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J. Electrical Systems 14-3 (2018): 26-35

JES
Journal of Electrical Systems

Regular paper

Broad Band Impedance Matching Transformer Design Consideration for High Power Electro-acoustic Transducer

Matching the output impedance of SONAR system's transmitter with the input impedance of high power electro-acoustic transducer is important to improve its transmitting efficiency by maximizing the transfer of power. In this work, an attempt has been made to match the output impedance of power amplifier (4 Ω)with the input impedance of high power (2000 watts) and high impedance (1387 Ω with phase angle of 85 ° at its resonant frequency i.e 2.5 KHz) Piezoelectric material based Electro-acoustic Transducer, by realizing a Broadband Matching Transformer. Designing of the matching transformer is undertaken using Lump Circuit Modeling and Network Theorem. Matching Transformer has been designed to meet the required specification by sequentially following measurement of transducer's impedance as a function of frequency using Impedance Analyzer and computation of its equivalent circuit element s values based on measured parameters of the transducer. Matching transformer was developed using composite Iron alloy based C-type and Toroid-type Cores. Impedance and phase angle of the tuned transducer were found to be equal to 3.6 Ω and phase angle of 14.5 °, respectively. It is pertinent to mention that no significant influence of the core type variation was observed on results. Impedance results of the tuned transducer were also taken as a function of frequency to evaluate the broadband performance of the Matching Transformer. Source Pressure Level of the resonating transducer with matching transformer was observed to increase from 137 to 164 dB/˘Pa @ 1m when gain of the amplifier was set on 6dB. Results of the work are promising and expected to contribute a lot in the development of Underwater Surveillance Systems in future.

Keywords:SONAR, Matching Transformer, Resonant Frequency, Impedance, Source Level

Article history: Received 15 March 2018, Accepted 24 July 2018

1. Introduction

Piezoelectric transducers have applications in various fields including underwater communication and noise generation, mapping of ocean floor, controlling of off-shore oil industry and monitoring of pollution in environmental systems, biomedical imaging, energy harvesting,non-destructive testing, etc[1-6]. Sensitivity and bandwidth of these ultrasonic transducers is the function of its electrical impedance which can be altered by connecting a two port LC Network or Transformer at its input [7, 8]. Optimal electro-acoustic performance of transducers can be achieved through impedance matching, by inserting a suitable impedance matching circuits/ networks between the transducers and driving circuitry. Most of the investigated impedance matching circuits provide matching at some fixed frequency i.e. resonant frequency which were based on simple L or LC Networks [7,

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9, 10].Recently, Shuyu Lin and Jie Xu [11]developed series inductance type impedance matching circuit for Piezoelectric Power Transducer and investigated its influence on the electromechanical properties of the transducer. These simple matching circuits, however, cannot be an appropriate choice for the broad band transducers.

In recent years, designing and development of impedance matching circuits for broadband electro-acoustic transducers has been undertaken using different techniques, so as to enhance the transmitting response of the transducers over its entire frequency range[12]. Carlin [13] realized two port lossless matching network using Real Frequency Technique (RFT) for the first time. Yarman et. al [14] introduced Simplified Real Frequency Technique (SRFT) in 1982 with no compulsion of Hilbert Transform which is required in RFT. Dedieu et al. [15] used Recursive Stochastic Equalization method (RSE) for solving of broadband impedance matching problem. Yongheng et. al [16] employed Real Frequency Direct computational Technique (RFDT) to develop broadband matching circuit for underwater communication. Compared to RFT, SRFT, RSE and RFDT techniques, Broadband Impedance Matching Network development using Smith is easier[17]which assumes the increase in bandwidth with the decrease of Quality Factor (Q). Both source and transducer impedances are measured and marked on smith chart while designing matching circuits using Smith Chart. Subsequently, the matching network designing is undertaken to match load impedance to source impedance by adding inductors or capacitors in either series or parallel. On Smith Chart, an inductor added in series moves impedance along constant resistance curves [18] which leads to cancellation of reactive part of load. Jianfei et al. [19] recently developed broadband impedance network by employing a well known Genetic Algorithm (GA).

