LETTER

Time-division multiplex auto-impedance matching system for high-intensity focused ultrasound

Xusheng Wang^{1a)}, Yuan Yang¹, Congjun Cao¹, Xueping Li¹, and Ming Zhang²

Abstract High-intensity focused ultrasound (HIFU) has been confirmed to be useful for cancer treatment. However, the miniaturization of traditional impedance matching networks for HIFU has limitations. In this paper, a time-division multiplex auto-impedance matching network is proposed for Class D power amplifiers used in HIFU systems to improve performance and reduce the system size. A comparison with previous articles shows that the proposed system can automatically compensate for the impedance drifting of five-channel transducers caused by temperature variations or manufacture tolerance. The operating frequency of the circuit is 1.25 MHz, and the power consumption is 416 mW.

Keywords: high-intensity focused ultrasound, time-division multiplex, automatic impedance matching

Classification: Devices, circuits and hardware for IoT and biomedical applications

1. Introduction

Recent studies on high-intensity focused ultrasound (HIFU) have shown great promise for cancer therapy. In a HIFU system, a designed transducer array is utilized to focus a beam of ultrasound (100 kHz~10 MHz) energy into small volumes of tissue inside human organs. The focused beam causes localized heating (45~90°C) in a small region, and the target tissues are ablated without the need for an incision [1, 2, 3, 4, 5]. Since magnetic resonance imaging (MRI) can provide real-time, noninvasive temperature measurement and 3D imaging with excellent contrast, the combination of MRI and HIFU has proven to be very useful in the mediated drug delivery [6, 7], and noninvasive functional neuro-surgery [8, 9, 10].

For a HIFU system to operate optimally, its power supply must be carefully designed to generate enough ultrasonic energy into the human body. Power amplification is usually achieved by a Class D or Class DE power amplifier because of its high-power efficiency [11, 12, 13, 14]. Most ultrasonic transducers can be considered complex impedance components. Furthermore, the output impedance of the Class D or Class DE amplifier is resistive. Therefore, a matching network must be applied between the amplifier and the transducer. Otherwise, there will be reflected power, which will cause a temperature rise or

even unrecoverable damage to the transducer. Static impedance matching network presented in [15, 16, 17] can solve this problem. However, during HIFU surgery, the impedance of the transducers has unavoidable variations that are caused by temperature drifting, aging and manufacturing dispersion, which will produce unpredictable results of the HIFU system.

A traditional solution is to use automatic resonance frequency tracking method [18, 19, 20] or variable components such as controllable capacitors, controllable inductors or varactors to solve the impedance matching and drifting problems [21, 22, 23]. However, for the methods presented in [18, 19, 20], the frequency of power signal applied on the transducer is changed by using automatic resonance frequency tracking system, which is not acceptable in a HIFU system. [21, 22, 23] use controllable components instead of frequency tracking method to solve the problem. But, these methods only focus on the impedance variation caused by manufacturing tolerance, and the impedance variations caused by temperature drifts during the HIFU surgery are not considered. In other words, these methods are not suit for the dynamic impedance matching during HIFU surgery. Moreover, the impedances of the transducers in the phased array need to be measured, and all of them require computer to store the measured impedances and calculate the switch control signal. Therefore, system size and power consumption will also limit these solutions.

In our previous study, a novel auto-tuning network based on a special phase locking loop (PLL) structure that use a zero-voltage switched (ZVS) capacitor to compensate the impedance drifting during the working period of wireless power transmission applications [24]. Another preliminary test confirmed that this circuit is also suitable for the dynamic impedance matching of HIFU system [25]. However, it can only be used for one-channel transducers, and the circuit size is still not sufficient for phased-array HIFU. Since, the time-division multiplex (TDM) technology has been used in many circuits to minimize the circuit size and reduce system complexity [26, 27, 28, 29]. In this paper, a time-division multiplex auto-impedance matching circuit is proposed. By reusing the proposed auto-matching circuit, we can reduce additional hardware and area overhead.

