

Research of Weighting Circuits for the Design of Optimum Beamforming

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In underwater acoustic detection system, the performance of the system is greatly affected by beamforming techniques. For that reason, the design of optimum beamforming has been studied for a long time by many researchers. Weighting circuits are necessary to implement an optimum beamformer. In this paper, we introduce an array design software. It consists beampattern design tool(BeamCAD Tool), equivalent circuit modeling tool(Sensor Modeling Tool), and matching circuit design tool(Impedance Matching Tool). Together with this software, we also present a calibration technique for array weighting by using ABCD transmission parameters. Finally, we discuss the construction of weighting circuits for the design of optimum beamforming.

1 Introduction

In underwater, ultrasounds are used to communicate from one site to another site. When we design the beampattern for the SONAR, optimal weightings of the array considering beamwidth, sidelobe level, and directivity have to be calculated. After the design of beampattern, electrical weighting circuits are needed to weight each sensor of the array. And, it is necessary to construct matching circuits for the maximum power transfer from electrical energy to ultrasonic energy. Also, equivalent circuit modelings are required. Finally, it is important to calibrate the weightings while considering mutual impedance and the characteristic of each sensor.

In our previous research, the method for finding the parameters in the electrical weighting circuits by using the measured impedance and the software for the equivalent circuit modeling are presented. [1] And the algorithm which finds the parameter values of the matching circuits directly from the measured impedance and the software based on this method are also presented. [2]

In this paper, ABCD transmission parameters are used to compensate the effects of the mutual impedance and the characteristic of each sensor. [3] We present the efficient design method for the weighting circuits which is made up of the optimum beamforming tool, equivalent circuit modeling tool, matching circuits tool, and the calibration by using ABCD transmission parameters.

2 Acoustic interactions in array

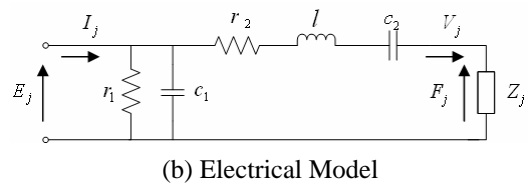
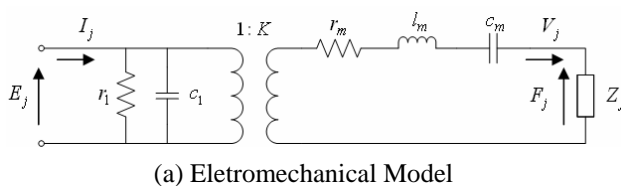


Figure 1 : Equivalent circuits used to model the transducers

In general, a transducer can be represented by an ABCD transfer matrix relating the input voltage and current, and the output force and velocity, i.e., in matrix form:

$$\begin{bmatrix} E_j \\ I_j \end{bmatrix} = \begin{bmatrix} A_j & B_j \\ C_j & D_j \end{bmatrix} \begin{bmatrix} F_j \\ V_j \end{bmatrix} \quad (1)$$

The coefficients A_j , B_j , C_j , D_j may be obtained by experiments or by different models.

The modeling is done using a simple equivalent circuit with constants, shown in Fig. 1. Here, K is the electromechanical ratio, r_m , l_m , c_m , respectively, are the mechanical resistance, equivalent mass, and elasticity of the resonant mechanical system, and Z_j the radiation impedance. The electromechanical model in figure 1 (a) can be changed to the electrical model in figure 1 (b).

