THE DESIGN OF BROADBAND AND EFFICIENT ACOUSTIC WAVE TRANSDUCERS

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Abstract

The basic design criteria for SAW transducers is typically a flat frequency response. The basic design criteria for bulk wave transducers in nondestructive evaluation and medical imaging is the compactness of the impulse response. This criteria is different from the usual flat frequency response criteria because a flat bandwidth does not necessarily imply a compact impulse response. Aniterative optimization program, based on a least mean square algorithm, has been developed and used to simultaneously optimize matching metworks and acoustic parameters to achieve either of the above design criteria. The optimization is first illustrated in the frequency domain for an IDT transducer. Then the optimization is done in the time domain for a bulk wave transducer with the criterion of reducing the length of the impulse response. The impulse response is thus reduced from about 15 cycles to 3 cycles and has an almost Gaussian frequency response. The increase in the round trip insertion loss of the transducer due to the tuning is of the order of a few dB. Transducers have been constructed at 5 and 35 MHz with a backing of epoxy $(Z = 3\ kg/m^2\text{-sec})$ and no front matching layer. The agreement between theory and experiment is excellent.

1. Introduction

A number of techniques have been developed to design broadband flat frequency response matching networks[1-4] for acoustic transducers. The load is usually modeled as a resistor and capacitor[3] or as a simple four-element circuit.[4] The problem with this approach is that the frequency response of acoustic transducers has a resonance characteristic which is difficult to accurately mimic with the use of fixed component networks. In most cases, improved results can be obtained if the network suggested by one of the techniques listed in Refs. 1-5 is used as a starting point for an optimization routine which accurately takes into account the frequency dependent radiation resistance and reactance. An algorithm is developed in this paper for that purpose.

This algorithm is extremely flexible and can be used in the frequency domain or in the time domain to reduce the length of the impulse response. The use of this algorithm in the design of transducers with and without acoustic matching layers has resulted in impulse responses which are better than those obtained using any other technique.[5] In one example presented here, the impulse response of a PZT transducer operated directly into water was reduced from 15 cycles to 3 cycles with the use of a four-element optimized tuning circuit

2. Theory

Consider the system shown schematically in Fig. 1. Suppose the response of the matching network and load is $Y(\omega)$, where $Y(\omega)$ is any parameter which is to be optimized, such as voltage, current, or power. If the desired response is $D(\omega)$, then the error in the response is

$$E(\omega) = D(\omega) - Y(\omega) \qquad (1)$$

The response $Y(\omega)$ is a function of N adjustable real parameters β_n . These parameters are generally matching network parameters, such as inductance, capacitance, transistor gain, etc. This algorithm can also be used to simulateously design the transducer (load) and matching network, and in this case, the matching parameters also include transducer width, acoustic impedance, quarter wave matching layer, apodization, etc.

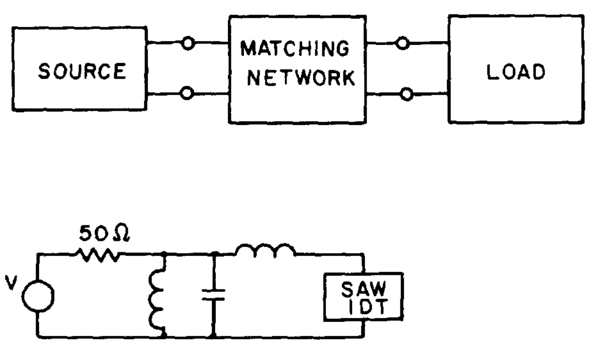

Figure 1 - Schematic drawing of source, matching network, and load.

The square error is

$$E(\omega)E^*(\omega) = [Y(\omega) - D(\omega)][Y^*(\omega) - D^*(\omega)] \qquad (2)$$

and the change in the square error due to a change $\Delta\beta_n$ is

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$$\frac{\partial[E(\omega)E^*(\omega)]}{\partial\beta_n} = E^*(\omega)\frac{\partial E(\omega)}{\partial\beta_n} + E(\omega)\frac{\partial E^*(\omega)}{\partial\beta_n} \quad (3)$$

$$= -2\mathrm{Re}\ E^*(\omega)\frac{\partial Y(\omega)}{\partial\beta_n} \quad (4)$$

The goal of this algorithm is to minimize the mean square error averaged over the frequency range ω_1 to ω_2, i.e. minimize ε where

$$\varepsilon = \int_{\omega_1}^{\omega_2} E(\omega)E^*(\omega)d\omega \quad (5)$$

To achieve this goal, we require that the change $\Delta\varepsilon$ for a change $\Delta\beta_n$ be negative

$$\Delta\varepsilon = \frac{\partial\varepsilon}{\partial\beta_n}\Delta\beta_n + \ldots < 0 \quad (6)$$

$$\approx -2\Delta\beta_n\ \mathrm{Re}\left[\int_{\omega_1}^{\omega_2} d\omega E^*(\omega)\frac{\partial Y(\omega)}{\partial\beta_n}\right] < 0 \quad (7)$$