2. Impedance matching analysis

The transducer used in the HIFU system consists of four parts: piezoelectric active element, transducer casing, backing layer, and coaxial cable. The ultrasound signal is

¹Xi'an University of Technology, Shaanxi 710048, China

²Microsystems, Bat 220/C2N, University of Paris Sud, Orsay 91405, France

a) xswang@xaut.edu.cn

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generated by a piezoelectric active element in the transducer. The modeling of the ultrasonic transducer can be simplified to model the piezoelectric active element, which can be considered an electromechanical vibration system. A well-known equivalent model of the piezoelectric transducer [30] based on electrical and mechanical characteristics is depicted in Fig. 1.

Fig. 1. Electrical model of the piezoelectric transducer [30].

This model is composed of a static branch and a motional branch. R_P and C_P represent the static electrical characteristics of the piezoelectric transducer, and L_M , C_M , R_M represent its mechanical characteristics. R_P is neglected because of its very large value. The equivalent electrical impedance of the transducer Z can be obtained by,

$$Z = R + Xj \quad (1)$$

where the resistance R and the reactance X of the transducer can be expressed as,

$$R = \frac{R_M}{w^2 C_P^2 R_M^2 + \left[1 - w C_P \left(w L_M - \frac{1}{w C_M} \right) \right]^2} \quad (2)$$

$$X = \frac{w L_M - \frac{1}{w C_M} - w C_P \left[R_M^2 + \left(w L_M - \frac{1}{w C_M} \right)^2 \right]}{w^2 C_P^2 R_M^2 + \left[1 - w C_P \left(w L_M - \frac{1}{w C_M} \right) \right]^2} \quad (3)$$

Fig. 2 presents the impedances of 256 transducers used in this study, working at their resonance frequency of 1.25 MHz. R and X define the resistance and the reactance of the impedances, respectively.

These impedances are measured at different temperatures by using a vector network analyzer (DG8SAQ VNWA 3E). The short-open-load-thru (SOLT) calibration method is used here to remove the parasitic effects introduced by the bayonet nut connectors. As seen in this figure, although the 256 elements are composed of the same piezoelectric material and have the same shape (6 mm diameter), impedance dispersions are noticeable.

Table I shows the impedance characteristics of the 256 transducers. The variations in the resistance and the reactance caused by manufacturing tolerances combined with temperature drifting are 98.5% and 58.6%, respectively.

The diagram and simplified circuit of auto-impedance matching system based on synchronous switched capacitor presented in our previous study [24] are shown in Fig. 3.

The reactance of the inductor L and the susceptance of the equivalent capacitor C_{Eq} that represents C_S and C_{Fix} in

Fig. 2. Impedances of 256 transducers measured at different temperatures (25°C~55°C) with a working frequency of 1.25 MHz.

Table I. Impedance characteristics of 256 transducers.

$T = 25^\circ\text{C}$	Minimum	Maximum	Average	Std
R	20.34 Ω	48.43 Ω	35.02 Ω	6.83
X	-360.78 Ω	-239.88 Ω	-305.97 Ω	28.31
$T = 32.5^\circ\text{C}$	Minimum	Maximum	Average	Std
R	19.61 Ω	47.02 Ω	33.82 Ω	6.63
X	-346.71 Ω	-233.76 Ω	-295.20 Ω	27.32
$T = 40^\circ\text{C}$	Minimum	Maximum	Average	Std
R	18.74 Ω	44.73 Ω	32.07 Ω	6.26
X	-329.40 Ω	-220.08 Ω	-279.78 Ω	25.94
$T = 47.5^\circ\text{C}$	Minimum	Maximum	Average	Std
R	17.74 Ω	42.42 Ω	30.31 Ω	5.90
X	-312.13 Ω	-205.21 Ω	-264.45 Ω	24.59
$T = 55^\circ\text{C}$	Minimum	Maximum	Average	Std
R	16.88 Ω	40.07 Ω	28.91 Ω	5.64
X	-298.25 Ω	-196.89 Ω	-252.86 Ω	23.81

the variable L-type tuning network are defined as X_L and B_{CEq} , respectively. Z_O represents the output impedance of the power supply.

