Simulation study of acoustic intermediate layer and electrical source impedance in an ultrasonic pulse system

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(Received 10 July 2003, Accepted for publication 4 September 2003)

Abstract: The systematized computer simulation of the short ultrasonic pulse system is performed using a transmission line model. Optimum condition of the acoustic impedance and thickness of the intermediate layer are considered first. The effects of electrical source impedance for the ultrasonic pulse waveform are also discussed. From the simulation results, the conventional quarter wave acoustic intermediate layer does not always realize optimum pulse performance. The importance of electrical source impedance in pulse performance is also emphasized.

Keywords: Intermediate layer, Electrical source impedance, Short ultrasonic pulse, Transmission line model

PACS number: 43.38.Fx [DOI: 10.1250/ast.25.203]

1. INTRODUCTION

The acoustic intermediate layer, especially the quarter wavelength acoustic matching layer (1/4 acoustic matching layer) is frequently used to broaden the operating frequency range of an ultrasonic transducer [1–5]. In most research, however, the optimum conditions of the intermediate layer were individually obtained for the acoustic impedance or the thickness of the layer. Moreover, consideration of electrical source impedance has been considered in few papers. As already known, the equivalent electrical circuit of piezoelectric transducer has two mechanical terminals and an electrical one. Electrical source connected to the electrical terminal of transducer works as the electrical load as well as the energy source. Thus, both mechanical and electrical matching at their terminals is essentially needed for generating a short ultrasonic pulse. Recently, the importance of electrical source impedance in the ultrasonic system has also been pointed out by the authors [6,7]. The importance of electrical properties, however, has not been fully discussed in the ultrasonic system. In this paper, a systematized computer simulation study is performed by introducing a transmission line model of an ultrasonic pulse-echo system to calculate an ultrasonic pulse response. Our transmission line model which is based on the modified version of NKC equivalent circuit of piezoceramic transducer [8,9] is used to evaluate the optimum conditions of the electrical source impedance as well as the acoustic impedance and the thickness of the intermediate layer for generation and reception of a short ultrasonic pulse.

2. METHOD

Figure 1 shows a typical ultrasonic pulse-echo system, consisting of a piezoelectric transducer, an intermediate layer and acoustic medium. The system in Fig. 1 can also be expressed in the equivalent electrical circuit shown in Fig. 2. In this figure, the piezoelectric transducer with two electrical-mechanical transformers (1 : φ, φ is the force factor (N/V)) acts as both input and output device; a single transducer works as both transmitter and receiver in the pulse-echo system. The intermediate layer and acoustic medium are expressed as a simple transmission line with impedances of $Z_m$ and $Z_a$, respectively. Two pairs of piezoelectric transducers and intermediate layers are identical components in the pulse-echo system. The length of the transmission line for an acoustic medium corresponds to a round-trip distance of an ultrasonic wave. $R_s$ and $R_L$ are the electrical source resistance and the external load resistance, respectively, and hereinafter are defined as equal. Using our transmission line model, the ultrasonic pulse propagation in the acoustic medium can be intuitively grasped. The loop voltage transfer function $V_H(\omega)$ at the

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electrical terminal of the ultrasonic transducer was derived from the equivalent circuit as,

$$V_H(\omega) = \frac{V_O(\omega)}{V_I(\omega)},$$  \hspace{1cm} (1)$$

where, $V_O(\omega)$ and $V_I(\omega)$ are the electrical output voltage function and the input voltage function in the frequency domain, respectively. An inverse Fourier transform was applied to calculate the ultrasonic output waveform in the time domain. Pulse width, defined as the time width that corresponds to the $-20$ dB lower than the peak amplitude ($-20$ dB pulse width), and amplitude were studied to evaluate the pulse performance.

In this analysis, PbTiO$_3$ piezoelectric transducer having the resonance frequency of 1 MHz, electro-mechanical coupling factor of 0.5, dumped capacitance of 750 pF and $Z_t$ of 31.7 Ns/m$^3$ was assumed. Water was used as an acoustic medium ($Z_g$).

