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Research and Application of Broadband Matching Technology for Single Crystal Underwater Acoustic Transducer

Research and Application of Broadband Matching Technology for Single Crystal Underwater Acoustic Transducer

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Abstract. To solve the broadband matching problem of underwater acoustic transducer, a matching method based on network theory analysis and Monte Carlo algorithm is studied in this paper. In this study, the network function expression is obtained by designing the matching network, and then the objective function is constructed. Monte Carlo algorithm is used to find the optimal solution of the matching network parameters to realize the broadband matching of a piezoelectric single crystal underwater acoustic transducer. By comparing the broadband matching of traditional piezoelectric ceramic transducer, the performance of single crystal material transducer is better after matching, that is to say, it can obtain good gain and broaden the frequency band at the same time. The whole matching process is simple and efficient, the matching effect is good. It provides a feasible reference for broadband matching of new single crystal underwater acoustic transducer.

1. Introduction

Broadband matching of underwater acoustic transducer is an important content in the field of underwater acoustic signal emission equipment. Broadband and high-power underwater acoustic signal emission system is an important support in underwater acoustic engineering, and it is also a difficult problem to be solved. At present, PZN-PT and PMN-PT piezoelectric single crystal materials can meet the requirements of large bandwidth and high resolution. The underwater acoustic transducer designed by them has smaller impedance, easier impedance matching and larger strain, so the frequency band can be greatly widened [1]. The broadband matching method is usually to design a passive network between the transducer and the power amplifier, converting the impedance at the transducer end into the impedance matching the impedance at the power amplifier end, reducing the variation range of the impedance, expanding the bandwidth, and improving the working efficiency of the transducer transmitting system. In this paper, the network analysis of a piezoelectric ceramic and a piezoelectric single crystal underwater acoustic transducer is carried out to design an effective matching network. The parameters of each component in the matching network are determined by Monte Carlo algorithm, so as to expand the working bandwidth of the transducer [2].

2. Broadband Matching of Underwater Acoustic Transducer

2.1. Design of Matching Network

The common way of broadband matching is to insert a passive network between the power amplifier and the load to make the impedance conjugate matching. This network is also called matching network. In order to ensure the accuracy of the simulation, it is necessary to use accurate circuit model to analyse the influence of acoustic parameters changes. The matching network usually has no fixed mode and needs to be designed according to the specific type of transducer and bandwidth requirements. Because of its inherent characteristics, piezoelectric underwater acoustic transducer can be generally equivalent to *RLC* circuit in the working bandwidth, as shown in figure 1. C_0 is static capacitance, L_1, C_1 and R_1 is dynamic inductance, dynamic capacitance and dynamic resistance [3].

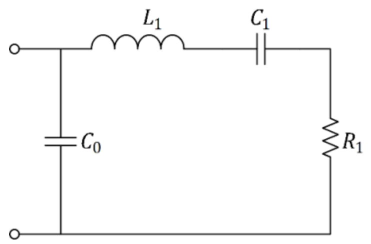

Figure 1. Equivalent circuit of transducer.

The input impedance Z_t and transfer function $H_t(s)$ of the transducer are shown in equations (1) and (2).

$$Z_t = \frac{R_1 + j[(-\omega^2 C_0 L_1 + C_0 / C_1 + 1)(\omega L_1 - 1/\omega C_1) - \omega C_0 R_1^2]}{(-\omega^2 C_0 L_1 + C_0 / C_1 + 1)^2 + (\omega C_0 R_1)^2} \tag{1}$$

$$H_t(\mathrm{s}) = \frac{sR_1}{s^2 L_1 + sR_1 + 1/C_1} \tag{2}$$

In equation (1), $\omega=2\pi f$ and f is frequency. When the transducer works near the resonant frequency, the input impedance is capacitive, while the output impedance of the power amplifier is pure resistance. There will be large reactive power in the system, and the power transmission efficiency is relatively low. Therefore, it is necessary to connect an inductor L_s in series with the transducer to adjust the load impedance and reduce the reactive power component. In order to adapt to the output signal with larger bandwidth, it is necessary to parallel capacitor C_p and inductance L_p to further reduce the reactive power component of the system, so that the output of the power amplifier is more stable and the output efficiency is maximized [4-5]. The equivalent circuit of the third order RLC matching network is shown in figure 2.

