Design of Impedance Matching Network for B&K 8104 Hydrophone via Direct Computational Technique for Underwater Communication

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Abstract— **Underwater acoustic communication is a rapidly growing field of applied research and is a technique of sending and receiving message below water. There are several ways of doing such communication but the most common one is realized by using transducers. In underwater acoustic communication, one of the most important problems is driving the transducers with matched network. In this study, design of impedance matching network for B&K 8104 hydrophone that can be used for underwater communication was performed via Direct Computational Technique (DCT).**

Keywords : Underwater communication; impedance matching, direct computational tecnique, real frequency technique.

I. Introduction

The need for underwater wireless communications exists in applications such as remote controls in off-shore oil industry, pollution monitoring in environmental systems, collection of scientific data recorded at ocean-bottom stations and by unmanned underwater vehicles, speech transmission between divers, and mapping of the ocean floor for objects detection and recovery. Wireless underwater communications can be established by transmission of acoustic waves. Radio waves are of little use because they are severely attenuated, while optical waves suffer from scattering and need high precision in pointing the laser beams. Underwater acoustic communication channels are far from ideal. They have limited bandwidth and often cause severe signal dispersion in time and frequency. For instance, energy absorption at f = 10 kHz is 3000 dB/km for electromagnetic waves and only 1 dB/km for sonic waves. Thus, using an acoustic carrier is considerably more energy-efficient than the use of electromagnetic radiation [1].

Among the first modern underwater communication systems was an underwater telephone, which was developed in the forties in the United States for communication with submarines [2]. This device used single side band (SSB) suppressed carrier amplitude modulation in frequency range 8-11 kHz and it was capable of sending acoustic signal over several kilometers [6].

Most of the current underwater acoustic solutions utilize analog techniques. Some common drawbacks with traditional analog implementations include accuracy limitations due to circuit complexity, device tolerances, and sensitivity to electrical noise. Digital Signal Processing addresses most of these limitations [7].

II. Underwater Sound Transmission

Sound is disturbances of the medium – here water – travelling in a 3 dimensional manner as the disturbance propagate with the speed of sound. Acoustic impedance is one of the most basic concepts of underwater sound because its definition is a constitutive equation (one from which others are derived) for underwater sound propagation. The relation is:

$$Z_a = \rho . c \tag{1}$$

This definition is analogous to Ohm's law for electrical circuits i.e. V=R·I and particle velocity (c), acoustic impedance (Z_a) and sound pressure (ρ) can be thought in the same way. It shows that particle velocity and pressure are in phase in a plane sound wave. Sounds originating from acoustic sources are measured in intensity level, which decreases as the distance to the source is increased due to transmission loss (TL) i.e. spreading and absorption:

$$IL = SL - TL = SL - 20\log(r) - \propto (r-1) \tag{2}$$

where r is the distance (m) from the source and α is absorption coefficient [dB/m]. The formula assumes spherical spreading for the transmission loss i.e. the sound is unbounded and spreads out as it was originating from a point the acoustic center of the source.

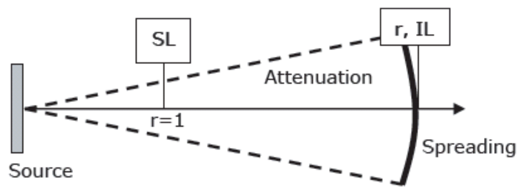

Figure 1. Schematic of sound transmission with spreading [8].

Schematic of sound transmission with spreading is shown in Figure 1. Spherical spreading is most common and is valid in the far field provided that the source is placed far enough from any large structure. The last term of the transmission loss is the attenuation, which increases very significantly with the frequency and furthermore varies with pressure, temperature, salinity and acidity. The transmit voltage response, TVR, is defined in such a way that the source level can be calculated from:

$$SL = TVR + 20\log(V_{rms}) \tag{3}$$

The TVR value is often measured at low power and since the electric-to-acoustic efficiency can drop significantly with increased power levels it is often best to use the TVR relation with caution. Transducer transmitting of the underwater sound is shown in Figure 2. The source level (SL) of a transmitter can be estimated (ignoring attenuation) by measuring the output voltage (OCV) of a hydrophone submerged in the vicinity of the transmitting transducer and the receive response (RR) of transducer:

$$SL = 20\log(OCV) - RR + 20\log(r/1m) \tag{4}$$

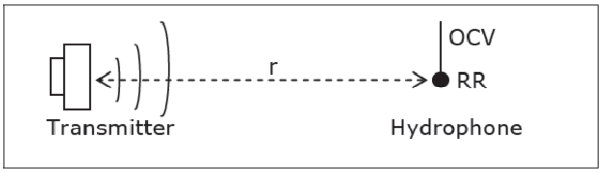

Figure 2. Transducer transmitting of the underwater sound [8].