In figure 1 (b), the following equation is established by Kirchhoff's voltage law,

$$-E_j + V_j \left(r_2 + j\omega l + \frac{1}{j\omega c_2} \right) + F_j = 0$$

that is,

$$\begin{aligned} E_j &= F_j + V_j \left(r_2 + j\omega l + \frac{1}{j\omega c_2} \right) \\ &= \begin{bmatrix} 1 & \left(r_2 + j\omega l + \frac{1}{j\omega c_2} \right) \end{bmatrix} \begin{bmatrix} F_j \\ V_j \end{bmatrix} \end{aligned} \quad (2)$$

From eq. (1) and (2), A_j, B_j take the form

$$A_j = 1, \quad B_j = r_2 + j\omega l + \frac{1}{j\omega c_2} \quad (3)$$

The j th transducer in the array is affected by other transducers because of mutual impedance. This can be described by following matrix representation.

$$\mathbf{F} = \mathbf{ZV} \quad (4)$$

$$\begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_N \end{bmatrix} = \begin{bmatrix} Z_{1,1} & Z_{1,2} & \cdots & Z_{1,N} \\ Z_{2,1} & Z_{2,2} & \cdots & Z_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{N,1} & Z_{N,2} & \cdots & Z_{N,N} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix}$$

From eq. (1), the relationship between E_j and F_j, V_j becomes

$$\mathbf{E} = \mathbf{AF} + \mathbf{BV}, \quad (5)$$

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_N \end{bmatrix} = \begin{bmatrix} A_1 & 0 & \cdots & 0 \\ 0 & A_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & A_N \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_N \end{bmatrix} + \begin{bmatrix} B_1 & 0 & \cdots & 0 \\ 0 & B_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & B_N \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix}$$

\mathbf{V} is eliminated from eq. (4) and (5) and the relationship between \mathbf{E} and \mathbf{F} becomes

$$\mathbf{E} = [\mathbf{A} + \mathbf{BZ}^{-1}]\mathbf{F} \quad (6a)$$

or,

$$\mathbf{F} = \mathbf{Z}[\mathbf{AZ} + \mathbf{B}]^{-1}\mathbf{E}. \quad (6b)$$

The matrix \mathbf{A}, \mathbf{B} are obtained from Sensor Modeling Tool. And, the vector \mathbf{F} is the optimal weightings which are calculated from BeamCAD Tool.

As shown in eq. (6), if we model the equivalent circuits of the transducer array, then not also mutual impedance but also the different characteristics of each transducers are considered. In the result, an efficient optimum beamformer can be made.

3 Design Procedure

Step 1. Optimal Weightings

When designing an optimum beamformer, designer must calculate the optimal weights. BeamCAD Tool make it possible to obtain the optimal weights which satisfy the sidelobe level(SLL), steering angle, etc. Figure 2 describes the concept of BeamCAD Tool.

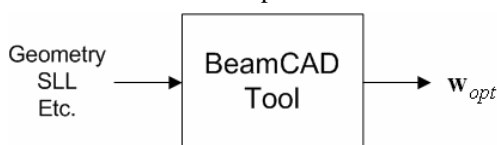


Figure 2 : Concept of BeamCAD Tool

Figure 3 is the snapshot of BeamCAD Tool.

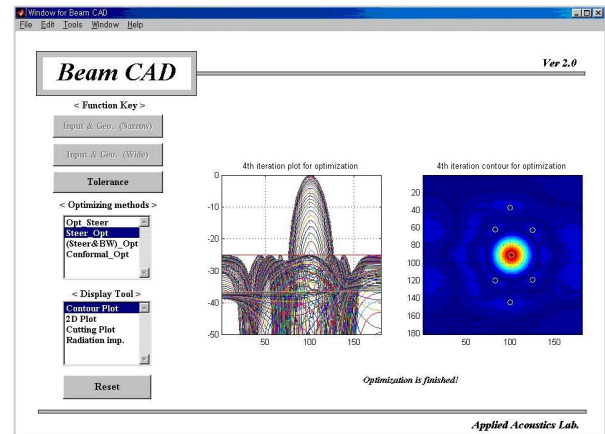


Figure 3 : BeamCAD Tool

Step 2. Measurement of Impedance

After the step 1 procedure, the impedance of each transducer has to be measured. These impedances are used in Sensor Modeling Tool and Impedance Matching Tool.