To ensure that the impedance of the transducer is well matched to the power supply, the following equation must be true.

$$Z_O = jX_L + \frac{1}{jB_{CEq} + 1/(R + X)} \quad (4)$$

As known previously, Z_O is purely resistive. Then, we can obtain the following simultaneous equations:

$$\begin{cases} B_{CEq}(X_L R - X Z_O) = R - Z_O \\ X_L(1 - B_{CEq} X) = B_{CEq} Z_O R - X \end{cases} \quad (5)$$

The impedance compensation range of the auto-impedance matching network is required to cover the impedance variations caused by manufacturing tolerances and temperature drifting. In our former paper, in order to achieve a linear transfer function, the inductor L in the L-type matching network is set to be constant, and X_L can be calculated by introducing the average value of R and X into Eq. (5). Then, the range of the values of B_{CEq} can be obtained.

Fig. 3. Diagram and simplified circuit of the one-channel impedance matching system [24].

$$\frac{R_{min} - Z_O}{R_{min}X_L + Z_OX_{max}} \leq B_{CEq} \leq \frac{R_{max} - Z_O}{R_{max}X_L - Z_OX_{min}} \quad (6)$$

where R_{max} , R_{min} , R_{avg} represent the maximum, minimum and mean values of the resistance, respectively, with temperature ranging from 25°C to 55°C. X_{max} , X_{min} , and X_{avg} define the maximum, minimum and mean values of the reactance, respectively.

According to the principle of switched capacitor, the range of the values of B_{CEq} can also be expressed as,

$$w[C_{Fix} + \text{Min}(C_{SEq})] \leq B_{CEq} \leq w[C_{Fix} + \text{Max}(C_{SEq})] \quad (7)$$

where C_{SEq} defines the equivalent capacitance of C_S , $\text{Max}(C_{SEq}) = C_S$, and $\text{Min}(C_{SEq}) = 0$. C_{Eq} and C_S can be calculated by solving Eqs. (6) and (7). For this study, $Z_O = 0.04 \Omega$, and the values of R_{mean} , R_{max} , R_{min} , X_{mean} , X_{max} and X_{min} are illustrated in Table I. Therefore, $L = 1.33 \mu\text{H}$, $C_{Fix} = 11.64 \text{ nF}$, and $C_S = 184.91 \text{ pF}$.

3. Time-division multiplex auto-impedance matching system

The diagram of the proposed time-division multiplex auto-impedance matching system based on our previous study is shown in Fig. 4. It consists of three parts: five-channel transducers, a digital control circuit, and a feedback loop.

The feedback loop is achieved by using the circuit presented in [25]. The digital control circuit consists of a microcontroller unit (MCU) and a ten-channel analog switch. The control signal of the analog switch is generated with the MCU. Fig. 5 illustrates flow chart of the proposed time-division multiplex auto-impedance matching system. The system has five working periods, and the core flows of the different periods are basically the same. Therefore, intermediate steps were omitted.

In period Channel 1, V_{PA} and V_{CFix} of the first channel are connected to the feedback loop. The first channel of the

Fig. 4. Diagram of the proposed time-division multiplex auto-impedance matching system.

Fig. 5. The flow chart of the proposed time-division multiplex auto-impedance matching system.

system is working in auto-impedance matching mode. The other channels are working as power amplifiers with static impedance matching networks. Switching control signal V_{PWM} output from port O1 of the MCU. Then, MCU starts

to check the status of the switching control signal (V_{PWM}). If V_{PWM} is stable, it is stored and continuously outputted at port O1, and the next period started. If V_{PWM} is unstable, then a check is performed on whether the operation time of period Channel 1 (T_{Per1}) exceeds the preset time (T_{Preset}). If the operation time of period Channel 1 exceeds T_{Preset} , period Channel 1 is ended, and the next period is started; otherwise the status of V_{PWM} is checked again. The settling time of the auto-matching network is less than 15 periods with a working frequency of 1.25 MHz in the worst case. To ensure the stability of the system, the preset time T_{Preset} is required to be greater than or equal to the settling time of the auto-matching network. Thus, in this paper, T_{Preset} is set to 15 periods.