### 3. RESULTS

Figure 3 shows the properties of a $-20$ dB pulse width and normalized amplitude against the normalized acoustic impedance $Z_m/Z_g$, where $Z_g$ is the geometrical mean of the acoustic impedance for an ultrasonic transducer $Z_t$ and acoustic medium $Z_a$. In the calculation, the input voltage function $V_I(\omega)$ was selected as 1 MHz one cycle burst sine wave. The electrical source resistance $R_s$ was normalized by the reactance of the damped capacitance $C_0$ at the resonance angular frequency $\omega_0$. The normalized electrical resistance $R_s\omega_0C_0$ was fixed to 0.25 ($R_s = 50 \Omega$), which is assumed to the impedance of a standard function generator. The normalized thickness $h/\lambda$ ($\lambda$: wave length) was defined to 0.25 as an initial value. Water and the piezoelectric transducer were assumed as $Z_a$ and $Z_t$, respectively. Optimum condition of $Z_m$ for pulse width and amplitude are located at almost the same value of $Z_m/Z_g = 0.7$, viz., the optimum condition is not obtained at $Z_m = Z_g (= \sqrt{Z_aZ_t})$. This remarkable fact is explained by the geometrical mean of $Z_g$ not being optimum where the resonance system, the piezoelectric transducer in this case, is immediately connected to the intermediate layer.

Figure 4 shows the properties of a $-20$ dB pulse width and amplitude against the normalized thickness of $h/\lambda$. Here, $Z_m/Z_g = 0.7$ and $R_s\omega_0C_0 = 0.25$. The minimum
pulse width is obtained at $h/\lambda = 0.28$, which does not correspond to a quarter wavelength ($h \neq \lambda/4$). The maximum amplitude is also located on the same thickness.

To explore the influence of an electrical condition on the pulse width and amplitude, the electrical source resistance $R_s$ was varied. Figure 5 shows the results of the simulation. To evaluate only an electrical effect, the dotted lines in the figure show the results without the intermediate layer. Normalized electrical source resistance $R_s\omega_0C_0 \equiv 1$ makes for the minimum pulse width. Moreover, the maximum pulse amplitude appears slightly smaller than 1. Thus, “electrical matching” is effective to suppress the electrical reaction to the mechanical vibration. Solid lines in Fig. 5 show the results for the case where the intermediate layer has the optimum condition of $Z_m/Z_e = 0.7$ and $h/\lambda = 0.28$. The pulse width and amplitude have different optimum conditions: pulse width and amplitude become optimum at 0.4 and 0.6, respectively. The importance of the electrical source impedance in the pulse performance is clearly demonstrated in the simulation. Figures 6(a) and 6(b) shows the ultrasonic pulse waveform obtained by our method: (a) is without treatment and (b) is optimized with our method, respectively. Total improvement of pulse performance by setting the optimum intermediate layer and the electrical source resistance is achieved at more than 50% in pulse width and 2.5 times in amplitude, respectively, compared to the case that has no intermediate layer and $R_s = 50\, \Omega$. When the acoustical optimum condition is satisfied, the contribution of the electrical effect is somewhat reduced.

4. CONCLUSIONS

We accomplished the computer simulation of an ultrasonic pulse-echo system using a transmission line model. If the intermediate layer is sandwiched by a resonance system and an acoustic medium, neither a quarter wavelength nor a geometric mean of acoustic impedance give the optimum pulse performance. To realize the optimum pulse performance, matching at both the acoustical and electrical ports needs to be simultaneously achieved.

Our simulation method including transmission line model and electrical source impedance will provide the useful technical information in the design of ultrasonic pulse system. Some results of this study are being verified experimentally. They will be published elsewhere in the future.

ACKNOWLEDGEMENT

The authors wish to thank Dr. Chubachi of emeritus professor of Tohoku University for his useful suggestions.

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