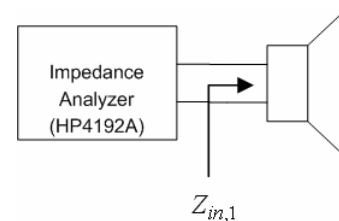


Figure 4 : Concept of measurement of the impedance

Step 3. Sensor Modeling Tool

Finding the parameters of equivalent circuit for each transducer is need to design the matching circuits and to consider the effects of mutual impedance and the characteristic of each sensor. Figure 5 describes the concept of Sensor Modeling Tool which calculates the components of the equivalent circuit from the impedance measured from procedure step. 2.

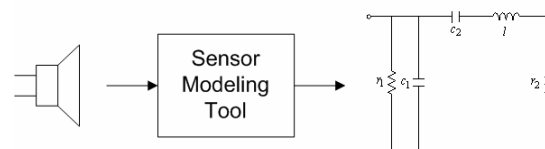


Figure 5 : Concept of Sensor Modeling Tool

Figure 6 is the snapshot of Sensor Modeling Tool.

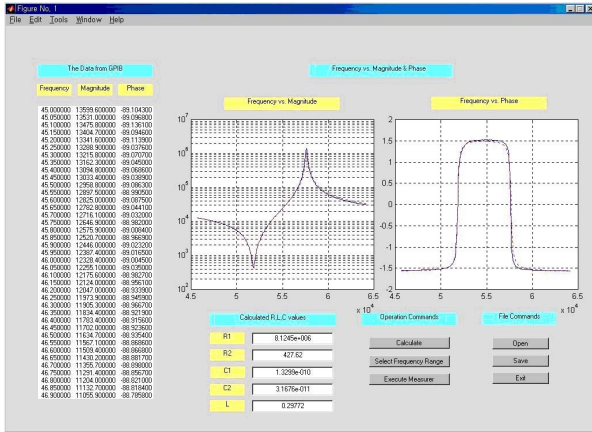


Figure 6 : Sensor Modeling Tool

Step 4. Impedance Matching Tool

Also finding the parameters of matching circuit for each transducer is need for maximum power transfer. Figure 7 describes the concept of the designing of matching circuits and Figure 8 is the snapshot of Impedance Matching Tool.

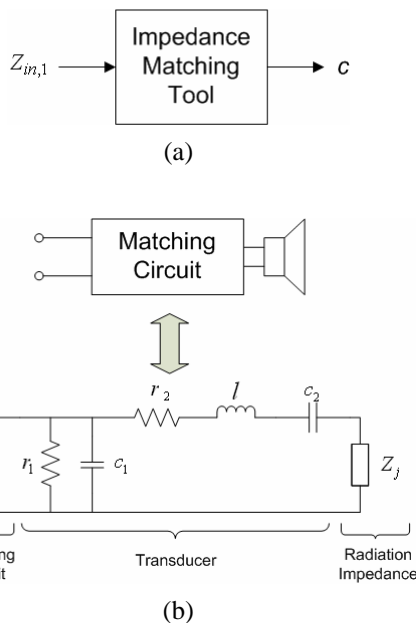


Figure 7 : Concept of designing matching circuits

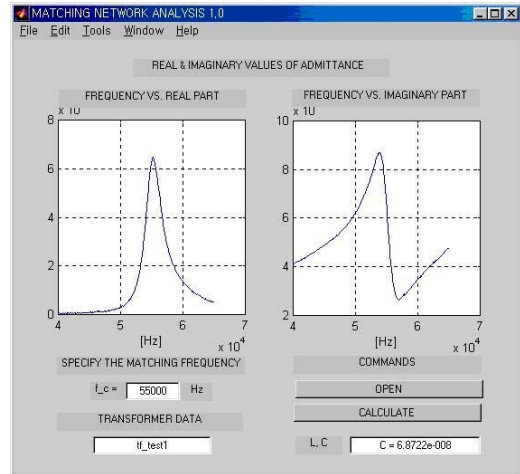


Figure 8 : Impedance Matching Tool

Step 5. ABCD transmission matrix

As explained in section 2, ABCD transmission parameters are used to compensate the effects of the mutual impedance and the characteristic of each sensor. The circuit in Figure 9 represents the equivalent circuit of a transducer which includes the matching circuit. In this case, the value of ABCD transmission parameters becomes like that of eq. (7) and (8).

