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Phase-canceled backing structure for lightweight ultrasonic transducer

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ABSTRACT

The overall weight of a medical ultrasonic transducer mainly depends on the weight of the backing layer. Therefore, a reduction of the thickness and the weight of the backing layer can be very useful for various types of array transducers whereby the user suffers from the inconvenience of the heavy weight. However, the backing layer with reduced thickness can cause distortions of the transmitted and received signals due to severe ripples reflected from the back-wall of the backing layer. In this study, a novel backing structure is proposed to solve this problem. The suggested backing layer is composed of multiple backing materials with different acoustic impedances to cancel the phases of the reflected signals. The rearmost material can dissipate the residual energy through the absorption effect. To verify these effects, a finite-element-method (FEM) simulation was conducted, and 4.5 MHz single-element transducers were fabricated. Although the thickness of the suggested backing layer was reduced by 1/5 compared with the conventional thick bulk-type backing layer, the ripples caused from the backing layer were successfully minimized. Therefore, the proposed backing structure can be a potential way to reduce the thickness of the backing layer resulting in a lightweight ultrasonic transducer.

1. Introduction

In general, the acoustic components of a medical ultrasonic transducer include the matching, piezoelectric, and backing layers. Among the components, a backing layer can dampen the vibration of the piezoelectric material, and it can also decrease the time durations of the transmitted and received signals, resulting in an improved axial resolution and a broadened frequency bandwidth [1–3,11]. Additionally, the backing layer dissipates the backward energy to prevent the unwanted backward energy from returning to the piezoelectric layer. To achieve the above-mentioned performance, the acoustic impedance and the attenuation coefficient should be considered [4–10]. Backing material with a high acoustic impedance can improve the frequency bandwidth by matching the impedance between the piezoelectric and backing layers [1–3,9–11]. However, such backing material decreases the sensitivity due to the low transmit/receive efficiency of the transducer. In contrast, a transducer for which a backing material with a low acoustic impedance is used has a high sensitivity, while the time durations of the transmitted and received signals are increased, causing a degradation of the axial resolution and a narrow frequency bandwidth, compared with a high-acoustic-impedance backing material. As a result, backing materials commonly have an acoustic impedance of approximately 2–10 MRayl, in consideration of the trade-off between bandwidth and sensitivity.

Generally, in a medical ultrasonic transducer, the backing material consists of a composite material of epoxy resin and metal powder [6,7,11–13,15,16], and the thickness of the backing material is thick enough to obtain a sufficient attenuation [4,5,13,15]. Moreover, quite a large transducer weight is supported. In this respect, reducing the thickness of the backing layer can be very useful to decrease the transducer weight, especially for several types of array transducers whereby the user suffers the inconvenience of the heavy weight. Nevertheless, a backing layer with a reduced thickness is affected by the problem of the back-wall echo signal that is generated at the rear boundary of a thin backing layer, and that hampers the transmitted and received main signals.

Regarding this problem, increasing the attenuation coefficient of the backing material is one possible solution. Several research groups have introduced a variety of composite materials [6–8,11–13,17–21]. For example, micro-size particles such as tungsten, alumina, and glass, or organic materials such as carbon fiber have been mixed with the original materials. By mixing

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such additional ingredients, the desired attenuation coefficient and acoustic impedance of the material can be achieved. Another possible solution is a structural modification of the backing layer. Backing structures such as a grooved backing and a backing block that includes an anechoic surface, which can prevent the back-wall echo signals from returning to the piezoelectric material, have been developed by a number of researchers [14–16].

To solve the aforementioned problems, a novel backing structure by using phase-cancelation scheme is proposed in this study. In the proposed backing structure, two types of reflections with the opposite phases were generated and canceled out each other. To verify the performance of the proposed backing structure, finite-element-method (FEM) simulations and experiments using a prototype 4.5 MHz single-element transducer were conducted. Additionally, the performance of the proposed transducer was compared with that of the conventional transducer for which a bulk-type backing layer was used.