For analysis and application purposes transducers may be represented as equivalent electrical circuits consisting of resistors, capacitors and inductors. Since piezoelectric transducers can be modelled much easier with parallel components, it is a common practice to use parallel admittance (Y) rather than series impedance (Z), which consists of resistance (R) and reactance (X); hence conductance (G) for the real part, and susceptance (B) for the imaginary part. The unit of Y, G or B is Siemens (S). R, X, G and B are related to each other by the following equations:

$$R = \frac{G}{G^2 + B^2}, X = \frac{B}{G^2 + B^2} \tag{5}$$

The existence of the imaginary part may give problems in matching an amplifier to a projector. Thus, a series or parallel inductor can be added to the input of a transducer to cancel this imaginary part. This is known as tuning. Transformers may also be used to match the output impedance of an amplifier to a projector. This is called matching. The electroacoustic efficiency of a projector is defined as the ratio of the acoustic power generated to the total electrical power input. Efficiency varies with frequency and expressed as percentage. The power input to a transducer, in terms of electrical watts, can be easily calculated from:

$$P_{in} = V_{in} \cdot G \tag{6}$$

where Vin is rms voltage input to the transducer. Since efficiency of a transducer is calculated from the measured parameters (DI from beam pattern, TVR and G) it may not be well defined and one is discouraged from specifying it [9].

III. Real Frequency Direct Computational Technique (RFDT)

Referring to Figure 3 in the real frequency direct computation technique (RFDT), the transducer power gain of the double matched system is described in terms of the driving point immittances of the generator $[Z_G \ or \ Y_G]$, equalizer $[Z_B \ or \ Y_B]$ and the load $[Z_L \ or \ Y_L]$

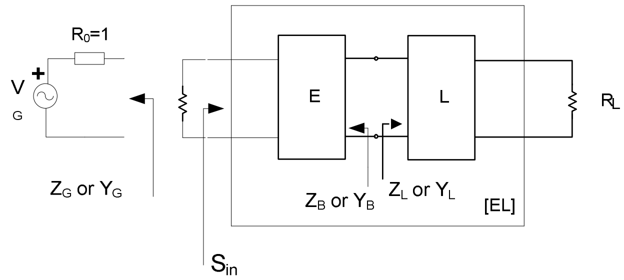

Figure 3. Cascaded connection of two lossless two-ports [G] and [EL].

In this case, transducer power gain of Figure 3 is given by

$$T(\omega) = \frac{1 - |G_{22}|^2}{|1 - G_{22}S_{in}|^2} T_{[EL]} \tag{7}$$

where

$$G_{22} = \frac{Z_G - 1}{Z_G + 1} = \frac{1 - Y_G}{1 + Y_G} \tag{8}$$

is the unit normalized generator reflectance.

The transducer power gain T_EL of the lossless two port [EL] is given by

$$T_{EL} = 1 - |S_{in}(j\omega)|^2 = \frac{4R_B R_L}{[R_B + R_L]^2 + [X_B + X_L]^2} \tag{9}$$

which is the immittance based conventional single matching gain. Assuming $Z_B(j\omega)$ as a minimum function, Eq. (7) is expressed as a function of the real part R_B as

$$T_G(\omega) = \left[\frac{1 - |G_{22}|^2}{|1 - G_{22}S_{in}|^2}\right]\left\{\frac{4R_B R_L}{[R_B + R_L]^2 + [X_B + X_L]^2}\right\} \quad (10)$$

where $X_B(\omega) = Hilbert\{R_B(\omega)\}$.

In the above formulation, the complex generator drives the lossless two port [EL]. Therefore, $T_G(\omega)$ is referred as the generator based transducer power gain of the double matching problem. On the other hand, we can turn the matching problem the other way around; feeding the equalizer [E] with a complex generator of internal impedance Z_L while terminating it in Z_G at the front-end. This type of formulation of the transducer power gain may be referred as the load based. In this case, it may be useful to make the following definitions.

Generator based transducer power gain $T_G(\omega)$: $T_G(\omega)$ of Eq. (10) is called the generator based transducer power gain of the matched system. Load based transducer power gain $T_L(\omega)$: Similarly; we can define the load based transducer power gain of the matched system as

$$T_L(\omega) = \left[\frac{1 - |L_{11}|^2}{|1 - L_{11}S_{in}|^2}\right]\left\{\frac{4R_B R_G}{[R_B + R_G]^2 + [X_B + X_G]^2}\right\} \quad (11)$$

where

$$L_{11} = \frac{Z_L - 1}{Z_L + 1} = \frac{1 - Y_L}{1 + Y_L}$$

In this case, $Z_B = R_B + jX_B$ is the driving point immittance of the resistively terminated equalizer at the front-end (or at the generator[Z_G] end). Obviously, generator and load based defined transducer power gains must be identical. Thus,

