Design of Broadband Matching Circuit for Underwater Acoustic Communication Transducer

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Abstract. The design of matching circuit for broadband underwater acoustic transducer is a key technology in sonar system. Matching circuit can reduce the energy loss of the power amplifier, extend the system bandwidth and improve the distortion of the transmitted waveform. In this paper, the theory of real frequency direct computational technique (RFDT) is discussed. Then, we design the matching circuit for a tubular transducer. Finally, the match performance is tested in anechoic pool. The results illustrate that the broadband matching circuit can expand the bandwidth and improve the efficiency of the transmitter. Compared with the transmitter without matching, the sound source level of the system increased about 10dB. Compared with the single inductor matching circuit, the work bandwidth is extended. The whole design process of broadband matching circuit completed with computer and without the equivalent circuit of the transducer, so the RFDT is fit for practical project.

Introduction

At present, the high speed underwater acoustic communications and underwater remote detection technology have been rapidly developed. The broadband signal technology is widely used in sonar equipment. The broadband transducer, wideband transmit system has become an important part of the sonar system, how to expand the operating frequency bandwidth and ensure the waveform with less distortion has become a key technology. In some sonar equipment which powered with battery, such as underwater acoustic buoy, portable communication sonar which has the limited energy that requires the transmit system with high work efficiency. Therefore the actual transmit system in the sonar equipment not only has a flat frequency response but also has a higher power factor and ideal waveform [1].

For the realization of sonar transmit system with high efficiency, a matching circuit must be used between the transducer and the power amplifier. In general, sonar system use linear power amplifier which has fixed output impedance, when determined the output power. For a piezoelectric ceramic transducer, the impedance varies with the frequency and difficult to be expressed by the analytical function, so it is difficult to achieve good broadband matching performance in a wide frequency range. At present, underwater acoustic transducer broadband matching circuits often used single inductor to get the available bandwidth or construct several resonance peaks to complete the matching circuit design in the transducer work band using multi-resonance method. But the actual matching effect cannot achieve the desired effect, it is difficult to satisfy the needs of broadband sonar [2] [3] [4] [5].

In recent years, the theory and method of broadband matching has been well developed, combined with computer aided (CAD) technology, a series of broadband matching numerical methods such as the direct optimization method, the real frequency method and genetic algorithm which widely applied in the antenna broadband matching and microwave amplifier design. Haiying Huang and Daniel Paramo [6] have described a method to estimation equivalent parameter with an ultrasonic piezoelectric transducer and completed the broadband matching circuit with Smith chart.

Yongshi [7] has described a computer-aided method to design the broadband FET amplifiers in microwave monolithic integrated circuit. Jianfei [8] has used genetic algorithm to design the matching network in a broadband ultrasonic transducer array. The above methods have got good matching results.

Real frequency direct computational technique

The real frequency technique is a kind of broadband matching methods of computer aided design. Its main idea is that the matching network impedance is described with the driving point function, while the transducer power (TPG) of the system can be expressed in a simple form of function by the driving point function and the actual data of the transducer. Use a nonlinear curve-fitting algorithm to optimize the TPG as high and flat as possible in the band of operation. Finally obtains the driving point function which optimized, synthesis the matching network which can be easy to realize in real engineering implementation. The real frequency technique without the load equivalent circuit model and analytical expression, also without selecting the topological structure and the analytical expression of the transfer function of the matching network, only need the initial value of the driving point function. The whole calculation is completed by the computer. Therefore, this method is suitable for practical engineering transducer with multi-resonant mode which the equivalent circuit parameters are difficulty to determine. The real frequency technology mainly includes the real frequency method, the real frequency direct computational technique (RFDT), simplified real frequency technique (SRFT) and parameter method. The basic idea of the above methods is the same, however, the computation complexity and computation stability are different [9].
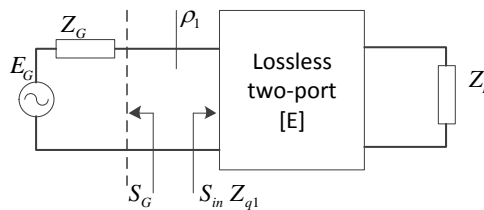

Figure 1.   The general matching problem diagram.