2. Materials and methods

2.1. Phase-canceled backing structure

The suggested backing structure was derived from the physical principle of fixed- and free-end reflections, which means that the phase of the reflected wave is reversed at the fixed-end boundary and is maintained equally at the free-end boundary. In acoustics, the relative difference of the acoustic impedance between two materials can form the boundary of the fixed- or the free-end reflection. When an acoustic wave enters into material with a higher acoustic impedance, the reflected wave is in-phase compared with the incident wave. Conversely, when the acoustic wave enters into material with a lower acoustic impedance, the reflected wave is out-of-phase compared with the incident wave [22–24]. This phenomenon can be described by the reflection coefficient of the acoustic-wave pressure, as shown in Eq. (1). The sign of the reflection coefficient R is positive in $Z_1 < Z_2$, and negative in $Z_1 > Z_2$. This means that the phase of the reflected pulse depends on the order relation of the acoustic impedance of the two different materials. The suggested backing block includes both a low-Z-to-high-Z interface and a high-Z-to-low-Z interface through the use of multiple backing materials. Therefore, reflected signals with the flipped and non-flipped phases can be generated simultaneously in the suggested backing structure, as follows:

$$R = [(Z_2 - Z_1)/(Z_2 + Z_1)], \tag{1}$$

where Z_1 and Z_2 are the acoustic impedances of material 1 and material 2, respectively. Note that these descriptions are based on the assumption that the total backward energies generated from the piezoelectric layer are transmitted to the backing material perpendicularly, i.e., normal incidence.

For the phase-cancelation effect, the generation time of the reflected pulses should be the same at both interfaces in the suggested backing block, as shown in Fig. 1. That is, the difference of the wave velocity of the materials is compensated by the thickness control of the two front materials. By controlling the thicknesses d_1 and d_2 based on the sound velocity of the individual material, the reflected waves with the opposite phase can be generated at the same time (Eq. (2)) [1,2], as follows:

$$d = t{\cdot}c/2, \tag{2}$$

where d is the thickness of the material, c is the sound velocity in the material, and t is the generation time of the reflected wave at the interface. For example, if the wave velocities of two materials are 1000 m/s and 2000 m/s, respectively, and the generation time of the echoes is randomly set to 1 μs, then each of the thicknesses d_1 and d_2 would be 0.5 mm and 1 mm according to Eq. (2). Therefore, the phase of the reflected waves can be canceled out through two different interface conditions that are controlled by the specific acoustic impedance and the thickness of the backing material. After the phase cancelation, the remaining energy is propagated to the rear-most attenuating material with the intermediate acoustic impedance of the other two materials. In the rear-most backing material, the remaining acoustic energy is dissipated because the energy becomes weak due to the abruption effect. Consequently, even if the total thickness of the backing layer is thin, the suggested phase-canceled backing structure can minimize the reverberation generation.

2.2. FEM simulation

The FEM simulation was conducted to demonstrate the performance of the proposed backing structure. By using the PZFlex (Weidlinger Associates, Los Altos, CA) program, a single-element transducer with the suggested backing structure was designed [25]. For the performance comparison, two single-element transducers with thin and thick bulk-type backing layers were also designed. All the specifications of the designed transducers were identical to each other except for the backing element. The simulation parameters are summarized in Table 1, and all the simulations were performed through three-dimensional transducer modeling with no matching layer to focus on the pure effect of the backing layer. The thickness of the suggested backing model was determined by setting the generation time of internal-reflected pulse to 0.45 μs. The acoustic properties of the backing materials were experimentally obtained to increase the reliability of the simulation. Because we considered the connection of the electrical cable and insulation, one side of the piezoelectric layer was fully filled with a

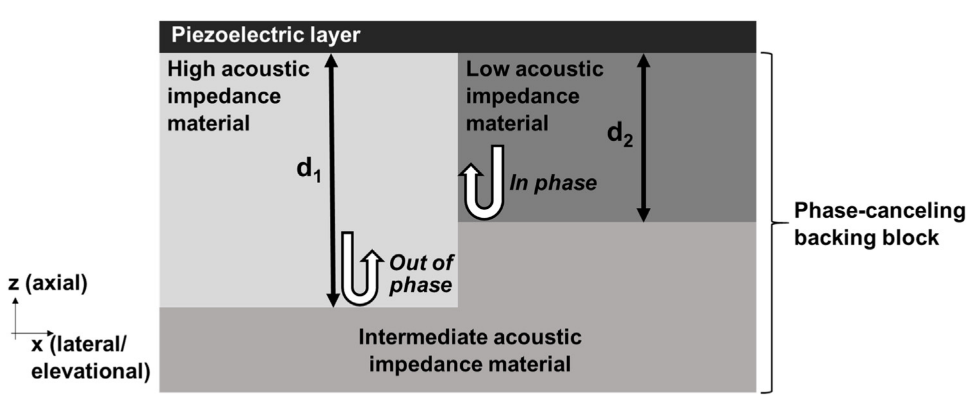

Fig. 1. Cross-sectional structure of the proposed phase-canceled backing structure.