There are a number of expressions that could be used to choose $\Delta\beta_n$. From Eq. (7) we see that $\Delta\varepsilon$ will be negative if we choose

$$\Delta\beta_n = \alpha_n\ \mathrm{Re}\left[\int_{\omega_1}^{\omega_2} d\omega E^*(\omega)\frac{\partial Y(\omega)}{\partial\beta_n}\right] \quad (8)$$

where α_n is a positive real constant. The change in ε is then

$$\Delta\varepsilon = -2\alpha_n\left\{\mathrm{Re}\left[\int_{\omega_1}^{\omega_2} d\omega E^*(\omega)\frac{\partial Y(\omega)}{\partial\beta_n}\right]\right\}^2 \quad (9)$$

which is negative as desired.

One of the conditions for convergence is that

$$\Delta\varepsilon < \varepsilon \quad (10)$$

Eq. (10) will be satisfied if

$$\alpha_n = \frac{\gamma\int_{\omega_1}^{\omega_2} d\omega E(\omega)E^*(\omega)}{2\left\{\mathrm{Re}\left[\int_{\omega_1}^{\omega_2} d\omega E^*(\omega)\frac{\partial Y(\omega)}{\partial\beta_n}\right]\right\}^2} \quad (11)$$

where γ is real and $0 < \gamma < 1$. The expression for $\Delta\beta_n$ becomes

$$\Delta\beta_n = \frac{\gamma\int_{\omega_1}^{\omega_2} d\omega E(\omega)E^*(\omega)}{2\mathrm{Re}\left[\int_{\omega_1}^{\omega_2} d\omega E(\omega)\frac{\partial Y(\omega)}{\partial\beta_n}\right]} \quad (12)$$

If we consider the simple case $N = 1$ in the limit $\omega_2 - \omega_1 \to 0$, then Eq. (12) becomes

$$\Delta\beta_n = \gamma\frac{E}{\frac{dY}{d\beta}} = \gamma\frac{E}{\frac{dE}{d\beta}} \quad (13)$$

This is the familiar expression used in Newton's method for finding the zero of the function E.

In general, the surface $\varepsilon(\beta_1, \beta_2, \ldots \beta_n)$ will have a number of local minima. Thus, it is important to use an appropriate set of starting conditions β_{n0} based on simple calculations, standard design rules, and intuition. This algorithm can then be used to find the local minimum. Alternatively, a set of starting conditions can be used and then the various minima compared.

The analysis given above is the same when the independent variable is frequency, time, phase, or any other parameter. For instance, consider the case where it is desired to optimize the impulse response $Y(t)$ of a transducer. The desired response $D(t)$ could be a one cycle sinusoid. From Eq. (12), a good choice for the change in each of the components for each iteration is

$$\Delta\beta_n = \alpha\frac{\int dtE^2(t)t}{2\int dtE(t)\frac{\partial Y(t)}{\partial\beta_n}} \quad (14)$$

However, the best results were obtained when an expression based on Eq. (8) is used for $\Delta\beta_n$:

$$\Delta\beta_n = \frac{G}{\frac{\partial G}{\partial\beta_n}} \quad (15)$$

where $G = 1/S^2\int_0^\infty E(t)tdt$ and S is the impulse peak amplitude. In this case, the algorithm tries to reduce the ripple, but also maximizes the transmission. If a larger exponent of S is used, then the importance of maximum transmission is emphasized. If a smaller exponent (1) is used, then minimum ripple is emphasized.

To calculate $\Delta\beta_n$, one starts with the measured or calculated transducer response and calculates the insertion loss of the network plus load, $Y(\omega)$. The Fourier transform $Y(t)$ is determined, and $\Delta\beta_n$ is calculated from Eq. (15). Due to the additional task of calculating Fourier transforms, the optimization in the time domain typically takes longer than optimization in the frequency domain.

However, as we shall see, the impulse response obtained optimization in the time domain is significantly better.

3. Results and Discussion

SAW Devices

The use of this algorithm will first be illustrated in the design of a matching network for a SAW Sezawa wave IDT. The goal was a frequency response which is between 0 and 1.5 dB over the frequency range 146 MHz to 183 MHz. The starting parameters for the optimization are given in Table 1. The optimization results after 1, 10, 100, and 130 iterations are shown in Fig. 2. The optimization was stopped after achieving a 1.5 dB bandwidth of 36 MHz. The final values of the network components (Table 1) are all easily realizable. Limits should be placed on the possible values of the network components during optimization so that a realizable filter is obtained.