The general matching problem is shown in Fig. 1. E_G is an ideal voltage source and its output impedance is Z_G. E is a lossless two-port matching network with impendence Z_L which from the signal source to the load end. The load impedance is Z_L. ρ_1 is complex normalized reflection coefficient. S_G and S_{in} are called units normalized reflection coefficient from load to signal and from signal to load, respectively.
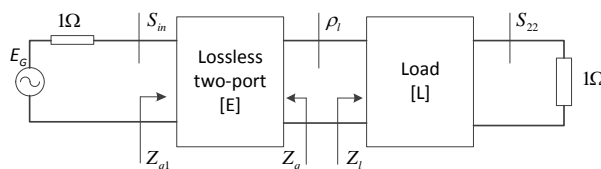

Figure 2.   The connection of the matching network.

Referring to Fig. 1 and Fig. 2, TPG of Fig. 2 is given by

$$T(\omega) = 1 - \left| \rho_1(j\omega) \right|^2 = 1 - \left| \frac{Z_G(j\omega) - Z_{q1}(-j\omega)}{Z_G(j\omega) + Z_{q1}(j\omega)} \right|^2 \quad (1)$$

The normalized reflection coefficient definition is given by

$$S_G = \frac{Z_G - 1}{Z_G + 1} \quad (2)$$

$$S_{in} = \frac{Z_{q1} - 1}{Z_{q1} + 1} \tag{3}$$

From (2) and (3), the TPG can be expressed as follows

$$T(\omega) = \frac{(1 - |S_G|^2)(1 - |S_{in}|^2)}{|1 - S_G S_{in}|^2} \tag{4}$$

As proven by the theorem of Carlin, S_{in} is given by (5)

$$S_{in} = \frac{h_q(s)}{h_q(-s)} \cdot \frac{Z_l(s) - Z_q(-s)}{Z_l(s) + Z_q(s)} \tag{5}$$

In (5), the function $h_q(s)$ is defined on the explicit factorization of the even part $R_B(s^2)$. The equation is given by

$$Z_q(s) = \frac{a(s)}{b(s)} \tag{6}$$

$$R_q(s^2) = \mathrm{E_v}\{Z_q(s)\} = \frac{A(s^2)}{B(s^2)} = \frac{n_q(s)n_q(-s)}{b_q(s)b_q(-s)} = h_q(s)h_q(-s) \tag{7}$$

$$h_q(s) = \frac{n_q(-s)}{b(s)} \tag{8}$$

Where $n_q(-s)$ is Hurwitz polynomial which includes the proper RHP and $j\omega$ axis zero of $R_q(s^2)$. $b(s)$ is Hurwitz polynomial which includes the proper LHP and $j\omega$ axis pole of $R_q(s^2)$.

Therefore, the TPG of the system can only expressed by a driving point impedance function of the matching network with a resistance terminated. Assuming $Z_q(s)$ as a minimum function, so $Z_q(s)$ can be expressed as $Z_q(s) = R_q(s) + jX_q(s) = R_q(s) + j\mathrm{Hilbert}\{R_q(s)\}$. Thus, for the direct method of broadband matching, the unknown of the problem is the rational from of the real part $R_q(s)$.

For practical matching problems, it's proper to choose the rational form of the real part is given by

$$R_q(\omega^2) = \frac{A_0 \omega^{2\,ndc} \prod_{i=1}^{nz} (\omega_i^2 - \omega^2)^2}{B_1 \omega^{2n} + B_2 \omega^{2(n-1)} + \ldots + B_n \omega^2 + 1}$$

$$= \frac{A(\omega^2)}{B(\omega^2)} \geq 0, \forall \omega \tag{9}$$

where

$$B(\omega^2) = \frac{1}{2}\left[c^2(\omega) + c^2(-\omega)\right] > 0 \tag{10}$$

Such that

$$c(\omega) = c_1 \omega^n + c_2 \omega^{(n-1)} + \ldots + c_n \omega + 1 \tag{11}$$

Once T_0 is selected, and the coefficients $\{c_j, j = 1, 2, \ldots, n\}$ and $A_0 = a_0^2 \geq 0$ of the real part $R_q(\omega^2)$ are initialized, the error function ε as follows

$$\varepsilon = \frac{(1 - |S_G|^2)(1 - |S_{in}|^2)}{|1 - S_G S_{in}|^2} - T_0 \tag{12}$$

Then the error function is minimized, which yields the realizable driving point input impedance $Z_q(s)$ of the lossless matching network. Finally, the driving point function is synthesized to get the parameter of the circuit.

