magnetically impelled arc butt welded drive shafts of motor vehicles [2] and many more. One of the primary applications of the immersion-based ultrasonic system is the viewing of fuel-sub assemblies (FSAs) which are usually submerged in the liquid sodium environment at high temperature in fast breeder reactor (FBR) core, during reactor shutdown period [3]. The higher axial resolution inside the material can be obtained by adopting the higher frequencies for NDT inspections. But it raises the attenuation in a liquid medium that significantly reduces the larger penetration length inside the material. It creates the trade-off between material penetration length and axial resolution. However, the increment in the dynamic range of the amplifier in the receiver stage can conquer this problem. But it may amplify the random as well as coherent noise in the receiving path which degrades the signal to noise ratio (SNR). Therefore, the front-end electronics of the ultrasonic system must require low noise as well as large signal handling capability especially for large dynamic amplifier [4]. The high Q transducer has a wider bandwidth which

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increases the ringing cycles when it is excited by a high voltage spike pulse. A more number of cycles provide lower axial resolution in the material. To overcome this issue, it requires the high electrical damping network but it losses the energy. Another difficulty is the acoustic impedance mismatch between the front-end electronics and ultrasonic transducer. For optimum energy transmission to the transducer, the electrical matching network is required [5]. For long water path immersion operations, the centre frequency of the transducer shifts downward because the higher frequency components of a wideband pulse attenuate more quickly than the lower frequency components [6]. The bandwidth mismatch can attenuate the signal due to the analog high-pass filter banks in the receiver circuit. Furthermore, electronics interfacing with ultrasonic transducer probes normally includes non-linear switching devices and semiconductor networks like MOSFET, MOSFET driver, Diodes, etc., which influences directly to the excited high voltage pulses and received echo signals [7]. Traditional approaches of pulse-echo system modeling adopt the ideal assumptions for the front-end hardware (electronics) and they do not consider their influences on ultrasonic echo signals. These non-ideal frequency dependent electrical components may disturb the operations of the transducer excitation circuit (pulser) and receiver limiter circuits. Previously published literatures have focused on spice modeling of either lossy or lossless ultrasonic transducer using different model circuits like Mason, Redwood, KLM, Leach, etc. Moreover, they consider a resistive and linear system for the spike pulser to excite the transducer [8], and so these are not relevant with the high voltage spike pulse generator used for real ultrasonic NDT inspection. In addition, receiver amplifier too contains rectifying diode based bridge limiter circuit for high voltage protection, frequency dependent RC filters and operational amplifiers. The co-axial cable is also accountable for signal attenuation and phase delay of echo signals.

Because of the availability of non-ideal, nonlinear and frequency-dependent behaviour of the front-end hardware (electronics) and an ultrasonic transducer, the ultrasonic imaging system involves many complications. So in order to determine and overcome all these challenges with precision and to get optimum performance during the ultrasonic examination, a detailed analysis, i.e. modeling of all stages of the ultrasonic imaging system is needed which combines transceiver electronic circuits, ultrasonic transducers, cables and propagation mediums. In this study, the lossless approach has been presented which consists of a lossless leach model of the ultrasonic transducer, front-end electronics, co-axial cables and propagation mediums. However, this provides only time domain information for pulse-echo analysis but it does not provide the exact amplitude based information. For the threshold amplitude based ultrasonic imaging mode like B-Scan or C-Scan, the accurate information of time, as well as voltage amplitude of detected echoes, are required. For that reason, the lossy modeling of the full ultrasonic imaging system has been presented which covers all the stages of the ultrasonic imaging system.

Simulation is an essential tool for the designers to understand the effect of system parameters in any field. One of the simulation method is based on the equivalent electrical circuit implementation using the simulation tools like Spice (P-Spice) [8–11] or VHDL-AMS [12]. The thickness mode plate transducer is considered mainly for simulation since it has significant practical applications in the generation and reception of longitudinal waves in solids, fluids, and gases [13]. The electrical and mechanical parts of the piezoelectric transducer are represented by only its equivalent electrical circuit. For derivations of the equivalent circuit of the piezoelectric transducer, its acoustic wave and piezoelectric equations are used. Mason [14] have proposed an equivalent electric circuit for the ultrasonic transducer based on the direction of electric field and mechanical force. The model consists of an ideal transformer that describes the conversions of mechanical quantities to electrical quantities and vice versa. The model also contains a negative value capacitor C_0 which represents the static capacitance of the transducer. Redwood [15] has introduced a method to solve the transient response of the piezoelectric transducer. The Redwood model comprises a transmission line for the time delay representation and it is significant for mechanical signals to travel from one face of the transducer to the other face. Krimholtz et al. [16] have proposed a different equivalent KLM Model for piezoelectric transducers. They changed mason's model equations and its circuit contains frequency depended components that connected to the middle of the transmission line. KLM model is more suitable for simulation of multilayer structures [17]. However, these described models are complex to implement in spice as they consist of frequency dependant transformers and a negative value capacitor. Morris and Hutchens [9] have come up with a Redwood variant of Mason's equivalent circuit to provide the computer simulation which comprises the hybrid representation of frequency dependant transformer, a true approximation of the negative capacitor and altered connection between a transformer and acoustic transmission line. Leach [10] have proposed a spice simulation model which encompasses the controlled current and controlled voltage sources instead of a transformer and a negative value capacitor. This model can be applied to the sandwich piezoelectric ceramic based ultrasonic transducer for high power applications [18].

The wave propagation medium can be modeled by the different implementations of the transmission line model [8,11,18–21]. Losses are introduced in the model by simulation of the effect of attenuation of the propagating wave. Johansson et al. [19] have measured diffraction losses experimentally and introduced this effect into a spice model via the lossy transmission line parameter G. The same way absorption losses are also modeled by the lossy transmission line parameter R [8]. Some researchers have adopted the analytical expression instead of experimentation for the computation of diffraction losses (G parameter) [20,21]. While propagating the ultrasonic wave in the distorted medium, the ultrasonic phase velocity varies, and this effect produces wave distortion (non-linearity) in the time domain. The effect of the nonlinearity of ultrasonic wave introduces in the spice model from the Burger's equation [12,21]. Aouzale et al. [22] have introduced a computational spice model for nonlinear ultrasonic wave propagation. A VHDL-AMS language based modeling concept for non-linear propagation using the Redwood transducer mode has also been presented in [12]. The non-linearity effect occurs usually in liquid propagation medium due to higher B/A nonlinear parameter. As water has a low B/A compared to other liquids like ethanol, etc., the effect of non-linearity is not being considered for the analysis of propagation wave. The absorption of the acoustic wave is the transformation of acoustic energy into heat while propagating through medium and it is mainly due to the viscosity of the material. Therefore, the losses due to viscous effect have been considered for simulation of the ultrasonic transducer, propagation mediums, and co-axial cables.