Table 1 - Values used in optimizing the matching network of a Sezawa wave IDT

IDT Parameters: R = 250 Ω , C_T = .5 pF , C_p = .2 pF, N = 4 , W = 1 mm , Δv/v = .028

Matching Network Parameters:

	L_1 (μH)	L_2 (μH)	L_3 (μH)	C_1 (pF)	C_2 (pF)	C_3 (pF)
Initial	1	.1	.1	10	10	10
Final	1.35	.047	.024	8.93	17.7	68.3

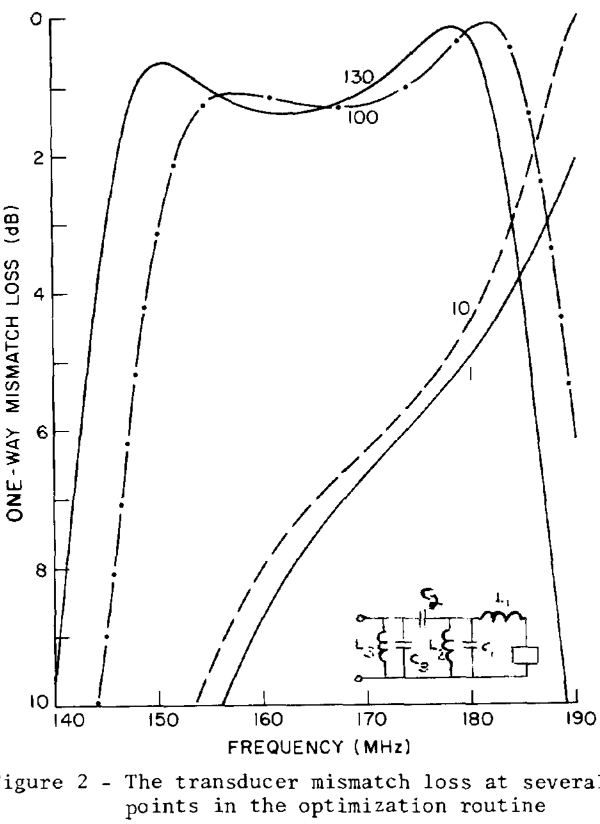

Figure 2 - The transducer mismatch loss at several points in the optimization routine

This algorithm can be used to simultaneously optimize the transducer beamwidth, number of finger pairs, finger width to spacing ratio, and apodization dependence, in addition to optimizing the values of the matching network.

Bulk Wave Transducer

The algorithm has been used to design a matching network for a longitudinal wave transducer. The transducer operates in water without any matching layers and has a lossy low impedance backing, namely epoxy with $Z_a = 3 \times 10^6$ kg/m^2-sec . Transducers have been designed and built to operate at a center frequency of 35 MHz . The transducer material used is Murata-PZT for the 35 MHz transducer. Figure 3 shows the insertion loss and impulse response of the 35 MHz transducer, where the active area is 2 mm in diameter. The design criteria used for the circuit components was a compact impulse response. A four-component matching network was designed in the configuration shown in Fig. 4. Figure 4 also shows the theoretical insertion loss and impulse response of the transducer with the proper matching network. Notice that the band shape is almost Gaussian and that the impulse response was reduced from 15 full cycles to 3 full cycles. Figure 5 shows the experimental results obtained for the transducer. The agreement between theory and experiment is excellent.

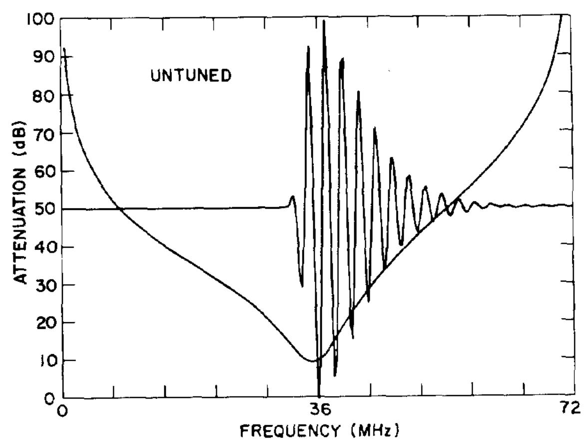

Figure 3 - Impulse response and frequency response of 35 MHz epoxy bonded PZT transducer operating into water

Bulk Wave Transducer Array

The algorithm has also been used to optimize the impulse response of the transducer elements in a linear array. Again, the design criteria used was a compact impulse response. The PZT-5H transducer elements are resonant at a center frequency of 3 MHz and have a width of 250 μm , a width-to-height ratio of 0.6 , a low impedance lossy backing $Z_a = 3 \times 10^6$ kg/m^2-sec , and one front matching layer. The optimized parameters in this case were: the transformer turn ratio (match into 50 Ω), the transformer inductance, and the length and impedance of the matching layer. Note that in this case both electrical and acoustic parameters are optimized. Figure 6 shows the insertion loss and impulse response of an array element designed with conventional method[5] assuming a matched source, namely $f/2f_0 = .9$ where f_0 is the resonant frequency of the piezoelectric ceramic and f is the resonant frequency of the matching layer. Figure 7 shows the insertion loss and impulse response of an array element designed with our optimization program. In this case, the thickness of the matching layer was such that $f/2f_0$ was 1.37 , and the impedance of the matching layer was 4.7×10^6 kg/m^2/sec. Notice that the impulse response in Fig. 7 is greatly improved over the impulse response of Fig. 6.