Application

Broadband Matching Circuit Design

According to the theory of the real frequency direct computational method, a broadband matching circuit for a tubular transducer with oil filled is designed. The transducer used in deep sea communication sonar equipment, the max pressure is 60MPa, the frequency range is $7\text{kHz} \sim 16\text{kHz}$. The impedance characteristic of transducer is tested by using the impedance analyzer WAYNE KERR 6500B; the results are shown in Fig. 3. Different from the traditional transducer with single resonance mode, this transducer shows the multi-peak resonance in the working bandwidth. The impedance varies rapidly in bandwidth, the resistance fluctuates from $R(7\text{kHz}) = 100\Omega$ to $R(9.9\text{kHz}) = 337\Omega$, the reactance fluctuates from $R(7\text{kHz}) = -1.5\text{k}\Omega$ to $R(14\text{kHz}) = -0.98\text{k}\Omega$.
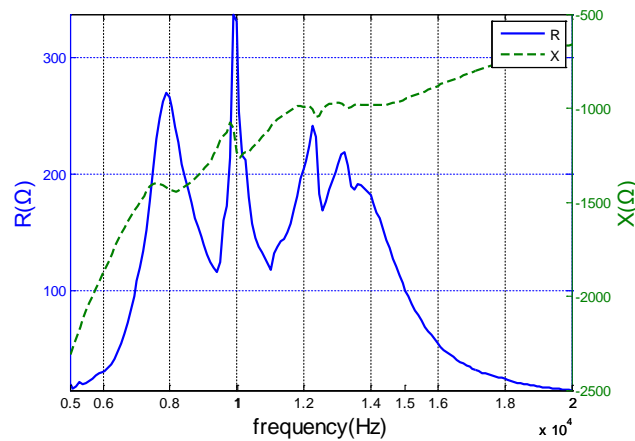

Figure 3.   The impedance curve of the transducer.

Determine the parameters of the RFDT program, target gain $T_0 = 0.75$; the matching network element number is 4; the bandwidth is 8kHz~14kHz; the matching circuit termination resistor is 100Ω. (The output impendence of linear power amplifier in the sonar system is 100Ω.) In order to make the TPG curve in the bandwidth as high and flat, the nonlinear least squares algorithm is adopted to optimize the error function in the program. The finally TPG curve is shown in Fig. 4 with the dotted line, the synthesized matching network circuit is shown in Fig. 5.

In order to observe the performance of the broadband matching circuit, a single inductor series matching circuit which commonly used in the engineering project is constructed, the circuit diagram as shown in Fig. 6. The transducer work frequency band which used in practical project is 8 kHz to 14 kHz. So constructed the series resonance peak at 11 kHz, the calculated series matching inductor is 13.5mH, the simulation curve of TPG is shown in Fig. 4 with the solid line.
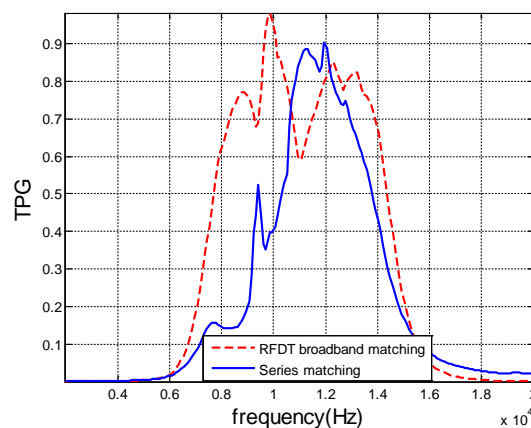

Figure 4.   The curve of TPG with different matching mode.

The TPG simulation curves with the two different matching methods show that the single inductor matching circuit has a low gain in the work band. Broadband matching circuit in the working bandwidth of TPG is higher than 0.6, but because of the resistance change in the bandwidth of the transducer, the TPG fluctuation is large, especially at 9.5 kHz and 11 kHz.

The simulation results show that the broadband matching circuit is better than single inductor series matching circuit in the working bandwidth of TPG.
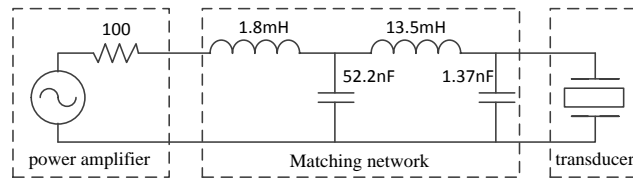

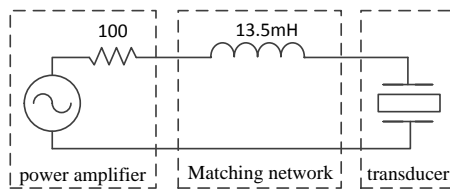Figure 5.   The schematic of Broadband matching circuit.