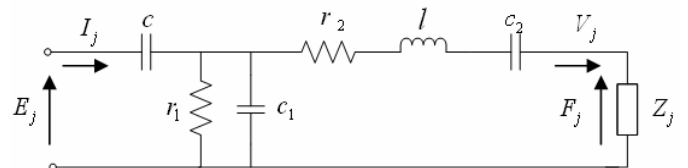


Figure 9 : Equivalent circuit of a transducer including matching circuit

$$\begin{bmatrix} E_j \\ I_j \end{bmatrix} = \begin{bmatrix} A_j & B_j \\ C_j & D_j \end{bmatrix} \begin{bmatrix} F_j \\ V_j \end{bmatrix} \quad (7)$$

$$A_j = \frac{1}{j\omega c} + Z_a, \quad B_j = \frac{Z_a + Z_b}{j\omega c} + Z_a Z_b \quad (8)$$

Here,

$$Z_a = \frac{1}{j\omega c_1 + \frac{1}{r_1}}, \quad Z_b = r_2 + j\omega l + \frac{1}{j\omega c_2}$$

Step 6. Calibration

Finally, the effects of the mutual impedance and the characteristic of each transducer are considered and the weightings are calibrated by using ABCD transmission matrix like eq. (9).

$$\mathbf{E} = [\mathbf{A} + \mathbf{BZ}^{-1}]\mathbf{F} \quad (9)$$

Step 7. Summary

Figure 10 describes the overall procedure for the design of weighting circuits. From this procedure, optimum beamforming is possible while considering the effects of the mutual impedance and the characteristic of each transducer efficiently.

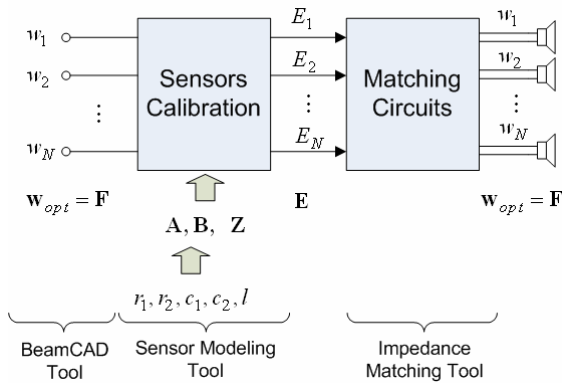


Figure 10 : Overall procedure for the design of weighting circuits

4 Conclusion

In this paper, ABCD transmission parameters are used to compensate the effects of the mutual impedance and the characteristic of each sensor. An efficient design method for the weighting circuits which is made up of the optimum beamforming tool, equivalent circuit modeling tool, matching circuits tool, and the calibration by using ABCD transmission parameters is presented. Through this method, optimum beamforming which considers the effects of the mutual impedance and the characteristic of each transducer is possible.

References

- [1] Nakjin Choi, Joon-il Song, Koeng-Mo Sung, Byung-Doo Jun, and Jun-seok Lim, 'Ultrasonic Sensor Modeling S/W Tool for Matching Circuit Design', *Conference Papers of Acoustical Society of Korea*, Vol. 19, No. 2(s), pp.341-344 (2000)
- [2] Nakjin Choi, Joon-il Song, Jun-seok Lim, and Koeng-Mo Sung, 'Implementation of the Designing S/W Tool for Impedance Matching Network', *Conference Papers of Acoustical Society of Korea*, Vol. 20, No.1(s), pp. 841-844 (2001)
- [3] Christian Audoly, 'Some aspects of acoustic interactions in sonar transducer arrays', *J. Acoust. Soc. Am.*, 89 (3), pp.1428-1433 (1991)