$$T(\omega) = T_G(\omega) \equiv T_L(\omega) \quad (12)$$

For the direct method of broadband matching, the unknown of the problem is the rational form of the real part R_B such that

$$R_B(\omega^2) = \frac{A_1\omega^{2m} + A_2\omega^{2(m-1)} + \cdots + A_m\omega^2 + A_{m+1}}{B_1\omega^{2n} + B_2\omega^{2(n-1)} + \cdots + B_n\omega^2 + B_{n+1}} \quad (13)$$

$$\geq 0 \; and\; bounded\; for\; all\; \omega\;, therefore, n \geq m$$

In this case, the coefficients $\{A_i, B_j; i = 1,2,..,m, and\; j = 1,2,...,n\}$ must be determined in such a way that TPG of Eq. (10) or equivalently, Eq. (11) is optimized as high and as flat as possible.

However, we should note that the general from of R_B specified by Eq. (13) is not practical at all. It may result in complicated equalizer structures which cannot be built. Therefore, we prefer to work with simple form of R_B which has all its zeros on the $j\omega - axis$.

$$R_B(\omega^2) = \frac{A_0\omega^{2ndc}\prod_{i=1}^{nz}(\omega_i^2 - \omega^2)^2}{B_1\omega^{2n} + B_2\omega^{2(n-1)} + \cdots + B_n\omega^2 + 1} = \frac{A(\omega^2)}{B(\omega^2)} \geq 0;\ \forall\omega \quad (14)$$

$where$

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

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

Once T_0 is selected; and the coefficients $\{c_j; j = 1,2,..n\}$ and $A_0 = a_0^2 \geq 0$ of the real part $R_B(\omega)$ are initialized, we can generate the generator based error function ε_G or equivalently the load based error function ε_L as follows.

$$\varepsilon_G = \left[\frac{1 - |G_{22}|^2}{|1 - G_{22}S_{in}|^2}\right]\left\{\frac{4R_B R_L}{[R_B + R_L]^2 + [X_B + X_L]^2}\right\} - T_0$$

or

$$\varepsilon_L = \left[\frac{1 - |L_{11}|^2}{|1 - L_{11}S_{in}|^2}\right]\left\{\frac{4R_B R_G}{[R_B + R_G]^2 + [X_B + X_G]^2}\right\} - T_0 \quad (15)$$

Then, the error function is minimized which in turn yields the realizable driving point input immittance $Z_B(p) = \frac{a(p)}{b(p)}$ of the lossless equalizer (Since it is not desired to loss power in the matching network, lossless element (inductor and capacitor) are used in the equalizer). Eventually, $Z_B(p) = \frac{a(p)}{b(p)}$ is synthesized yielding the desired lossless equalizer in resistive termination R . Finally, resistive termination is replaced by an ideal transformer with transformer ratio $[R = n^2{:}\,1]$ which completes the design [10].

The designed matching network is different from KLM or Mason's electro-mechanical equivalent circuits of a piezoelectric resonator [11]. The designed circuit is not an equivalent network. It is designed to transfer maximum power in the frequency band from the amplifier which will drive the transducer.

IV. Result of Direct Computational Technique to Design Matching Network for B&K 8104 Acoustic Transducer

B&K 8104 is a high power piezoelectric ultrasonic transducer which resonates in the frequency range of 4 kHz-200 kHz. It is utilized for various commercial and military underwater applications. B&K 8104 can also be used as a sound transmitter (projector) which makes it ideal for calibration purposes by the reciprocity, calibrated-projector and comparison methods.

For the ultrasonic piezoelectric B&K 8104 transducer, the real and the imaginary parts of the measured impedance data are shown in Table 1. Frequency range of the measurements is given by $8\ kHz\ to\ 10\ kHz$.

TABLE 1. The real and the imaginary parts of the measured impedance data.

Frequency (KHz)	Real Part RL (ohm)	Imaginary Part XL (ohm)
8.00	11.59	-3065
8.50	11.20	-2888
8.80	10.97	-2787
9.50	10.50	-2600
10.00	10.14	-2452

We can normalize the data with respect normalization frequency *fo = 10 kHz* and the standard resistance *Ro = 4 ohms*.

Transducer power gain of the matched system is optimized over the normalized frequency band of 8 kHz and 10 kHz. Firstly, we will try to hit *To = 0.70* flat gain level using a transformer in the equalizer. To make the equalizer as simple as possible, we put all transmission zeros at infinity. The coefficients in (14) were chosen arbitrarily, in an alternating manner of +1 and -1. After running the program, the obtained result is summarized as follows. Transducer power gain (TPG) performance of the matched piezoelectric ultrasonic transducer B&K 8104 is shown in Figure 4. The desired TPG level *(To = 0.70)* has been reached at 8.8 kHz with a bandwidth 40Hz.