Figure 6.   The schematic of series matching circuit.

Design Results and Discussions

Fig. 7 is a transmitter-receiver system in the anechoic tank, with this system, the matching characteristics of the transducer was tested, the output power factor of the power amplifier and the source level of the transmit system were measured in order to evaluate the effect of broadband matching circuit. The transmitter and receiver separation of 2m was selected as shown in Fig. 7. Tone burst signal, used for the measurement, were produced by an Agilent 33522 function generator. Through a standard linear power amplifier JYH500A for the power amplified, the amplified signal via the matching circuit excite to the acoustic transducer for transmit signal. The Reson company TC4040 standard hydrophone was used to receive the acoustic signal, the phase difference between the output voltage and current of the power amplifier is measured by AngilentDSO7034B Oscilloscope. Then the output power factor was calculated. The output signal amplitude of the measure amplifier was observed by AngilentDSO7034B Oscilloscope to calculate the system sound level.
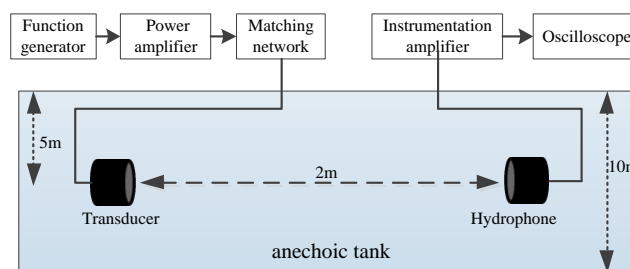

Figure 7.   Schematic diagram of experimental

The input impedance of the matching network and transducer was tested by impedance analyzer WAYNE KERR 6500B. Fig. 8 is the input impedance of matching network and transducer with single inductor series matching. The fluctuation of the resistance in the work frequency bandwidth is from $R(9.4\text{kHz}) = 117\Omega$ to $R(9.9\text{kHz}) = 333\Omega$, the fluctuation of the reactance in the work frequency is from $X(8\text{kHz}) = -670\Omega$ to $X(14\text{kHz}) = 411\Omega$. Compared to the original impedance of the transducer, the resistance of the transducer with series matching without too much change, the reactance of the transducer with series matching can be reduced, but only at the resonant point $f = 11\text{kHz}$ the reactance

of transducer is completely canceled, the reactance at other frequency is still large. Fig. 9 is the input impedance of the matching network and transducer with broadband matching circuit which designed in the last part. The fluctuation of the resistance in the work frequency bandwidth is from $R(8\text{kHz}) = 30\Omega$ to $R(12.6\text{kHz}) = 292\Omega$, the fluctuation of the reactance in the work frequency is from $X(8\text{kHz}) = -78\Omega$ to $X(11\text{kHz}) = 157\Omega$. In the operating frequency bandwidth, the reactance tends to 0, and the reactance value is 0 at frequency of 9 kHz, 12.6 kHz and 15 kHz. Therefore, from the part of input reactance of the matching network and transducer, the broadband matching is better than the single matching.

The output power factor of the power amplifier with different matching methods are shown in Fig. 10. For the 8 kHz to 14 kHz bandwidth, because the transducer presents capacitive, the output power factor of power amplifier with no matching circuit is from 0.1 to 0.2, the power amplifier in a mismatch state. About the single inductor series match, the output power factor is from 0.35 to 1, the best working characteristic is only at the resonance frequency. For the broadband matching mode, the output power factor is from 0.68 to 1. So, the broadband matching circuit can improve the output efficiency of power amplifier better, compared to the single inductor series matching circuit.

With the output voltage and impedance of the power amplifier unchanged. The source level of the transmit system with different matching methods are shown in Fig. 11. In the bandwidth over the 8 kHz to 14 kHz, compared with no matching system, the broadband matching circuit could improve the sound source level above 10dB for each frequency point. The single inductor series match system fluctuation is 10dB, the broadband matching system is 6.5dB. So the broadband matching circuit could improve the source level and extend the work band for the whole system.

