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High-Resolution Determination of Transit Time of Ultrasound in a Thin Layer in Pulse-Echo Method

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SUMMARY In this paper we propose a new method for removing the characteristic of the piezoelectric transducer from the received signal in the pulse-echo method so that the time resolution in the determination of transit time of ultrasound in a thin layer is increased. The total characteristic of the pulse-echo system is described by cascade of distributed-constant systems for the ultrasonic transducer, matching layer, and acoustic medium. The input impedance is estimated by the inverse matrix of the cascade system and the voltage signal at the electrical port. From the inverse Fourier transform of input impedance, the transit time in a thin layer object is accurately determined with high time resolution. The principle of the method is confirmed by simulation experiments.

key words: *medical electronics and medical information, piezoelectric transducer, pulse-echo method, inverse filter, cascade matrix, impulse train*

1. Introduction

The ultrasonic pulse-echo method is essential in the fields of noninvasive testing of materials and medical ultrasonics. An ultrasonic pulse radiated from a piezoelectric transducer is reflected at the boundary of the acoustic impedance. By receiving the reflected waves using the same transducer, the internal structure of the object can be determined. However, the piezoelectric transducer has a long transient response, which decreases the spatial resolution in the determination of thickness of a thin layer object. In a practical ultrasonic probe, a backing material and the quarter-wave matching layers are employed to make the transient response short. However, it is difficult to completely remove the transient response from the received signal using these materials and it will be serious problem to remove the resonant characteristic of the transducer especially when the transit time of the ultrasound in a thin layer object is to be compared with the transient response of the ultrasonic transducer. With regard to this problem, numerous studies on inverse filtering designed based on the equivalent circuits [1] have been reported. The transient response of the piezoelectric transducer is described by Redwood [2], Hunt *et al.* [3]. Furthermore, Hayward [4] and Stepanishen [5] have proposed the discrete-time approach. In these studies, the transfer system, $H(\omega)$, from voltage V_3 at the electrical port to force F_2 at the acoustical port is employed (Fig. 1). In these studies, however, both the force and the particle velocity are not effectively employed and the input impedance cannot be considered. Moreover, as shown in the simulation experiments below, the impulse response of the transfer function $H(\omega)$ is long due to the resonant characteristic of the ultrasonic transducer. It is, therefore, difficult to accurately obtain the finite-impulse-response (FIR) inverse filter for this resonant characteristic. Alternatively, Yamada [6] has recently applied the discrete-time scattering matrix for the pulse-echo system to design the infinite-impulse-response (IIR) inverse filter. However, it is not easy to obtain the elements of the scattering matrix for the cases of multiple matching layers and it is also difficult to confirm the stability of the IIR filtering. For these problems, we proposed a method to estimate the acoustic impedance at the surface of the object from the electrical port of the ultrasonic transducer [7]. However, the details have not considered thoroughly by comparing the proposed method with the previous inverse filtering method.

In this paper a new method to accurately determine the transit time of the ultrasound in the thin layer of an object is described, in which the input impedance at the surface of the object is estimated from the voltage at the electrical port of the piezoelectric transducer. The estimation is achieved by the cascade of distributed-constant systems of the characteristics of the thickness-mode piezoelectric transducer, the matching layers, and the medium. The estimated input impedance has an impulsive train in the time domain, the interval of which

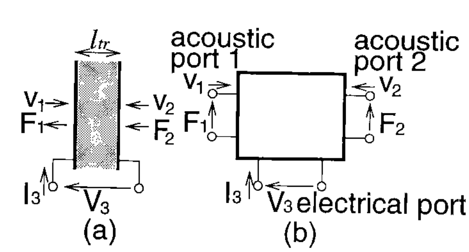

Fig. 1 (a) The physical parameters of the piezoelectric transducer; (b) the transducer regarded as a three-port black box.

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is double that of the transit time in the thin layer. Since the transient response of the transducer is completely removed in the resultant impulsive train, the accuracy of the determination of the transit time in the thin layer is improved by the proposed method even if the transit time in the layer is compared with the length of the transient response of the transducer. The method is applicable to both the pulse-echo method and the frequency-scanning method which uses continuous sound.