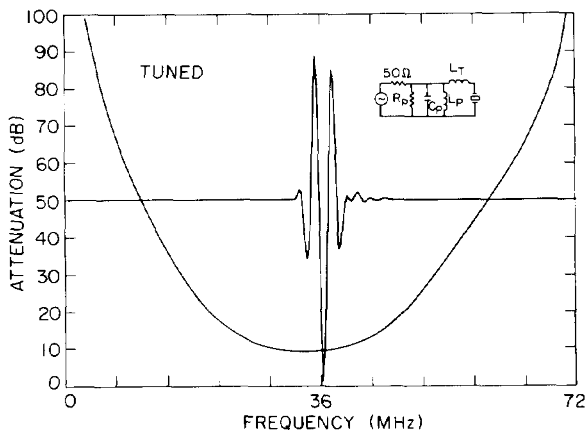

Figure 4 - Optimized impulse response and frequency response after 30 iterations

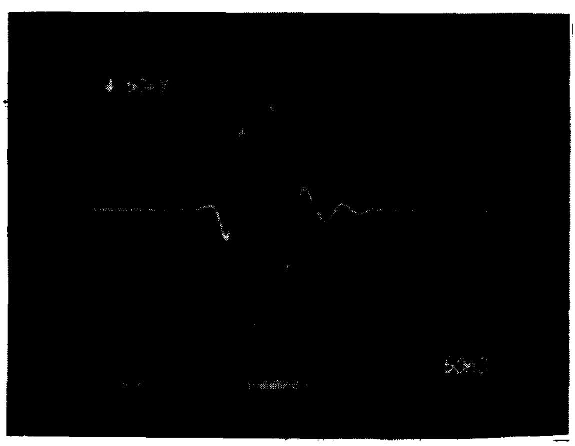

Figure 5 - Experimental results for the impulse response with and without matching network

4. Conclusion

A flexible algorithm has been developed which is important to the design of improved bulk and surface acoustic wave transducers. The impulse response of a PZT transducer operating into water was reduced from 15 cycles to 5 cycles with the use of this algorithm. The agreement between theory and experiment was excellent.

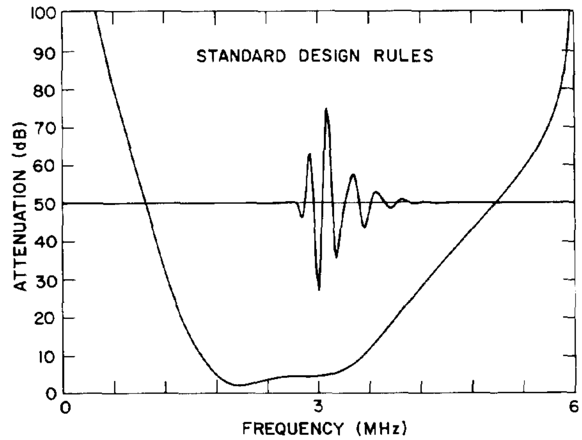

Figure 6 - Impulse response and frequency response of a 3 MHz PZT transducer with epoxy backing and a single matching layer. Standard design rules were used to obtain matching layer parameters

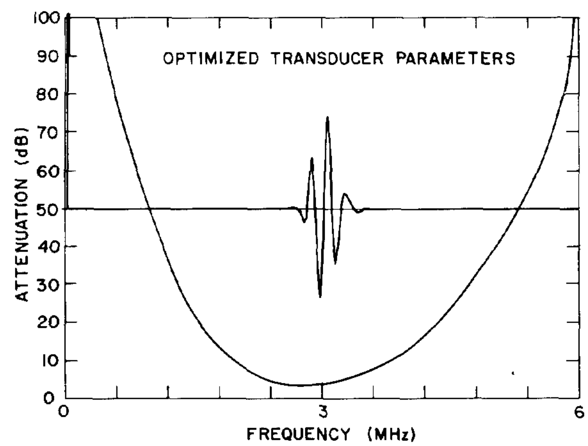

Figure 7 - Optimized impulse response and frequency response of the transducer shown in Fig. 6

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