4. Test results

Fig. 6 shows the equivalent impedances of 256 transducers using impedance matching methods presented in [17, 23] and this paper, respectively. $Im(Z)$ presents the imaginary part of the impedance, and $Re(Z)$ is the real part of the impedance. The output impedance of the class D amplifier used in this work is 0.04Ω . Table II gives out the impedance characteristics of 256 transducers with different matching methods.

As can be known from the test results, the method proposed in [17] is unable to compensate the variations of the impedances caused by the temperature variations as well as the manufacturing tolerance.

Fig. 6. Equivalent impedances of the 256 channel transducers using different matching methods. Equivalent impedances using impedance matching network presented in [17] (a), Equivalent impedances using impedance matching network presented in [23] (b), Equivalent impedances using impedance matching system presented in this paper (c).

Fig. 7. Power efficiencies of the 256-channel power amplifiers with different matching networks. Power efficiency using impedance matching network presented in [17] (a), Power efficiencies using impedance matching network presented in [23] (b), Power efficiencies using impedance matching system presented in this paper (c).

However, the imaginary impedance variations mainly caused by temperature is not compensated. For our method presented in this paper, the impedance variations caused by the temperature variations and the manufacturing tolerance are well compensated.

Table II. Impedance characteristics of 256 transducers with different matching methods.

Parameters	[17]	[23]	This work
$T = 25.0^{\circ}\text{C}$	$\text{avg}(Z)$	$0.040 - 0.002i\ \Omega$	$0.039 - 0.0002i\ \Omega$
	$\text{std}(Z)$	0.0346	0.0044
$T = 32.5^{\circ}\text{C}$	$\text{avg}(Z)$	$0.041 + 0.011i\ \Omega$	$0.041 - 0.0004i\ \Omega$
	$\text{std}(Z)$	0.0357	0.0063
$T = 40.0^{\circ}\text{C}$	$\text{avg}(Z)$	$0.043 + 0.031i\ \Omega$	$0.043 + 0.0002i\ \Omega$
	$\text{std}(Z)$	0.0377	0.0048
$T = 47.5^{\circ}\text{C}$	$\text{avg}(Z)$	$0.046 + 0.053i\ \Omega$	$0.046 - 0.0001i\ \Omega$
	$\text{std}(Z)$	0.0398	0.0091
$T = 55.0^{\circ}\text{C}$	$\text{avg}(Z)$	$0.047 + 0.072i\ \Omega$	$0.048 - 0.0002i\ \Omega$
	$\text{std}(Z)$	0.0421	0.0118

Power efficiencies of the amplifiers with different matching networks are shown in Fig. 7. The maximum power efficiency of the class D amplifier used in this paper is 91.2%. Fig. 7(a) presents the test results by using the matching system proposed in [17]. Fig. 7(b) gives out the results by using the matching method presented in [23]. The results of the matching system in this paper is illustrated in Fig. 7(c).

Table III illustrates the comparison between different references and this study. As can be seen from this table, the power consumption of the proposed five channel system is less than 500 mW, which is much less than five times of the one channel solution presented in [25]. And the power efficiency is significant improved than [17] and [23].

Table III. Comparison between different references and this study.

References	[17]	[23]	This work
Working frequency	125 kHz	1.5 MHz	1.25 MHz
Average efficiency	49.9%	61.9%	82.5%
Standard deviation	0.26	0.25	0.06
Minimum efficiency	4.7%	14.4%	45.8%
Support channels	1	1	5

Fig. 8 shows the prototype of the five-channel time-division multiplex auto impedance matching system. The feedback network has been implemented and the time-division multiplex circuit has been achieved by using PCB with a size of $5\text{ cm} \times 10\text{ cm}$.

5. Conclusion

In this paper, a time-division multiplex auto impedance matching system is proposed for the class D power amplifiers used in the HIFU system. Different from the traditional solutions, it can automatically compensate for the

Fig. 8. Prototype of the time-division multiplex auto impedance matching system

impedance drifting of five channel transducers that caused by temperature variation or manufacture tolerance. The power consumption less than 500 mW with 1.25 MHz working frequency. The average power efficiency is 82.5%.

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