2. Principle of the Optimum Inverse Filtering Using Acoustic Input Impedance

2.1 Estimation of Acoustic Input Impedance $Z_{in\text{-}obj}(\omega)$ at the Surface of the Object

Let us consider a uniform piezoelectric transducer with cross-sectional dimensions of many wavelengths as shown in Fig. 1 (a). As extensively reported in the literature [2], the characteristics are described by a three-port network as shown in Fig. 1 (b). Forces F_1 and F_2 at the acoustical ports and voltage V_3 across the transducer are described in matrix form using particle velocities v_1 and v_2 and current I_3 as follows:

$$\begin{bmatrix} F_1 \\ F_2 \\ V_3 \end{bmatrix} = -j \begin{bmatrix} Z_C \cot\beta_a \ell_{tr} & Z_C \csc\beta_a \ell_{tr} & h/\omega \\ Z_C \csc\beta_a \ell_{tr} & Z_C \cot\beta_a \ell_{tr} & h/\omega \\ h/\omega & h/\omega & 1/\omega C_0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ I_3 \end{bmatrix} \tag{1}$$

where $C_0 = \varepsilon^S A/\ell_{tr}$ and $Z_C = AZ_0$ are the clamped capacitance of the transducer and the acoustic impedance of an area, A, of the piezoelectric material having a thickness of ℓ_{tr}, a density of ρ_m, and a permmitivity constant of ε^S. The parameters c^D, $\beta_a = \omega\sqrt{\rho_m/c^D}$, and $h = e/\varepsilon^S$ are the stiffness constant, the propagation constant, and the piezoelectric constant, respectively.

By assuming that acoustical port 1 is terminated by backing material with an acoustic impedance of Z_b, let us describe the characteristic of the transducer by the cascade matrix, K_{tr}, in Fig. 2 (b) as follows: By substituting the relation,

$$F_1 = -Z_b \cdot v_1, \tag{2}$$

into Eq. (1),

$$-Z_b v_1 = -j\left(Z_C v_1 \cdot \cot\beta_a \ell_{tr} + Z_C v_2 \cdot \csc\beta_a \ell_{tr} + \frac{h}{\omega} I_3\right) \tag{3}$$

$$F_2 = -j\left(Z_C v_1 \cdot \csc\beta_a \ell_{tr} + Z_C v_2 \cdot \cot\beta_a \ell_{tr} + \frac{h}{\omega} I_3\right) \tag{4}$$

$$V_3 = -j\left(\frac{h}{\omega} v_1 + \frac{h}{\omega} v_2 + \frac{1}{\omega C_0} I_3\right). \tag{5}$$

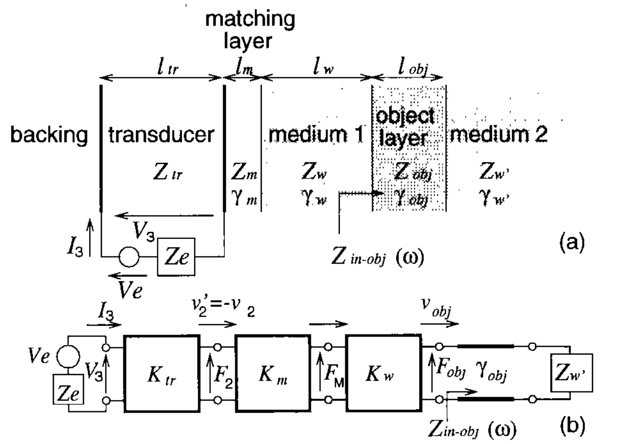

Fig. 2 (a) The physical model of the estimation of the thickness and the acoustical impedance of an object from the electrical port of the transducer via the matching layer and acoustical medium 1. (b) Exact equivalent circuit of the model for the compressional plane wave using backing material.

From Eq. (3), v_1 is described by v_2 and I_3 as follows:

$$v_1 = \frac{1}{-jZ_b - Z_C \cot\beta_a \ell_{tr}}\left\{(Z_C \csc\beta_a \ell_{tr}) v_2 + \frac{h}{\omega} I_3\right\}. \tag{6}$$

From Eqs. (4) and (6), I_3 is given by F_2 and v_2 as follows:

$$I_3 = \frac{Z_b - jZ_C \cot\beta_a \ell_{tr}}{\Delta} F_2 - \frac{Z_C(Z_C - jZ_b \cot\beta_a \ell_{tr})}{\Delta} v_2, \tag{7}$$

where

$$\Delta = -j\frac{h}{\omega}\left(jZ_C \tan\frac{\beta_a \ell_{tr}}{2} + Z_b\right). \tag{8}$$