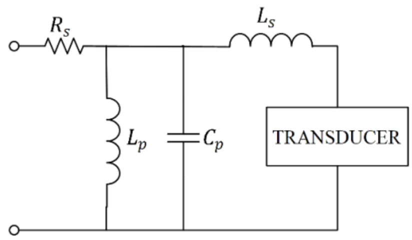

Figure 2. Equivalent circuit of matching network.

In figure 2, R_s is the internal resistance of the power amplifier, which has an important impact on the matching results. Therefore, it is analyzed together with the matching network to achieve the

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purpose of optimal matching. After the matching network is connected, the input impedance and transfer function of the equivalent circuit are shown in equations (3) and (6).

$$Z_m = R_s + \frac{\omega^2 L_p^2 R + j[\omega L_p (1-\omega^2 L_p C_p)(R^2 + X^2) + \omega^2 L_p^2 X]}{R^2 (1-\omega^2 L_p C_p)^2 + [X(1-\omega^2 L_p C_p) + \omega L_p]^2} \tag{3}$$

$$R = \frac{R_1}{(-\omega^2 C_0 L_1 + C_0 / C_1 + 1)^2 + (\omega C_0 R_1)^2} \tag{4}$$

$$X = \frac{(-\omega^2 C_0 L_1 + C_0 / C_1 + 1)(\omega L_1 - 1/\omega C_1) - \omega C_0 R_1^2}{(-\omega^2 C_0 L_1 + C_0 / C_1 + 1)^2 + (\omega C_0 R_1)^2} + \omega L_s \tag{5}$$

$$H_m(s) = \frac{Z_1}{Z_2 + R_s(1 + Z_2 / Z_3)} \cdot H_t(\mathrm{s}) \tag{6}$$

R and X in equation (3) are shown in equations (4) and (5). In equation (6), Z_0 is the impedance of series circuit of transducer, Z_1 is impedance of transducer, Z_2 is impedance of transducer connected with inductance, and Z_3 is impedance of capacitance and inductance in matching network. Their expressions are shown in equation (7).

$$Z_0 = R_1 + sL_1 + \frac{1}{sC_1}, \; Z_1 = \frac{Z_0}{sC_0 Z_0 + 1}$$

$$Z_2 = sL_s + Z_1, \; Z_3 = \frac{sL_p}{s^2 L_p C_p + 1} \tag{7}$$

It can be seen from equations (1) and (3) that the impedance of the transducer varies with the frequency, and the reciprocal of the impedance is the admittance, that is $Y=1/Z$, the real part is conductance G and the imaginary part is susceptance B. Therefore, the impedance or admittance characteristics of the network can directly reflect the matching results [6].

2.2. Objective Function

The current problem is how to select the optimal values for the four component parameters listed in the matching network, which requires a clear understanding of the optimal characteristics of transducer broadband matching. Generally speaking, the shorter the pulse response duration is, the wider the bandwidth is, and the better the broadband matching effect of the transducer is [7]. This property can be easily observed in the time domain, but in the frequency domain, we hope to have a wider passband. For this reason, the impulse response $h(t)$ of the system is calculated and the objective function F is defined as equation (8).

$$F = \frac{\int_{t_0}^{+\infty} |h(t)|(t - t_0)\mathrm{d}t}{A^2} \tag{8}$$

Where A is the peak value of the pulse response after matching, which is used to normalize the integral in molecules, and t_0 is the time of zero crossing after the peak value of impulse response. The expression indicates that the objective function is the normalized time weighted integral of the impulse response $h(t)$ after time t_0. The network satisfies the LTI(Linear Time Invariant) condition, so that $s=j\omega$ can be transformed into time domain by using the IFFT(Inverse Fast Fourier Transform) function in MATLAB to obtain $h(t)$. Based on the analysis of the component parameters of matching network, Monte Carlo algorithm is used to determine the values of four component parameters in the matching network to minimize the value of the objective function to meet the requirements of broadband matching. Therefore, the selection of t_0 is very important. If t_0 is selected too early, the system will have over damping, the peak value of impulse response is small, the energy is consumed by resistance, and the system gain is small. If t_0 is selected too late, there will be under damping or even no damping, and the impulse response duration is longer, which can't achieve the purpose of broadband matching.