In this work, we applied a relatively simple technique in which designing of Impedance Matching Transformers was undertaken using Network Theorem following Lumped Equivalent Model development of Transducer [20]. Lumped Equivalent Circuit of the Transducer was developed using Butterworth-Van Dyke Model [21]. The values of lumped equivalent model were computed using measured results of the transducer in water. Fabrication of the transformer was carried out using Composite Iron Alloy based C and Toroid type cores. Purpose of using two different types of cores was to analyze the effect of core structure variation on the performance parameters of the transducer. Source Pressure Level (SPL) and Impedance results of the transducer were measured with and without Matching Transformers. Impedance of the transducer with matching transformer was noted to be equal to 4±0.5 Ω over the entire frequency band of the transducer i.e. 2KHz to 6KHz which leads to significant enhancement in the SPL level of the transducer. It is pertinent to mention that no significant effect of the core type variation was observed on results.

2. Impedance matching transformer design steps

2.1 Problem Statement

Purpose of Broadband Impedance Matching Transformer between Power Amplifier and Transducer is to match Input Impedance of Transducer with the output Impedance of Power Amplifier over the entire frequency band (2 - 6 KHz) of Transducer so as to maximize its transmitting response. Such Transducers are commonly employed in Underwater Surveillance Systems. Output Impedance of Power Amplifier is 4 Ω with maximum power rating of 2000 watts and input impedance of the Transducer was noted to be equal to1572 Ω at its resonant frequency of 2.5 kHz as shown inFig.1.

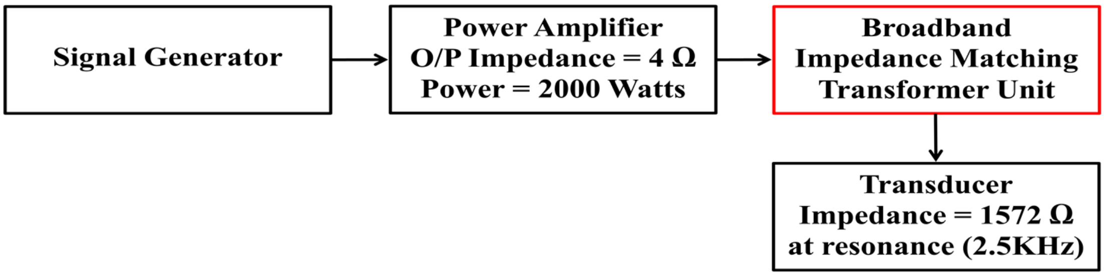

Fig.1. Problem statement for Broadband Impedance Matching Transformer

2.2 Impedance Results of the Transducer

Precision Impedance Analyzer 4294A was used to measure impedance and capacitance of the Transducer after dipping it in water. Impedance magnitude and phase parameters were determined as a function of frequency as shown in Fig.2.

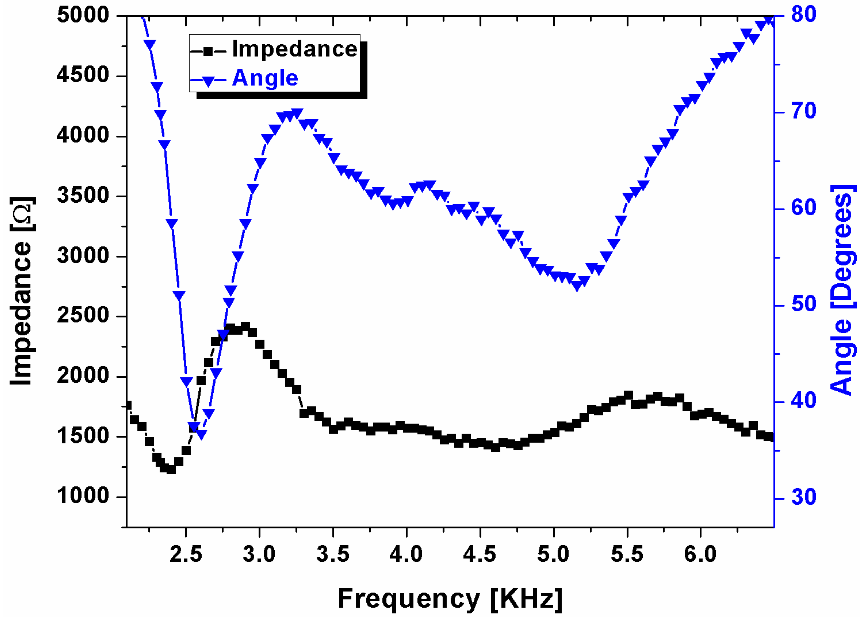

Fig.2. Impedance Results of Transducer Vs Frequency

Impedance Magnitude and Phase Angle values were noted to be equal to 1387 Ω and 85°, respectively. Table 1 ispresenting the values of other important electrical parameters of the of high power (maximum of 2000 watts) transducer which includes Resonant frequency, Quality Factor, Coupling Coefficient and Capacitance.

