Design and Fabrication of Linear Array Transducer for Ultrasonic Medical Imaging System

초음파 의료 진단기용 선형 배열 변환기의 설계 및 제작

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ABSTRACT

In this paper, design and fabrication of linear array transducer for ultrasonic medical imaging system are described. Design is done by computer simulation using KLM model which is very useful for the case of pulse excitation. The operating frequency of designed transducer is 3.5MHz and the length of it is 120mm with the width of 13mm. The designed transducer has 64 elements each of which is composed of 8 sub-elements. The designed and fabricated transducer has 2 matching layers to increase bandwidth and energy transfer and focusing is done by the shape of piezoelectric ceramic. The performance of fabricated transducer is evaluated and compared with the performance of commecial transducers under the same condition. In conclusion, the fabricated transducer has good characteristics and it can be applied to ultrasonic medical imaging system.

요 약

본 논문에서는 초음파 의료 진단기용 선형 배열 변환기의 설계 및 제작을 수행하였다. 설계시에는 펄스 인가시의 경우 유용한 등가회로인 KLM 모델을 이용한 전산기 모의실험을 행하였다. 설계된 변환기는 동작 주파수 3.5MHz, 길이 120mm인 변환기이며 폭은 13mm이며 8개의 부소자로 이루어진 64개의 소자를 갖는 변환기이다. 설계, 제작된 변환기는 효율적인 에너지 전달과 광대역 특성을 갖도록 하기 위하여 2개의 음향 정합층을 갖도록 하였으며 압전 물질의 형태에 의해 집속되도록 하였다. 제작된 변환기의 성능 비교를 위해 제작된 변환기와 상용의 변환기의 성능을 동일한조건에서 측정하였다. 측정결과, 제작된 변환기는 우수한 성능을 갖는것을 확인하였으며 실제 초음파 영상진단기에 사용할 경우 좋은 상을 얻을 수 있었다.

I. INTRODUCTION

Although the beginning of the acoustical imaging technology is generally credited to Paul Langevin, a French scientist, the use of acoustical signal to produce image information was first proposed by the Russian scientist, S.J.Sokolov, who is best known for the discovery of the utility of sound as a means of encoding image information[1]. After Sokolov's work, the acoustical imaging systems have been developed very rapidly with the development of the piezoelectric materials. Ultrasonic imaging system has been used in such fields as

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the underwater probes or geological investigation in which light wave or electromagnetic wave can not be applied. Nowadays, ultrasound can be applicable to NDT(non-destructive testing), SAM (scanning acoustic microscopy), and medical diagonostic imaging system, etc.

Medical ultrasonic imaging system which can be used to obtain the image of human body in real time is noninvassive and more economic when compared to the other medical imaging systems such as X-ray system or MRI(magnetic resonance imaging) system. But it has poor resolution compared to the other systems.

Medical ultrasonic imaging system can be divided largely into three parts. The first is transducer which performs the conversion of electrical energy into mechanical energy, and conversely mechanical energy into electrical energy. And the second is signal processing unit. The display unit is the third. In those three parts of the system, the transducer is the heart of any medical ultrasound imaging system because it determines the resolution of the system which is the key characteristics of the imaging system.

In this paper, the design by computer simulation and fabrication of the linear array transducer for medical ultrasonic imaging system and the measurement of the fabricated transducer are described.

Ⅱ. WIDE BAND ULTRASONIC TRANSDUCER

1. Basic structure and performance of the wide band ultrasonic transducer

Transducers for ultrasonic imaging systems are basically wide band transducers with the frequency range of 0.1-10 MHz. The basic structure of the wide band transducers is illustrated in figure 1.

The role of each part is as follows[2].

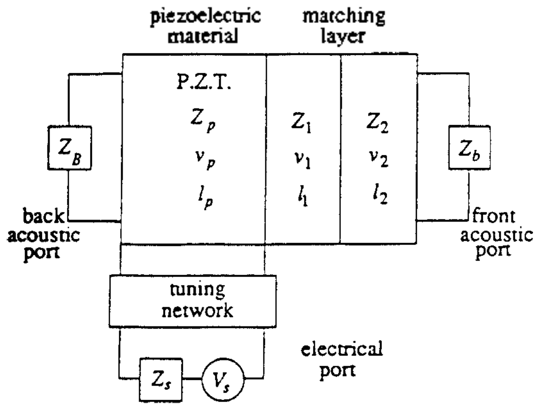


Figure 1. Basic structure of wide band ultrasonic transducer.