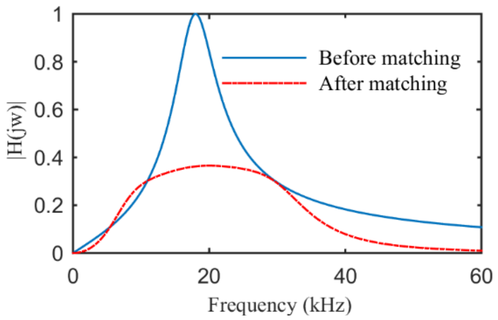
3. Simulation Analysis

At present, the component parameters of the equivalent circuit of a piezoelectric ceramic underwater acoustic transducer and PZN-PT single crystal piezoelectric transducer are available. In order to ensure the reliability of the comparison results, the central frequency and bandwidth of the two transducers are similar. The matching network and Monte Carlo global optimization algorithm are used to match the two kinds of underwater acoustic transducers, and the parameters of each component in the matching network are finally obtained [8-9]. After many simulations, the best result can be obtained when t_0=40*us*. The amplitude frequency characteristic curve, impulse response and input admittance varying with frequency can be obtained by combining the parameters of transducer elements, and then the bandwidth, amplitude, response speed and impulse response duration of the system before and after broadband matching can be analyzed.

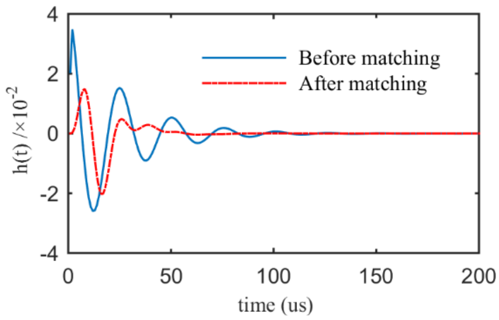
The center frequency of piezoelectric ceramic underwater acoustic transducer is 18*kHz* and the bandwidth is 5.92*kHz*. The equivalent circuit of transducer and the parameters of each element in the matched network are shown in table 1, and the matching results are shown in figure 3.

Table 1. Parameters of piezoelectric ceramic underwater acoustic transducer.

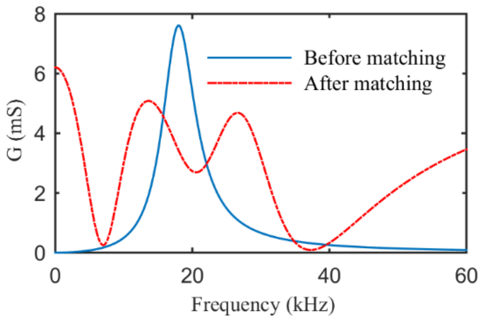
Transducer	Value	Matching network	Value
C_0	46.67*nF*	L_s	1.309*mH*
L_1	3.53*mH*	L_p	4.317*mH*
C_1	22.15*nF*	C_p	26.22*nF*
R_1	131.4*Ω*	R_s	161.12*Ω*