Table 1: Transducer's Electrical Parameters without matching unit

S. No.	Parameters	Values
01	Resonant Frequency (Fr)	2.5KHz
02	Quality Factor (Q)	5.39
03	Coupling Coefficient (k)	0.417
04	Capacitance (C_T)	30776pF

2.3 Lumped Equivalent Model of Transducer

Modeling of Transducer was undertaken using Butterworth-Van Dyke (BVD) Model which is commonly employed for modeling of the Piezoelectric Transducers [22]. The simplified Butterworth-Van Dyke Model of the transducer is shown in Fig.3. It consists of 5 electrical components named as LM, CM, RM, C0 and R0. In the model, the series components LM, CM and RM represent electrical equivalent of mechanical characteristics of the piezoelectric Transducer. Whereas clamped components R0 and C0 are the representative of the electrical behavior of the transducer. Mathematically input admittance of the transducer using its Lumped Equivalent Model (Fig.3) can be described as under [23]:

$$Y = \frac{1}{R_0} + j\omega C_0 + \frac{1}{(R_M + j\omega L_M + \frac{1}{J\omega C_M})} \quad (1)$$

At mechanical resonance of the transducer, ωLM and 1/ωCM cancel out each other and admittance of transducer is maximized.

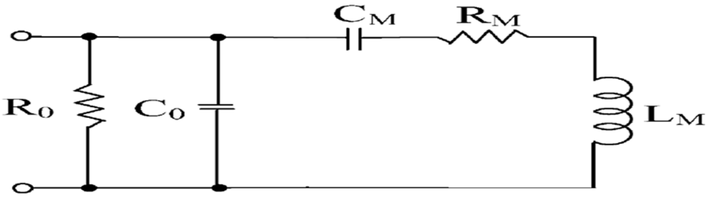

Fig.3. Lumped Equivalent Model of Transducer

Values of circuit elements of Lumped Equivalent Model were calculated using the following equations [24]:

$$R_0 = \frac{1}{\omega C_T tan\delta} \quad (2)$$

$$R_M \approx \frac{1}{G_s} \quad (3)$$

$$f_s = \frac{1}{2\pi\sqrt{L_M C_M}} \quad (4)$$

$$C_M = C_T K^2 \quad (5)$$

Where tanδ represents piezoelectric loss, f_s is the resonant frequency, G_s is the conductance of the transducer at resonance, C_T represents DC Capacitance of the transducer and K denotes effective electromechanical coupling coefficient.

$$C_0 = C_T(1 - K^2) \quad (6)$$

2.4 Impedance Matching Transformer Design Details

Transformer which is schematically shown in
Fig.4, is implemented to match the impedances of driving Electrical System (Power Amplifier) and Transducer over the entire frequency band of the transducer i.e 2 - 6 KHz. Aim is to make impedance andphase angle of the transducer equal to 4Ω & 0°, respectively, at its mechanical resonance by varying the inductances and turn ratio of the transformer which is interfaced at its input. Broadband performance of the transformer was achieved by careful selection of core material. The broadband impedance matching transformer is thus mandated to maintain input impedance of the transducer, approximately equal to impedance of source i.e. 4Ω.

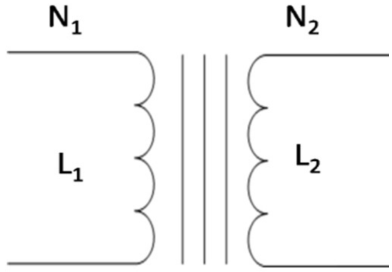

Fig.4. Schematic Description of Single Input/ Output based Ideal Transformer

The electrical admittance of the transducer with matching transformer at resonance takes the relation as indicated below [24]:

$$Y_{IN} = \left[j\omega_s C_0 + \frac{1}{j\omega_s L_2} + \frac{1}{R_M + j\left(\omega_s L_M - \frac{1}{\omega_s L_M}\right)} \right] \times \left[\frac{n_2}{n_1}\right]^2 = \frac{1}{R_M}\left[\frac{n_2}{n_1}\right]^2 \quad (7)$$