(1) Piezoelectric material

Piezoelectric material is an active component which generates and receives ultrasonic signal. Thus it is the most important part in transducer. The sensitivity and axial resolution are closely related to the electrical and mechanical properties of the piezoelectric material. The most frequently used piezoelectric material in ultrasonic transducer is piezoceramics, especially Lead Zirconate Titanate (which is called P.Z.T.) because they have high piezoelectric and electromechanical coupling constant and stable characteristics and can be easily matched to the electrical circuits.

(2) Matching layer

The large acoustic mismatch between the ceramic and the biological tissue makes it difficult to transfer acoustic energy into biological tissue. Thus it is necessary to use special matching arrangement to improve the bandwidth and sensitivity of transducer by lowering the gradient of acoustic impedance between ceramic and biological tissue.

For three layer system(ceramic : matching layer : biological tissue), complete transmission will take place for

$$Z_m = \sqrt{Z_c \cdot Z_b}, \quad l = \lambda / 4 \qquad (1)$$

where Z_m : the acoustic impedance of matching layer

Z_c : the acoustic impedance of piezoceramic

Z_b : the acoustic impedance of biological tissue

l : the thickness of the matching layer

λ : the wavelength of ultrasonic wave in matching layer[3].

(3) Backing layer

The ultrasound wave that is propagated into the back side of the piezoelectric material is reflected to increase the ringing of the ultrasonic pulse. Thus the train of pressure impulses generated by a transducer must be damped efficiently by using lossy backings whose acoustic impedance Z_B is comparable to the impedance Z_c of the piez oelectric ceramic. But the absorption of sound by the backing is increased by using Z_B as close as Z_c, and the sensitivity of the transducer is lowered. So it must be comprised between sensitivity and short pulse.

(4) Tuning

Piezoelectric ceramic is a kind of dielectric material. Thus capacitance of the ceramic increases the rise time of the transducer when using the transducer as a transmitter and it reduces the output of receiver operating as a load.

Therefore it is necessary to cancel out the capacitance by using inductance.

(5) Acoustic lens

To improve the lateral resolution of the transducer, acoustic lens is used. The shape of the lens is circular or parabolar. When the sound speed of acoustic lens is less than that of biological tissue, acoustic lens should be convex. And when the sound speed of lens is more than that of biological tissue, acoustic lens should be concave. The materials for acoustic lens are epoxy or rubber because they have low absorption. If the material for the acoustic lens is epoxy, the lens should be concave and if it is rubber, the lens should be convex.

2. Performance Characteristics[4]

(1) Resolution

The most important characteristic of medical ultrasonic transducer is resolution. Axial resolution is the ablity to discriminate reflectors in axial direction. Axial resolution is improved when the ultrasonic pulse generated by the transducer is short. And the ultrasonic pulse can be short when transducer has wide bandwidth characteristic. The parameters for axial resolution is -20dB or -40 dB ring down time of the pulse-echo or -3dB or -6dB bandwidth of the frequency spectrum of the ultrasound pulse.

Lateral resolution is determined by the material characteristics of transducer such as size, shape, and frequency of the transducer. For clinical application, focused transducers or electronically focused transducers are used so that the lateral resolution is improved. Specially for array transducer, the lateral resolution of length direction of the array is improved by electronic focusing wheras that of width direction is improved by using acoustic lens.

Usually the resolution of transducer is improved by increasing operating frequency but as frequency is higher, the sensitivity of transducer is lowered and the range will be shortened. Therefore, there must be a trade off between resolution and sensitivity.