From Eqs. (5), (6), and (7), V_3 is also described by F_2 and v_2 as follows

$$V_3 = \frac{1}{\Delta}\left(-\frac{Z_C}{\omega C_0} \cdot \cot\beta_a \ell_{tr} + \frac{h^2}{\omega^2} - j\frac{Z_b}{\omega C_0}\right) F_2 - \left\{\frac{\Delta}{jZ_C \cot\beta_a \ell_{tr} - Z_C} - j\frac{Z_C(Z_C - jZ_b \cot\beta_a \ell_{tr})}{\Delta}\Psi\right\} v_2, \tag{9}$$

where

$$\Psi = \frac{1}{\omega C_0} - \frac{h^2}{w^2} \cdot \frac{1}{jZ_b + Z_C \cot\beta_a \ell_{tr}}. \tag{10}$$

Thus, from Eqs. (7) and (9), V_3 and I_3 at the electrical port are described by F_2 and $v_2' \stackrel{\text{def}}{=} -v_2$ at acoustical port 2 and then the 2-by-2 cascade matrix K_{tr}, which denotes the characteristic of the ultrasonic transducer, in Fig. 2 (b) is determined as follows:

$$\begin{bmatrix} V_3 \\ I_3 \end{bmatrix} = \begin{bmatrix} A_{tr} & B_{tr} \\ C_{tr} & D_{tr} \end{bmatrix} \begin{bmatrix} F_2 \\ -v_2 \end{bmatrix} = K_{tr} \begin{bmatrix} F_2 \\ v_2' \end{bmatrix}, \tag{11}$$

where

$$A_{tr} = \frac{1}{\Delta}\left(-\frac{Z_C}{\omega C_0}\cot\beta_a\ell_{tr} + \frac{h^2}{\omega^2} - j\frac{Z_b}{\omega C_0}\right)$$
$$B_{tr} = \frac{\Delta - (h^2/\omega^2)D_{tr}}{jZ_C\cot\beta_a\ell_{tr} - Z_b} - j\frac{D_{tr}}{\omega C_0}$$
$$C_{tr} = \frac{1}{\Delta}(Z_b - jZ_C\cot\beta_a\ell_{tr})$$
$$D_{tr} = \frac{1}{\Delta}Z_C(Z_C - jZ_b\cot\beta_a\ell_{tr})$$
$$\Delta = -j\frac{h}{\omega}\left(jZ_C\tan\frac{\beta_a\ell_{tr}}{2} + Z_b\right). \quad (12)$$

In the actual measurement system, there are a matching layer and acoustic medium 1 between the transducer and the object as shown in Fig. 2 (a). We assume that length ℓ_w and acoustic impedances Z_w and $Z_{w'}$ in media 1 and 2 are known. The total characteristic of the matching layer and the acoustic medium 1 are given by the cascade of each distributed-constant system. Let us define these characteristics by cascade matrices K_m and K_w as follows:

$$K_m = \begin{bmatrix} \cosh\gamma_m\ell_m & Z_m\sinh\gamma_m\ell_m \\ \frac{1}{Z_m}\sinh\gamma_m\ell_m & \cosh\gamma_m\ell_m \end{bmatrix} \quad (13)$$

$$K_w = \begin{bmatrix} \cosh\gamma_w\ell_w & Z_w\sinh\gamma_w\ell_w \\ \frac{1}{Z_w}\sinh\gamma_w\ell_w & \cosh\gamma_w\ell_w \end{bmatrix}, \quad (14)$$

where γ_m and γ_w are each propagation constants, and ℓ_m and ℓ_w are the thickness of the matching layer and length of medium 1, respectively.

Using K_m and K_w, V_3 and I_3 in Eq. (11) are rewritten by force F_{obj} and particle velocity v_{obj} at the surface of the object as follows:

$$\begin{bmatrix} V_3 \\ I_3 \end{bmatrix} = K_{tr}K_mK_w\begin{bmatrix} F_{obj} \\ v_{obj} \end{bmatrix}. \quad (15)$$

From Eq. (15), force F_{obj} and particle velocity v_{obj} at the surface of the thin layer object are estimated from V_3 and I_3 at the electrical port as follows:

$$\begin{bmatrix} \widehat{F}_{obj} \\ \widehat{v}_{obj} \end{bmatrix} = (K_{tr}K_mK_w)^{-1}\begin{bmatrix} V_3 \\ I_3 \end{bmatrix}. \quad (16)$$