Compared the output power factor of the power amplifier and system sound level with different matching methods, The results shows that broadband matching circuit can effectively improve the work efficiency, source level and extend the work band for the transmit system.
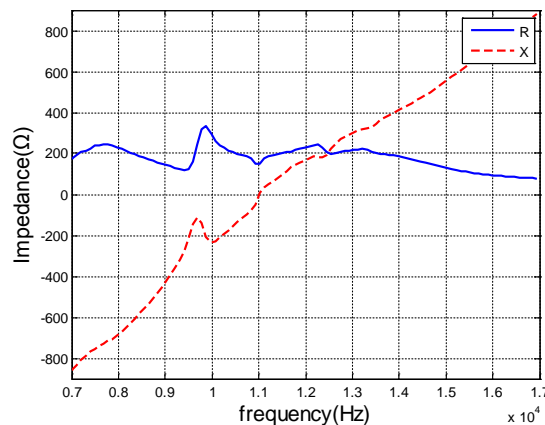

Figure 8.　　　　The impedance of series matching network and transducer
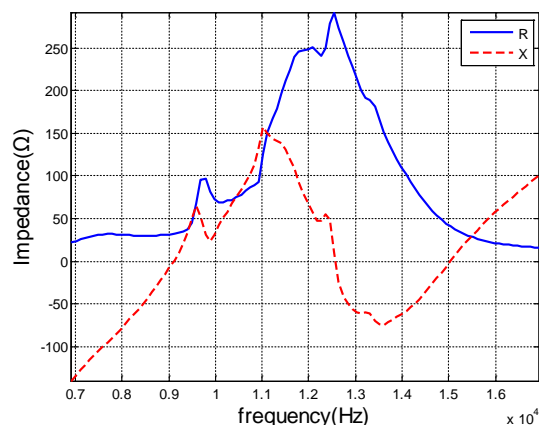

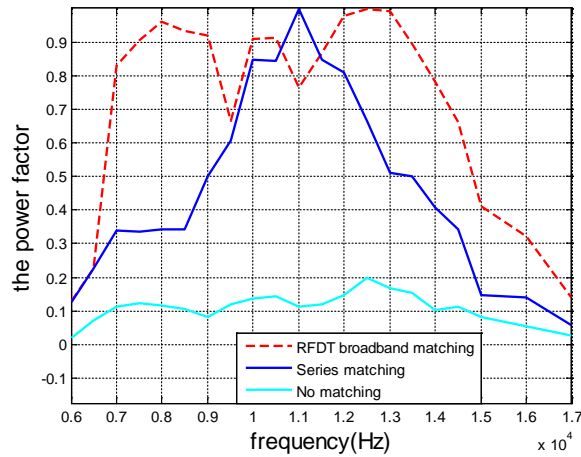Figure 9.　　　　The impedance of series matching network and transducer

Figure 10.   The output power factor of the power amplifier with different matching methods.
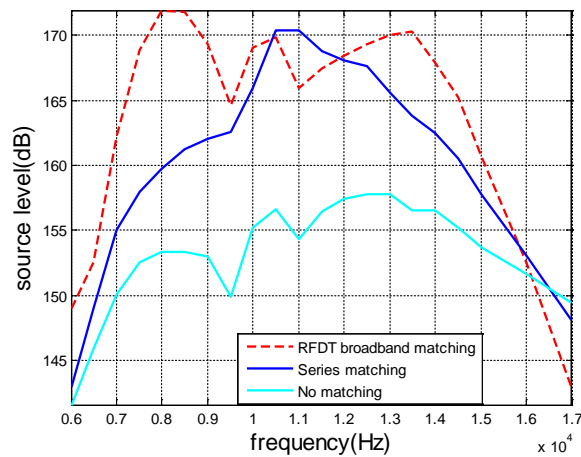

Figure 11.   The source level of the transmit system with different matching methods.

Conclusion

It is important to guarantee the transmit system which is an important part of sonar equipment with high efficiency and less distortion of transmitted signal. This paper adopted the real frequency technique to design the broadband matching circuit for transducer which causes the transmission system with low work efficiency and narrow work bandwidth. The experimental results indicated that the design of broadband matching network for the communication transducer improved the efficiency and extended the bandwidth of the system. Compared with the transmit system without matching, the sound source level increased about 10dB. Meanwhile the design of broadband matching circuit is completed by computer without the equivalent circuit of transducer. The matching circuit complex, the bandwidth of the matching circuit and the gain of TPG can be easily adjusted in this RFDT technique. Therefore, the real frequency technique has a great value in the actual project.

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