(2) Sensitivity

Sensitivity is difficult to define because it is related with many variables such as transmitting and receiving circuit, signal processing and display unit. Usually sensitivity is represented by the voltage which is received in pulse-echo in same condition or the round trip insertion loss(RTIL) in pulse-echo. RTIL means energy conversion efficiency excluding other effects except transducer. As mentioned before, since sensitivity and resoultion are conflicted, it is necessary to make compromises between them depending on the purposes of the transducer.

(3) Dynamic range of the image

The effective resolution of most ultrasonic imaging system is related to the off-axis amplitude of the beam. Dynamic range of the image is defined by the ratio of on-axis response to maximum off-axis response. The causes of off-axis response are side lobe and grating lobe which is the result of systematic arrangement. When the off-axis amplitude of the beam is high, it reduces the dynamic range of the image and in extreme cases, produces multiple images of the same target. Other causes of degrading the dynamic range of the image are cross coupling between array elements and quantization error of the delay time

Ⅲ. DESIGN AND FABRICATION OF LINEAR ARRAY TRANSDUCER

1. Design of linear array transducer

As operating frequency increases, the resolution of transducer is improved both axial and lateral direction but it limits the depth that can be used because the attenuation of sound in biological tissue is proportional to the square of frequency. Therefore, there must be a compromise between operating frequency and resolution. In this paper, the operating frequency is determined as 3.5MHz and length 120mm. The designed and fabricated transducer has 64 elements and each element has 8 sub-elements to reduce side lobe amplitude, and the width of transducer is 13mm. Figure 2 shows the structure of linear array transducer.

The acoustical impedance of matching layer can be calculated from complete transmission condition equation (1). But the condition is applicalbe only to a single frequency and not applicalbe to wide band case. Moreover, it doesn't reflect the case where the medium is not infinite. In this paper, the acoustical impedance of matching layer is calculated from the result of DeSilet et al., considering finiteness of biological tissue as in equation (2)[5].

$$Z_{m1} = \sqrt[7]{Z_c^4 \cdot Z_b^3}$$
$$Z_{m2} = \sqrt[7]{Z_c \cdot Z_b^6}$$

where Z_{m1} : the acoustic impedance of 1st matching layer

Z_{m2} : the acoustic impedance of 2nd matching layer

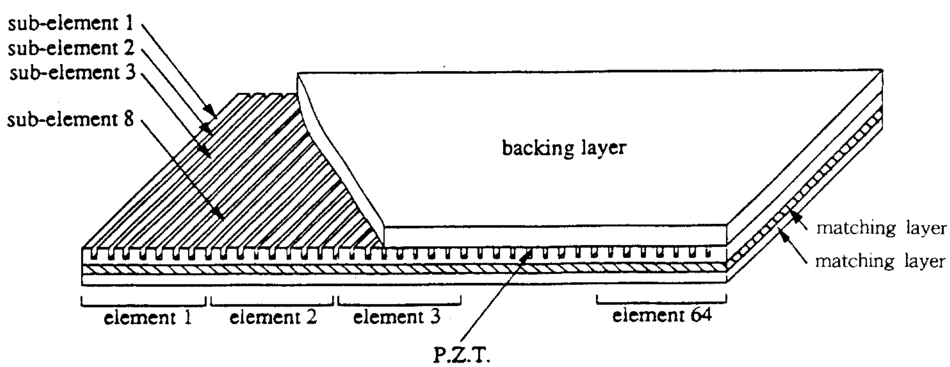


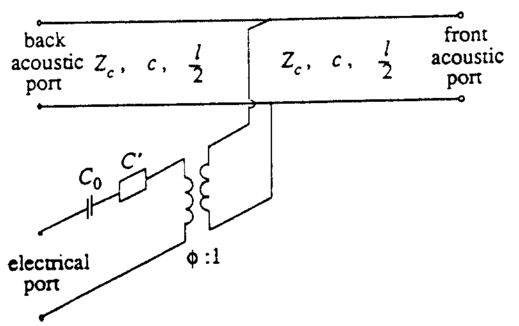
Figure 2. The structure of linear array transducer

Z_c : the acoustic impedance of piezoelectric ceramic

Z_L : the acoustic impedance of medium(biological tissue)

In the design process of ultrasonic transducer, it is helpful to use equivalent circuit simulation because the equivalent circuit simulation is based on its ability to predict the frequency-dependent electrical impedance, and the transmitted and received ultrasound waveforms for a specific transducer. Numerous equivalent circuits have been proposed to explain the electrical and mechanical characteristics of ultrasonic transducers. A particularly useful equivalent circuit was proposed by Krimholtz, Leedom, and Matthaei(KLM model)[6]. The parametes used in the KLM model are summarized in figure 3. Here, the roles of the electrical and mechanical parts are clearly distinguished. The KLM model is very useful for the case of pulse excitaion. Figure 4 is the result of computer simulation which shows the impulse response of the designed transducer.