In many applications, it is not easy to measure RF current I_3. Thus, let us connect voltage source V_e having an internal impedance of Z_e with the electrical port as shown in Fig. 2. Since the current I_3 is given by

$$I_3 = \frac{(V_e - V_3)}{Z_e}, \quad (17)$$

the input impedance $Z_{in\text{-}obj}(\omega)$ defined by $\widehat{F}_{obj}/\widehat{v}_{obj}$ of Eq. (16) is estimated from V_3 and V_e as follows:

$$\widehat{Z}_{in\text{-}obj}(\omega) \stackrel{\text{def}}{=} \frac{\widehat{F}_{obj}}{\widehat{v}_{obj}} = \frac{k_{11}V_3 + k_{12}(V_e - V_3)/Z_e}{k_{21}V_3 + k_{22}(V_e - V_3)/Z_e}, \quad (18)$$

where k_{11}, k_{12}, k_{21}, and k_{22} are the components of the inverse matrix $K = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \stackrel{\text{def}}{=} (K_{tr}K_mK_w)^{-1}$ in Eq. (16).

2.2 Impulse Train $z(t)$ Estimated from the Input Impedance $Z_{in\text{-}obj}(\omega)$

Using the distributed-constant system of the thin layer object, the input impedance $Z_{in\text{-}obj}(\omega)$ at the surface of the thin layer object in Fig. 2 (a) is given by

$$Z_{in\text{-}obj}(\omega) = Z_{obj}\frac{1 + \Gamma_{o2}\exp(-2\gamma_{obj}\ell_{obj})}{1 - \Gamma_{o2}\exp(-2\gamma_{obj}\ell_{obj})}, \quad (19)$$

where γ_{obj} and ℓ_{obj} are the propagation constant and thickness of the object layer and Γ_{o2} is the reflection coefficient from the object to medium 2, defined by

$$\Gamma_{o2} \stackrel{\text{def}}{=} \frac{Z_{w'} - Z_{obj}}{Z_{w'} + Z_{obj}}. \quad (20)$$

Since Eq. (19) is decomposed into an infinite series, $Z_{in\text{-}obj}(\omega)$ is rewritten as follows:

$$Z_{in\text{-}obj}(\omega) = Z_{obj} + 2Z_{obj}\sum_{n=1}^{\infty}\Gamma_{o2}^{n}e^{-2n\gamma_{obj}\ell_{obj}}. \quad (21)$$

By describing γ_{obj} by $\alpha_{obj} + j\omega/v_o$, where α_{obj} and v_o are the attenuation constant and the longitudinal velocity in the object, respectively, and defining $\tau_{obj} = \ell_{obj}/v_o$, the term $\gamma_{obj}\ell_{obj}$ in Eq. (21) is given by $\alpha_{obj}\ell_{obj} + j\omega\tau_{obj}$. Using these terms, $Z_{in\text{-}obj}(\omega)$ of Eq. (21) corresponds to the following impulse train, $z(t)$, in the time domain:

$$z(t) = Z_{obj}\delta(t) + 2Z_{obj}\sum_{n=1}^{\infty}\Gamma_{o2}^{n}e^{-2n\alpha_{obj}\ell_{obj}} \times \delta(t - 2n\tau_{obj}). \quad (22)$$

where $\delta(t)$ is the Dirac delta function. By applying the inverse Fourier transform to the resultant $\widehat{Z}_{in\text{-}obj}(\omega)$, impulse train $\widehat{z}(t)$ is obtained. Since the estimated characteristics $Z_{in\text{-}obj}(\omega)$ is independent of the input voltage and both of the characteristics of the transducer and the matching layer are completely removed in the resultant estimate $\widehat{z}(t)$, the transit time of the ultrasound in the object layer is accurately determined from the interval between the impulses in the resultant time series $\widehat{z}(t)$.

3. Simulation Experiments

A PZT-5A piezoelectric disc ($Z_0 = 33.7\times10^6$ kg/m^2·s, $h = 21.5\times10^8$ V/m) having a center frequency of 3 MHz and a diameter of 10 mm was tested to confirm the principle described above. The acoustic impedance and the thickness of the quarter-wave matching layer are $Z_m = 4.0\times10^6$ kg/m^2·s and $\ell_m = 0.2$ mm, respectively.