Where, ω_s is the angular frequency at resonance, n_2 and n_1 specify the turns of secondary and primary side of the transformers, respectively. The primary inductance (L_1) and secondary inductance (L_2) of the transformer has the relation as follows:

$$L_2 = \left[\frac{n_2}{n_1}\right]^2 L_1 \quad (8)$$

The secondary inductance (L2) cancel out clamped capacitance (C_0) and also turns impedance phase angle to zero. This behavior of the secondary of transformer is mathematically described as follows [24]:

$$(\omega_s)^2 = \frac{1}{C_0 L_2} \quad (9)$$

The primary and secondary inductances of the transformers at resonance of the Transducer were determined to be equal to 0.34mH and 159mH, respectively. The primary and secondary currents of the transformer can be found using following equations so as to determine the wire gauges:

$$I_1 = I_{max} = \sqrt{\left(\frac{P_{max}}{Z_{in}}\right)} \quad (10)$$

$$I_2 = I_1 \times \left(\frac{n_1}{n_2}\right) \quad (11)$$

The primary and secondary currents of the transformers were determined to be equal to 22A and 1A, respectively. The core size was selected to fulfill the following criterion:

$$A_e A_w = \left(\frac{2.75 \times P \times D}{f \times B_{max} K_p}\right) [in^4] \tag{12}$$

Where A_w is window area, A_e is the cross-sectional area of the core flux path, P is output power, B_{max} is the maximum operating flux density, kp is winding space factor. Transformers were developed using two different types of cores i.e. C type and Toroid type core based on special Composite Iron Alloy based material. C and Toroid Type Cores are schematically described inFig.5. Detailed design parameters of the transformers are presented inTable 2. In order to ascertain that dynamic range of the AC signal lies in the linear region of B–H curve, Bmax is set equal Bsat/2, where Bmax is the maximum flux density and Bsat is saturation flux density. If the primary winding space factor (kp) is 0.2, minimum AeAw product is determined to be equal to 0.4 in4 which is less than AeAw product values of selected cores (see Table 2), thus supports our core size selection.

(a) **(b)**

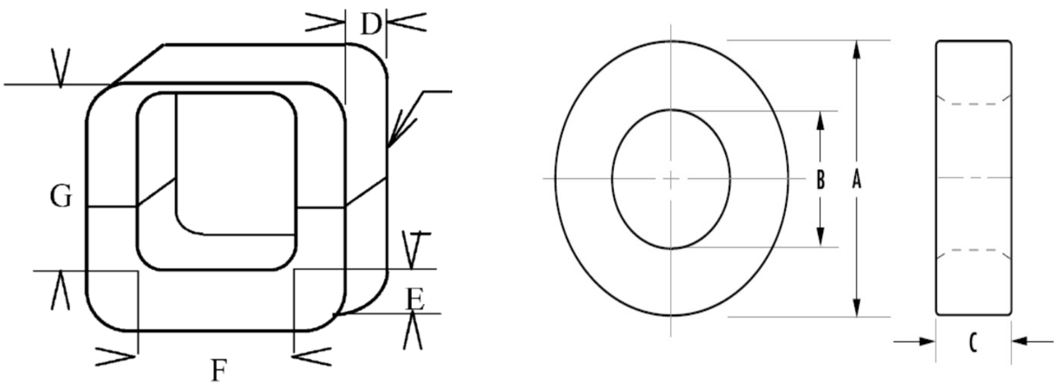

Fig.5. Schematic description of cores (a) C Type (b) Toroid Type

Table 2: Design Parameters of Matching Transformers

Parameters	Description of Parameters	Values
L_2	Inductance of Secondary side	159 mH
L_1	Inductance of Primary	0.34 mH
N_1	Primary Turns	12
N_2	Secondary Turns	274
P_{max}	Maximum Operating Power	2000 W
I_1	Maximum Primary winding Current	22A(SWG-11)
I_2	Maximum Secondary winding Current	1 A(SWG-23)
D	Density in circular	500 mil/A
A	Toroid Core Dimension	2.1 in
B	Toroid Core Dimension	1.2 in
C	Toroid Core Dimension	0.85 in
A_eA_w	A_eA_w for Toroid Core	1.3in^4
D	C Core Dimension	1.125 in
G	C Core Dimension	1.75 in

F	C Core Dimension	1 in
E	C Core Dimension	0.625 in
A_e	Cross-sectional Area of C Core Flux	0.703 in^2
A_w	Window Area of C Core	1.75 $inch^2$
A_eA_w	A_eA_w for C Type Core	1.23in^4

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The developed transformers are shown in Fig.6.