Usually, focusing along width direction is accomplished by acoustic lens. In this paper, however, piezoelectric material is curved so that focusing is done by the shape of piezoelectric ceramic itself as illustrated in figure 5. The curvature of piezoelectric ceramic is 80mm, which determines the focal point of the transducer.



l : thickness of the piezoelectric material

c : sound velocity in the piezoelectric material

k_t : piezoelectric coupling constant

ω : resonance angular frequency

$C_0=\frac{\varepsilon^s A}{l}$ (clamped capacitance)

$Z_c=Z_0 \cdot A$

Z_0 : acoustic impedance of piezoelectric material

A : area

$$\phi = k_t\sqrt{\frac{\pi}{\omega_0 C_0 Z_c}}\,\mathrm{sinc}\left(\frac{\omega}{2\omega_0}\right)$$

: acousto-electric transformer ratio

$$C' = \frac{-C_0}{k_t^2\,\mathrm{sinc}\left(\frac{\omega}{\omega_0}\right)}$$

Figure 3. KLM model.

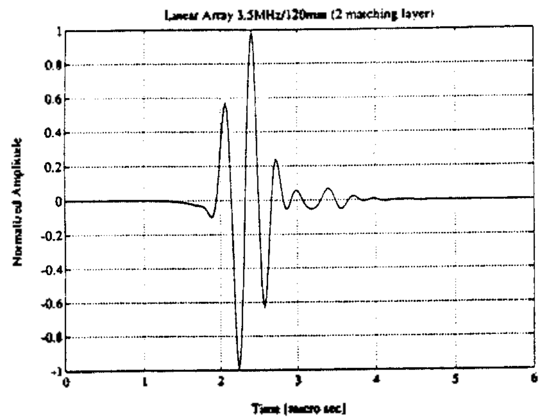


Figure 4. Simulation result of impulse response of the designed transducer.

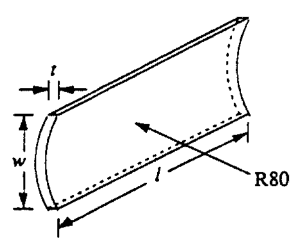


Figure 5. The shape of line focusing type piezoelectric ceramic

2. Fabrication process

For piezoelectric material, P.Z.T. made by Daewon Ferrite Co. is employed to make linear array transducer. The characteristics of employed ceramic is measured by Hewlett Packard's LF 4192A vector impedance analyzer and the result is showed in table 1.

The fabrication process is as follows.

(1) Apply 1st matching layer to the negative side of piezoelectric plate. The acoustic impeadance of 1st matching layer is 8.92 Mrayl from equation (2) where the acoustic impedance of ceramic is 34 Mrayl and the acoustic impedance of biological tissue is 1.5 Mrayl. Materials for matching layer should easily control the acoustic impedance of matching layer and have low internal loss not to lower the sensitivity. In this paper, tungsten carbide powder and epoxy are used into appropriate ratio, and the realized acoustic impedance of 1st matching layer is 8.51 Marayl.

(2) After curing 1st matching layer, grind it into required thickness.

(3) Apply 2nd matching layer. The acoustic impedance of 2nd matching layer is 2.34 Mrayl from equation (2). And the epoxy whose acoustic impedance is 2.92 Mrayl is used.

(4) After curing and grinding of 2nd matching layer, cut the P.Z.T. ceramic to form the elements of transducer into the specified size to 80-90% of whole thickness. Cutting is done by dicing saw DAD-2H / 5 of Disco Company.