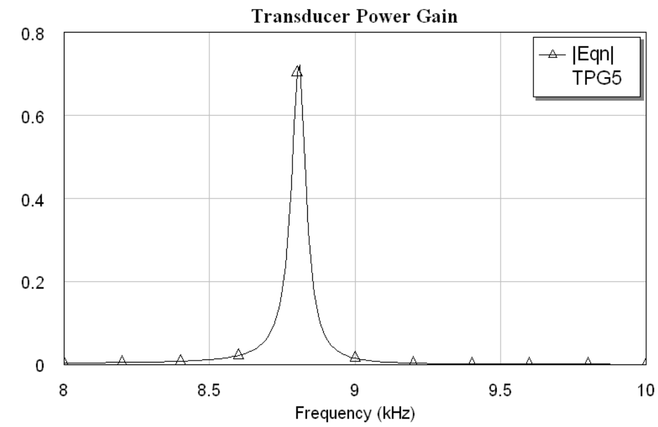

Figure 4. Transducer power gain of the matched transducer B&K 8104.

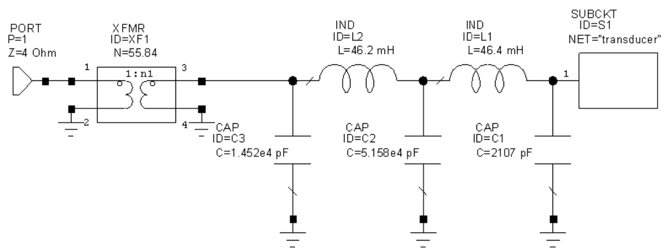

Figure 5. Design of single matching equalizer for B&K 8104 piezoelectric transducer.

We should mention that, by reiteration, gain performance of the matched transducer may be improved.

Synthesis of $Z_B(p)$ which in turn yields the desired equalizer is shown in Figure 5.

Finally, by de-normalization actual element values have been obtained and given in Table 2.

TABLE 2. ACTUAL ELEMENT VALUES.

Element	Value
C1	2.107 *nF*
C2	5.153e4 *pF*
C3	1.452e4 *pF*
L1	46.4 *mH*
L2	46.2 *mH*

CONCLUSIONS

In this study, a matching network has been designed to drive an acoustic transducer via a 4-Ohm output resistance power generator. The matching network acts as a transformer and also as a filter network. This behavior is named as "TRANSFILTER". This shows that, in some certain frequency band, the network boosts the input voltage like a transformer. For example at 8.8 kHz, the input voltage is boosted and the power gain is close to 0.7. But in some other frequencies outside the pass band, the network behaves as a low pass filter (actually band pass because of the capacitive load). In this stop-band, the input signal from the power generator is reflected back to the generator.

The designed network can be used as an impedance matching structure to an acoustic transducer.

REFERENCES

[1] Brekhovskikh L., Lysanov Y., "Fundamentals of Oceans Acoustics", New York – Springer, (1982).
[2] Quazi A., Konrad W., "Underwater Acoustic Communications", IEEE Comm. Magazine, 24-29, (1982).
[3] Catipovic J., "Performance limitations in underwater acoustic telemetry", IEEE J. Oceanic Eng., 15, 205-216, (1990).
[4] Baggeroer A., "Acoustic telemetry – an overview", IEEE J. Oceanic Eng., 9, 229-235, (1984).
[5] Stajanovic M., "Recent advances in high rate underwater acoustic communications", IEEE J. Oceanic Eng., 125-136, (1996).
[6] Istepanian R.S.H., Stojanovic M., "Underwater Acoustic Digital Signal Processing and Communication Systems", Kluwer Academic Publishers, (2002).
[7] Yagnamurthy N.K., Jelinek H.J.,, "A DSP Based Underwater Communication Solution", OCEANS 2003, 1, 120-123 , ABD, (2003)
[8] Basic Acoustics, Catalogue Standard Transducers And Hydrophones, Reson Inc., 125 -129, (2009)
[9] Kuntsal E., Bunker W.A., "Guidelines For Specifying Underwater Electroacoustic Transducers", UDT '92 Conference, London, England (1992).
[10] Yarman B.S., "Design Of Ultra Wideband Power Transfer Networks", John Wiley & Sons, Ltd (2010)
[11] Sheritt S., Leary S.P., Dolgin B.P., Bar-Cohen Y., "Comparison of the Mason and KLM Equivalent Circuits for Piezoelectric Resonators in the Thickness Mode", IEEE Ultrasonic Symposium, vol:2, pp.921-926, (1999).