(a) **(b)**

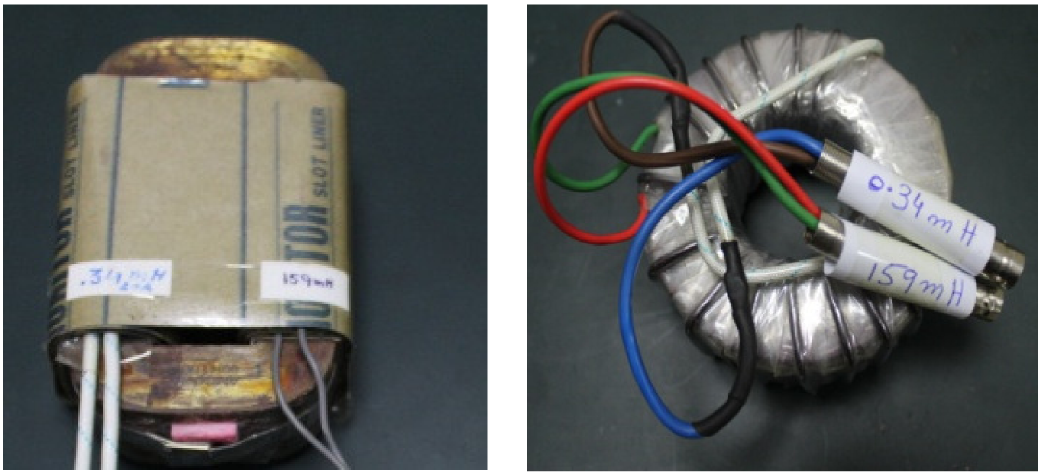

Fig.6. Photographs of developed transformers using (a) C and (b) Toroid Type Core

3. Results and discussion

The performance of developed matching transformers was evaluated by measuring impedance as well as Source Pressure Level (SPL) level of the transducer with matching transformers. Impedance (magnitude as well as phase) of the transducer with matching transformers was investigated as a function of frequency as shown Fig.7. No significant difference in impedance results was observed due to variation of transformer core. Objective of the impedance matching is to cancel out imaginary part of impedance of Transducer, to make its real part equal to source Impedance and phase angle equal to zero.As shown in Fig.7, transformers demonstrated good broadband band performance maintaining impedance of high impedance transducer almost equal to source impedance. The impedance of the transducer with matching transformer was found to be equal to 3.6 Ω with phase angle of 14.5° at resonance frequency. The imaginary impedance part of the Transducer (X) with matching transformer was reduced to 0.6 Ω. Its value without matching transformer was noted to be equal to 960 Ω. Source Pressure Level (SPL) of the transducer which is the function of its sensitivity or Transmit Voltage Response (TVR), can be mathematically described as under [25]:

$$SPL = TVR + 20 \log V_{rms} \quad (13)$$

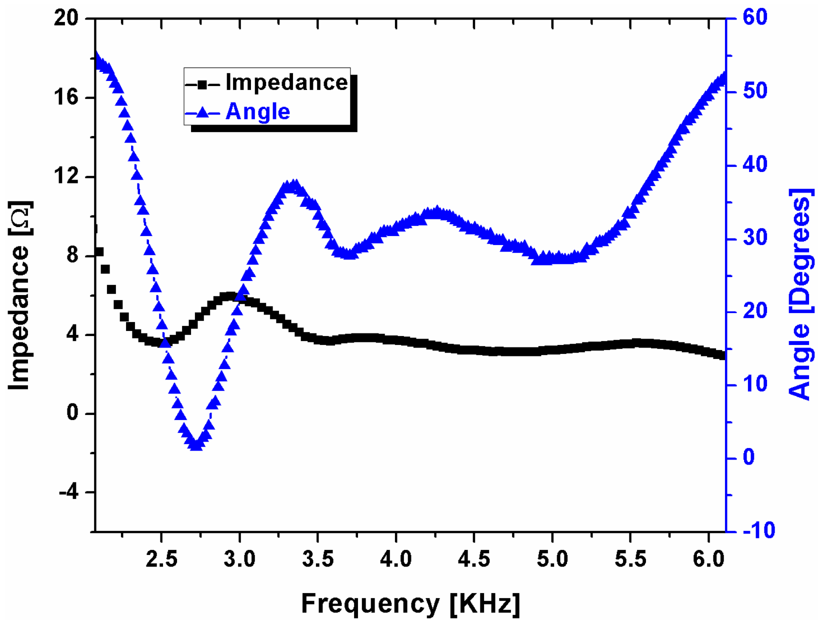

Fig.7. Impedance Results of Transducer with Matching Transformer Vs Frequency

SPL level of a Transducer while operating as a Transmitter can also be estimated by measuring the Open Circuit Voltage (OCV) of a reference hydrophone which is having receive sensitivity of 'RR' and water submerged at a distance of 'r' from transducer as mathematically described below:

$$SPL = 20\log(OCV) - RR + 20\log(r) \qquad (14)$$

We analyzed SPL of the transducer with and without developed matching transformers using measurement setup as schematically described in Fig.8. Source Pressure Level which is also sometimes termed as Source Level (SL) of the Transducer was observed toincrease significantly by the interconnection of developed Impedance Matching Transformers between signal generator and Transducer over the entire frequency band of the Transducer. At resonance frequency of the Transducer, SL of the Transducer was observed to increase up to 164 dB/μPa @ 1m with matching transformer which was noted to be equal to 137 dB/μPa @ 1m without matching transformer. Results of the work are promising and expected to help researcher, working on the realization of broadband Impedance Matching Circuits for High Power Complex Loads such as Piezoelectric Electro-acoustic Transducers.

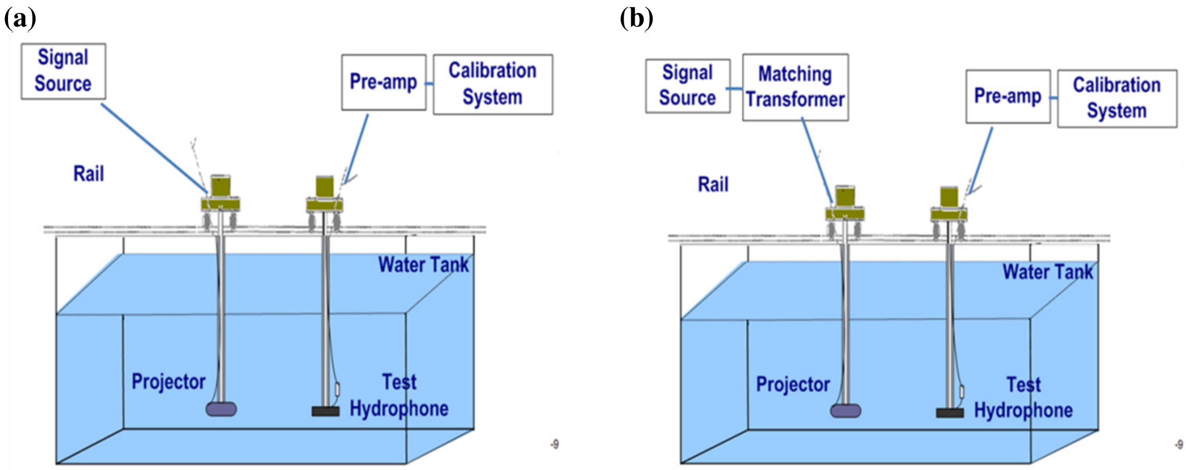

Fig.8. Schematic description of the source level measurement methodology of Transducer (a) without matching transformer and (b) with matching transformer

4. Conclusion

In this work, we have realized a broadband impedance matching transformer for a high power electro-acoustic transducer resonant at 2.5 kHz, with an aim to enhance its transmitting efficiency. Designing of matching transformer was carried out following measurement of Transducer using Impedance Analyzer, its modeling using BVD Model and transformer parameters calculation steps in sequence at resonance frequency of the transducer. Transformers prototypes were developed using composite Iron Alloy based C type and Toroid type Cores. Selection of the core material was made ensuring its capability to pass operating frequency and to show broadband performance. Impedances and Source Pressure Levels of the Transducer were evaluated with and without matching transformers. Impedance of the Transducer becomes approximately equal to source impedance over the entire frequency band of the transducer which led to significant enhancement in its Source Pressure Level. We presume that results of the work are promising and would contribute a lot in the ongoing efforts for enhancing the transmitting efficiencies as well as broadband performance of the Electro-acoustic Transducers.

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