(5) Solder copper wire at the edge of the diced ceramic along the length direction.

(6) Cut copper wire on the ceramic using sawing machine so that 8 sub-elements form 1 element.

(7) Connect each element to PCB electrically with wire by soldering. When soldering, care must be taken not to depolarize the ceramic.

(8) Apply backing layer. In this paper, alumina powder, silicon rubber, and epoxy are mixed in proper ratio to form the backing layer, whose acoustic impedance is 2.74 Mrayl.

(9) After curing backing layer, put the fabricated transducer into housing and mold it with epoxy.

Table 1. The performance characteristics of used piezoelectric ceramics.

length[mm]	120	coupling constant k_t	0.51
width[mm]	13	mechanical Q	74.2
thickness[mm]	0.58	capacitance[nF]	54.9
piezoelectric charge constatn $d_{31}[\times 10^{-12} m / V]$*	-173	piezoelectric volatage constatn $g_{31}[\times 10^{-3} Vm / N]$*	-10.9
density[kg / m^3]	7270		

*3-1 mode is easy to measure and these constants are listed to compare the performance of piezoelectric ceramic.

Ⅳ. EXPERIMENT AND RESULT

The performance of fabricated transducer is measured as in figure 6 and the result is illustrated in figure 7. In figure 7, (a) is the impulse response of transducer and (b) is the frequency specturm. The performance characteristics of the fabricated transducer is listed in table 2. For medical ultrasonic transducer, pulse width should be within 1 μs and bandwidth should be above 40%. Pulse width of the fabricated transducer is 0.9μs and bandwidth of it is 44.3% so both characteristics of the fabricated transducer are good when compared to standard characteristics.

To compare the performance of the fabricated transducer, two commercial transducers are measured under the same condition. The results of measurement of the commercial transducers are listed in table 2. Pulse width of the fabricated transducer is a little longer than that of commercial transducer A but the sensitivity of fabricated transducer is better than those of commercial transducers.

As for frequency spectrum, the commercial transducers have somewhat wider bandwidth than fabricated transducer and the shapes of spectrum are almost same. As the impulse response is the

Fourier transform of the frequency response, the ideal bandpass characteristic for a short impulse response with minimum ringng is a Gaussian shape, and both fabricated and commercial transducers have Gaussian shape of frequency response. The center frequency of the fabricated transducer is somewhat lower than was originally designed. This is because neither bulk waves nor surface waves may propagate when the transducer dimensions become smaller or nearly equal to the acoustic wavelength in the ceramic transducer material. Only guided waves of the Lamb type may occur with symmetrical or antisymmetrical mechanical displacement fields[7]. So the optimum thickness of the transducer departs from the classical half--resonance-wavelength value, computed from the bulk longitudinal wave velocity. The performance characteristics of all transducers are listed in table 2. Here, the values in table 2 are averages of measurements of 16 elements.

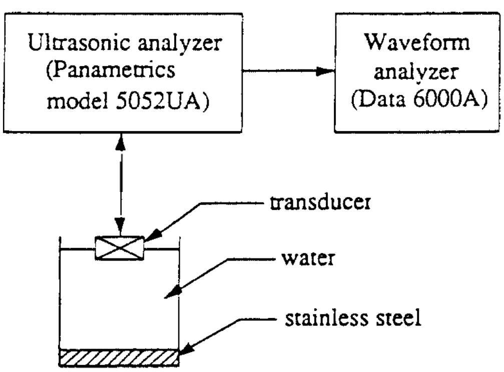
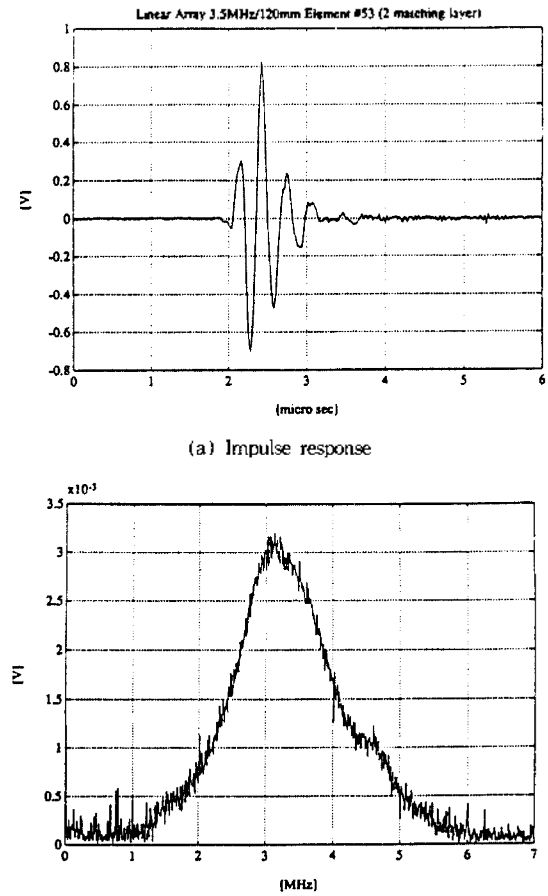