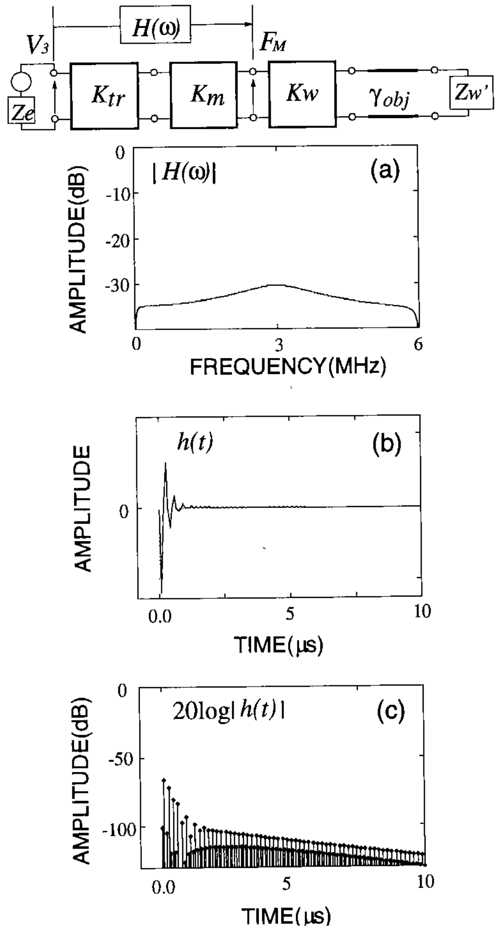

Fig. 3 (a) The amplitude of the transfer function $H(\omega)$ from voltage V_3 at the electrical port to force F_M at the surface of the matching layer. (b) The impulse response $h(t)$ of the transfer function $H(\omega)$. (c) The amplitude $20\log|h(t)|$ of the impulse response $h(t)$ in log scale.

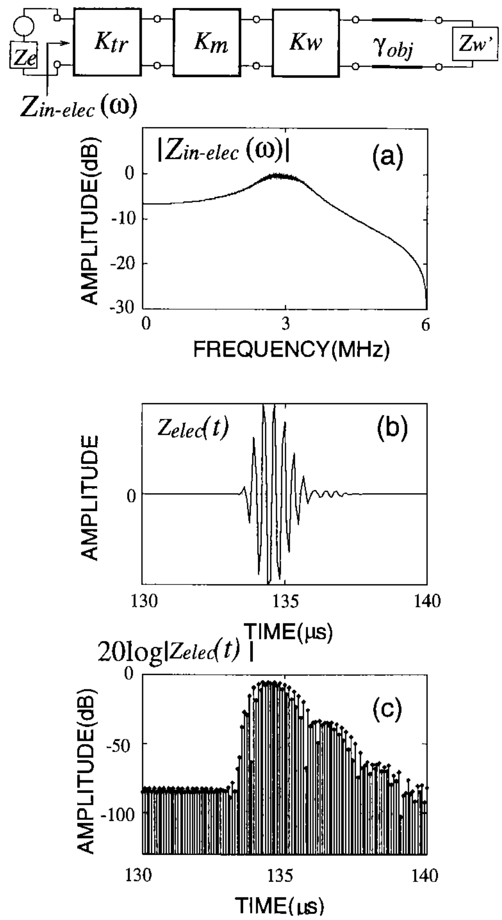

Fig. 4 (a) The amplitude of the input impedance $Z_{in\text{-}elec}(\omega)$ at the electrical port in Eq. (23). (b) The time response $z_{elec}(t)$ at the electrical port obtained from the inverse Fourier transform of $Z_{in\text{-}elec}(\omega)$ at the electrical port. (c) The amplitude $20\log|z_{elec}(t)|$ of the impulse response $z_{elec}(t)$ in Fig. 4 (b).

For the media 1 and 2 and the thin layer object, the parameters were assumed as follows: $Z_w = Z_{w'} = 1.5 \times 10^6\,\mathrm{kg/m^2 \cdot s}$, $Z_{obj} = 1.6 \times 10^6\,\mathrm{kg/m^2 \cdot s}$, $\ell_w = 100\,\mathrm{mm}$, $\ell_{obj} = 0.2\,\mathrm{mm}$ and $v_o = 1.6 \times 10^3\,\mathrm{m/s}$.