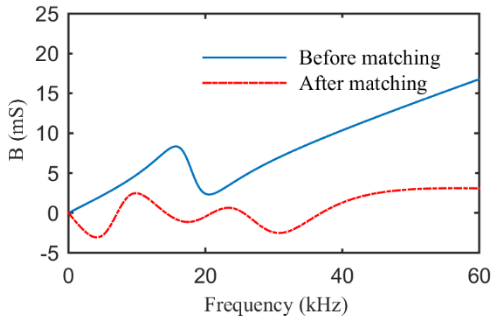
(A) Amplitude frequency characteristic



(B) Impulse response



(C) Conductance



(D) Susceptance

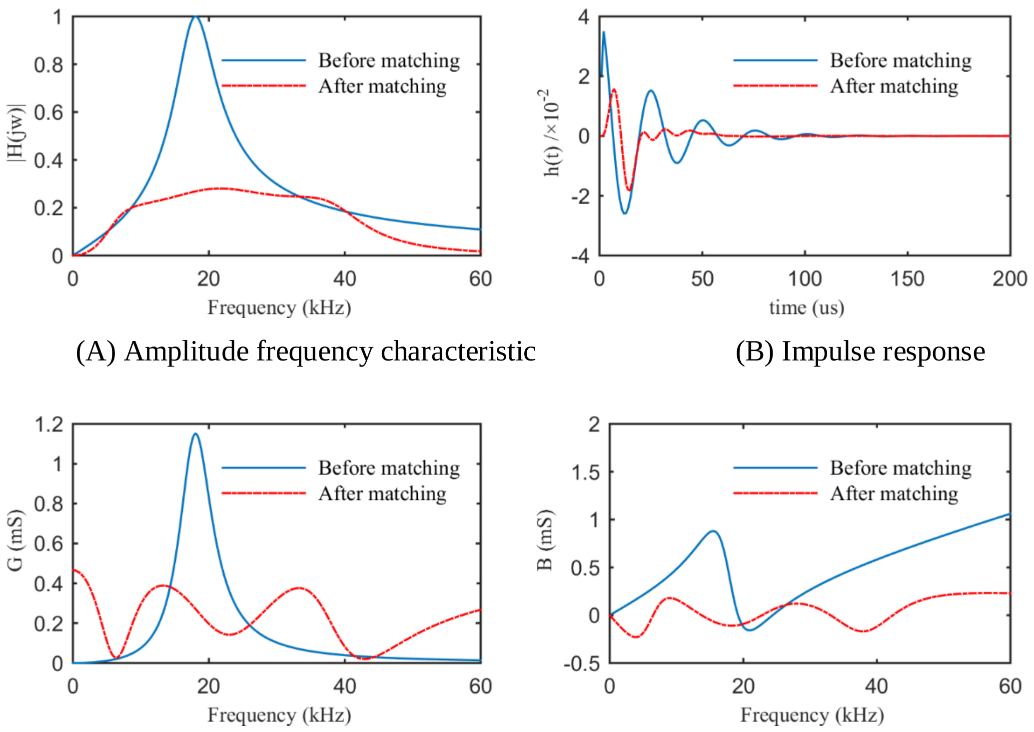
Figure 3. Matching results of piezoelectric ceramic underwater acoustic transducer.

According to the amplitude frequency characteristic curve in figure 3, the center frequency is 20.18*khz* and the bandwidth is 22.41*khz* after matching. Within the working bandwidth, the conductance before matching is between 3.8*mS* and 7.61*mS*, and the susceptance is between 2.31*mS* and 8.35*mS*, the conductance after matching is between 1.767*mS* and 5.085*mS*, and the input susceptance is between -2.52*mS* and 2.47*mS*.

The center frequency of single crystal underwater acoustic transducer is 18.05*kHz* and the bandwidth is 5.99*kHz*. The equivalent circuit of transducer and the parameters of each element in the matched network are shown in table 2, and the matching results are shown in figure 4.

Table 2. Parameters of single crystal underwater acoustic transducer.

Transducer	Value	matching network	Value
C_0	3.1458*nF*	L_s	11.57*mH*
L_1	23.105*mH*	L_p	36.8*mH*
C_1	3.3665*nF*	C_p	1.41*nF*
R_1	868.98*Ω*	R_s	1923*Ω*



(A) Amplitude frequency characteristic (B) Impulse response

(C) Conductance (D) Susceptance

Figure 4. Matching results of single crystal underwater acoustic transducer.

According to the amplitude frequency characteristic curve in figure 4, the center frequency is 23.97*khz* and the bandwidth is 30.9*khz* after matching. Within the working bandwidth, the conductance before matching is between 0.59*mS* and 1.15*mS*, and the susceptance is between -0.16*mS* and 0.88*mS*, the conductance after matching is between 0.11*mS* and 0.39*mS*, and the input susceptance is between -0.17*mS* and 0.18*mS*.

Through the simulation results, it can be seen that this method has achieved good broadband matching effect for two kinds of transducers with different materials. It can be judged from the amplitude frequency characteristic curve that the signal gain in the working bandwidth decreases after matching, that is, the attenuation of the signal increases, and the peak value of the corresponding impulse response curve decreases, but the bandwidth is widened several times. According to the impulse response curve, the response speed becomes slower, but the impulse response duration is shorter. After matching, the admittance range is reduced, the admittance is stable around 0 *mS*, and the system is closer to pure resistance in the working bandwidth. However, it is obvious that the matching effect of single crystal underwater acoustic transducer is better, the bandwidth is wider, the impulse response duration is shorter, and the admittance range is smaller.

4. Conclusion

This paper studied a broadband matching method, that is, a reasonable matching network is designed through network analysis, and an effective objective function is established. By comparing the broadband matching results of the two kinds of transducers, it can be seen that the performance of this method for single crystal underwater acoustic transducer is better than that of piezoelectric ceramic underwater acoustic transducer, the former is easier to match impedance, the frequency band range can be greatly widened to meet the needs of different working environments, and the underwater acoustic detection ability is improved.

Acknowledgments

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