Figure 6. System for measurement of pulse-echo.

Figure 9 shows the image of phantom by the fabricated transducer. The phantom is made by ATS Laboratories which is equivalent to human body and the original looking is illustrated in figure 8. The system used to take these pictures is made by Medison Co. and it operates 16 channels simultaneously and has 4 foci along the axial direction.



(a) Impulse response

(b) Frequency response

Figure 7. Measurment result of the fabricated transducer.

Table 2. Performance of the fabricated transducer.

transducers / items	Fabricated transducer	Commercial transducerA	Commercial transducerB
sensitivity $V_{p\text{-}p}$[V]	1.70	1.59	1.43
-20dB ring down time[μs]	0.90	0.87	0.96
center frequency f_c[MHz]	3.07	3.37	3.19
-6dB bandwidth[MHz]	1.36	1.45	1.60
-6dB bandwidth[%]	44.3	43.0	50.2

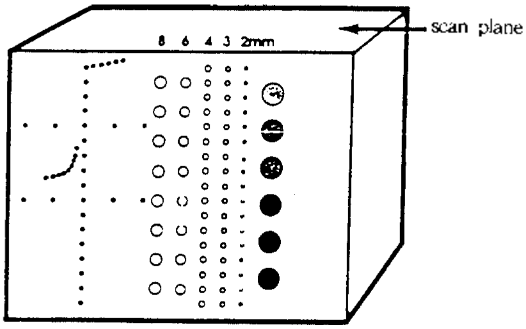


Figure 8. The original looking of the phantom.

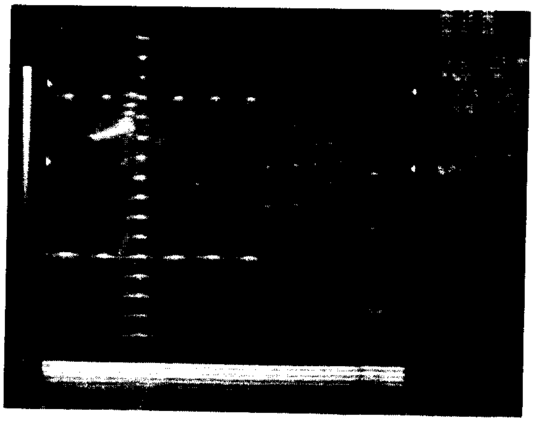


Figure 9. The image of the phantom by the fabricated transducer.

V. CONCULUSION

In this paper, the design and fabrication of linear array transudcer for ultrasonic medical imaging system is decribed. And the performance of the fabricated transducer is evaluated.

In the design and fabrication of ultrasonic transducer, the most significant problem is reproducability because the characteristics of transducer are related with many variables. Because of that, the design of linear array transducer is done by computer simulation using KLM model. The fabricated transducer has 64 elements each of which is composed of 8 subelements and the length of the transducer is 120mm, the width, 13mm and the operating frequency of it is 3.5MHz.

The performance of the fabricated transducer is measured and, for comparision, the performance of commecial transducers are measured in same condition. In conclusion, the fabricated transducer has good characteristics and when it is applied to ultrasonic medical imaging system, good image can be obtained.

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