Figure 3 (a) shows the transfer function, $H(\omega)$, from voltage V_3 at the electrical port to force F_M at the boundary between matching layer and medium 1. In many studies in literature, the inverse characteristic of the transfer function, $H(\omega)$, has been considered for designing the inverse filtering. Figures 3 (b) and 3 (c) show the impulse response, $h(t)$, of the frequency characteristic $H(\omega)$ of the transfer function. As shown in Fig. 3 (c), the impulse response is long due to the resonant characteristic of the transducer. Thus, it is not easy to accurately design the FIR inverse filter and it is necessary to employ large taps for the FIR inverse filter in order to remove the transient response.

Figure 4 (a) shows the frequency characteristic of the input impedance $Z_{in\text{-}elec}(\omega)$ at the electrical port, defined by

$$Z_{in\text{-}elec}(\omega) \stackrel{\mathrm{def}}{=} \frac{V_3}{I_3} = \frac{k'_{11} Z_{in\text{-}obj}(\omega) + k'_{12}}{k'_{21} Z_{in\text{-}obj}(\omega) + k'_{22}}, \tag{23}$$

where $Z_{in\text{-}obj}(\omega)$ is calculated from Eq. (19) and k'_{11}, k'_{12}, k'_{21}, and k'_{22} are the components of the matrix $K' = \begin{bmatrix} k'_{11} & k'_{12} \\ k'_{21} & k'_{22} \end{bmatrix} \stackrel{\mathrm{def}}{=} K_{tr} K_m K_w$ in Eq. (15). Figure 4 (b) shows the time response, $z_{elec}(t)$, obtained from the inverse Fourier transform of $Z_{in\text{-}elec}(\omega)$. Figure 4 (c) shows the same response in the log-scale. The physical meaning of, $z_{elec}(t)$, in Figs. 4 (b) and (c) is the voltage signal response to the impulsive current which is inputted at the electrical port. Thus, $z_{elec}(t)$ shows the total characteristics including the transducer, the matching layer, the medium, and the object in the time domain. Since the transient response of the piezoelectric transducer is dominant in the resultant time response, $z_{elec}(t)$, as shown in these figures, it is difficult to estimate the transit time of the ultrasound in the thin layer object.

Figure 5 (a) shows the frequency characteristic of

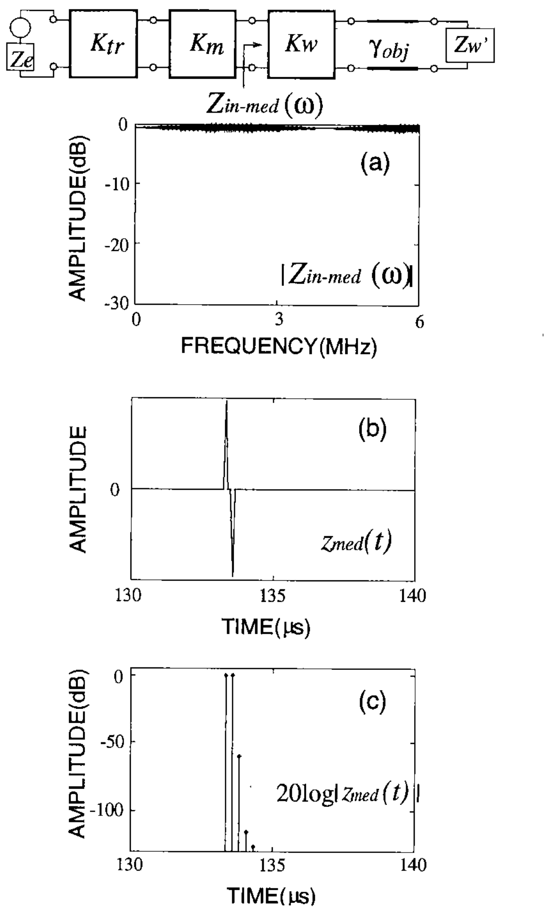

Fig. 5 (a) The amplitude of the input impedance $Z_{in\text{-}med}(\omega)$ at the boundary between the matching layer and the medium 1 in Eq. (24). (b) The time response $z_{med}(t)$ obtained from the inverse Fourier transform of $Z_{in\text{-}med}(\omega)$. (c) The amplitude $20\log|z_{med}(t)|$ of the impulse response $z_{med}(t)$ in Fig. 5 (b).

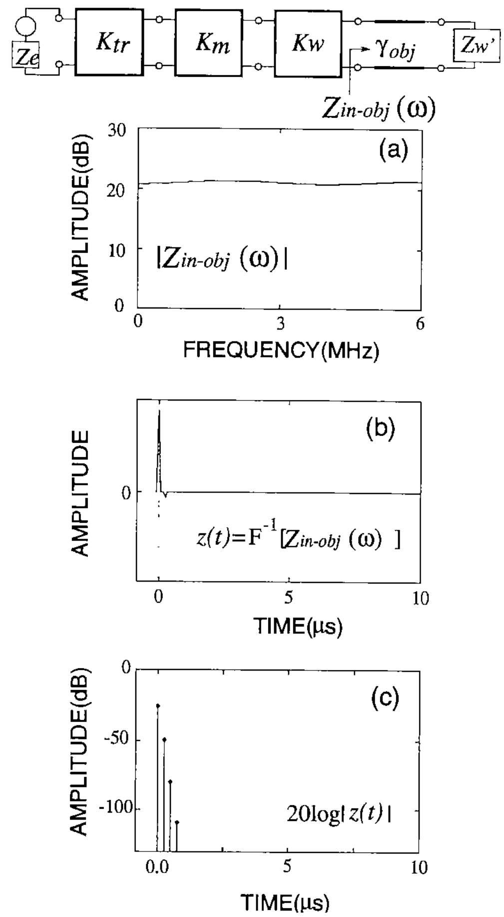

Fig. 6 (a) The amplitude of the input impedance $Z_{in\text{-}obj}(\omega)$ at the surface of the object in Eq. (19). (b) The time response $z(t)$ obtained from the inverse Fourier transform of the input impedance $Z_{in\text{-}obj}(\omega)$ at the surface of the object. (c) The amplitude $20\log|z(t)|$ of the impulse response $z(t)$ in Fig. 6 (b).

input impedance $Z_{in\text{-}med}(\omega)$ at the boundary between the matching layer and the medium 1, defined by,

$$Z_{in\text{-}med}(\omega) = \frac{k_{w11} Z_{in\text{-}obj}(\omega) + k_{w12}}{k_{w21} Z_{in\text{-}obj}(\omega) + k_{w22}}, \tag{24}$$

where k_{w11}, k_{w12}, k_{w21}, and k_{w22} are the components of the matrix $K_w = \begin{bmatrix} k_{w11} & k_{w12} \\ k_{w21} & k_{w22} \end{bmatrix}$ in Eq. (15).

Figure 5 (b) shows the time response, $z_{med}(t)$, obtained from the inverse Fourier transform of $Z_{in\text{-}med}(\omega)$ and Figure 5 (c) shows the same response in the log-scale.

Figure 6 (a) shows the frequency characteristics of the acoustic input impedance $Z_{in\text{-}obj}(\omega)$ of Eq. (19). By applying the inverse Fourier transform to $Z_{in\text{-}obj}(\omega)$, impulse train $\hat{z}(t)$ of Eq. (22) was estimated as shown in Figs. 6 (b) and (c). The transient response of the transducer is completely removed and an impulse train with an interval, $2\times\tau_{obj} = 2\times l_{obj}/v_o$, corresponding to double of the thickness of the thin layer object is obtained.

4. Conclusion

In this paper we have proposed a new method to increase the spatial resolution in the measurement of the thickness of an object using a piezoelectric transducer in the pulse-echo method. The characteristic of the thickness-mode piezoelectric transducer is described in 2-by-2 cascade matrix by assuming that one acoustic port is terminated by a backing material. The total characteristic including the quarter-wave matching layer and an acoustic medium between the transducer and the object are obtained by the multiplication of the cascade matrices of the transducer and each layer. Force F_{obj} and particle velocity v_{obj} at the surface of object are estimated from voltage V_3 at the electrical port and the employed voltage source V_e. The impulse train $z(t)$ is obtained from the inverse Fourier transform of the input impedance $Z_{in\text{-}obj}(\omega) = F_{obj}/v_{obj}$, and the transit time of the ultrasound in the thin layer object is obtained from the interval of the resultant impulse train. Since the acoustic input impedance has a wide range of frequency characteristics, this procedure is optimum for determination of the thickness of a thin layer.

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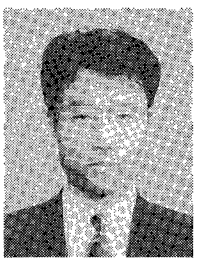

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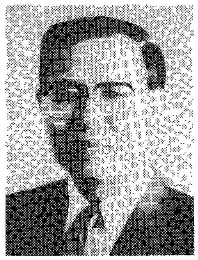

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