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Dissimilar trend of nonlinearity in ultrasound transducers and systems at resonance and non-resonance frequencies

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ABSTRACT

Several factors can affect performance of an ultrasound system such as quality of excitation signal and ultrasound transducer behaviour. Nonlinearity of piezoelectric ultrasound transducers is a key determinant in designing a proper driving power supply. Although, the nonlinearity of piezoelectric transducer impedance has been discussed in different literatures, the trend of the nonlinearity at different frequencies with respect to excitation voltage variations has not been clearly investigated in practice. In this paper, to demonstrate how the nonlinearity behaves, a sandwich piezoceramic transducer was excited at different frequencies. Different excitation signals were generated using a linear power amplifier and a multilevel converter within a range of 30–200 V. Empirical relation was developed to express the resistance of the piezoelectric transducer as a nonlinear function of both excitation voltage and resonance frequency. The impedance measurements revealed that at higher voltage ranges, the piezoelectric transducer can be easily saturated. Also, it was shown that for the developed ultrasound system composed of two transducers (one transmitter and one receiver), the output voltage measured across receiver is a function of a voltage across the resistor in the RLC branches and is related to the resonance frequencies of the ultrasound transducer.

1. Introduction

High power converters utilized in ultrasound systems play a significant role in different applications where an energy conversion at different ranges of voltage and frequency is required. In such a system, a high power ultrasound transducer converts electrical energy to mechanical energy (ultrasound wave) and vice versa [1–7] and the transducers can be employed as transmitters, receivers or both. As shown in Fig. 1, as a transmitter, the ultrasound transducer converts an electrical energy (v_{input}) to a mechanical energy (ultrasound waves) and as a receiver it converts a mechanical energy back to an electrical energy (v_{output}) [2].

To achieve a high power energy conversion, a transmitter should be excited by a high power signal tuned at a specific frequency. Power electronic converters are key technology to converter different power types – DC or AC ⇔ DC or AC – and generate a desirable voltage and/or frequency suitable for many applications including the ultrasound system. The associated control system generates a desired reference signal through an output feedback for which the accuracy of such a control system highly depends on the load behaviour. The nonlinearity of the load can affect the accuracy of the system and hence a proper control system needs to be developed based on the load and system characteristics [8]. A high power ultrasound system as a load for a power electronics converter can deteriorate the performance of the system and increase the power consumption if its nonlinear behaviour is not well understood. Thus, to attain a better control, the behaviour of the ultrasound system should be studied.

The system characteristic can be affected by the characteristic of the ultrasound transducer. The intensity of the generated ultrasound wave is highly related to the mechanical deformation of a material within the transducer which depends on the applied

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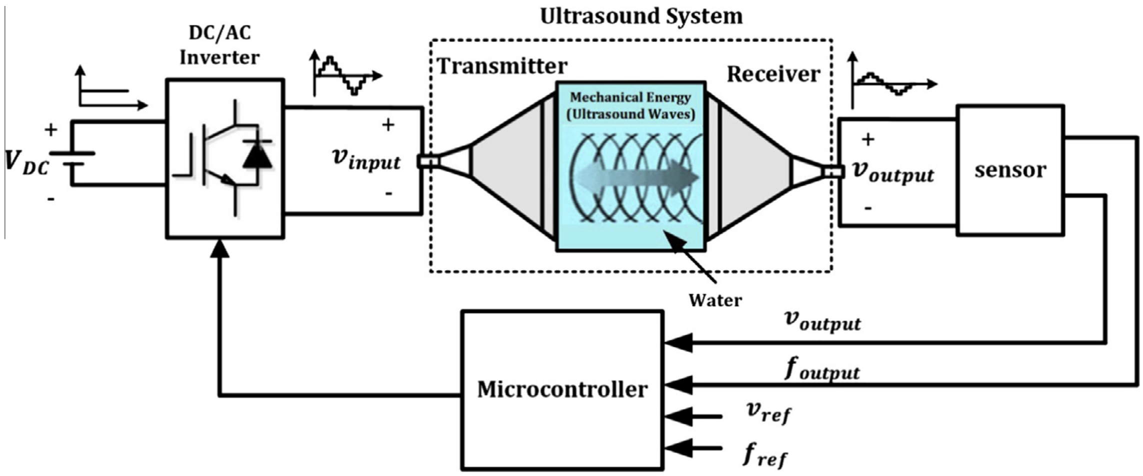

Fig. 1. Block diagram of the ultrasound system.

electrical energy across the ultrasound transducer. In this case, to have a better performance, an appropriate excitation signal with high quality (low distortion) is required [2,3,8].

In high power ultrasound systems used in industrial and biomedical applications [9,10], a flexible power supply is required to convert an electrical energy into a desirable signal with adjustable amplitude and frequency in order to efficiently excite the high power transducer [11]. Thereby, investigating the ultrasound transducer behaviours at both device and system levels within different voltage and frequency ranges can give a better insight in maximizing the energy conversion performance.

An ultrasound transducer has several resonance frequencies in which its lowest electrical impedance results in a high efficient energy conversion compared to non-resonant frequencies (high impedances) [12–14]. Usually the resonant frequencies are represented and modelled by a parallel combination of RLC legs. Several electrical models of an ultrasound transducer are introduced in literature [12,15–17]. Fig. 2 illustrates the most well-known models.

The *Van Dyke model* is the basic model of the transducer which is a parallel connection of a series RLC leg and a capacitor [17]. The *Sherrit model* proposes a parallel combination of a series LC leg and a capacitor. The *Easy model* is another type of electrical model in which a resistor and a capacitor are in series with a parallel RLC leg [12]. An electrical model of the ultrasound transducer with multiple resonance frequencies is shown in Fig. 2(d) and is used for further analysis through this paper.

According to Fig. 2(d), (Z_{input}) is the total input impedance of the transducer which is given in (1).

$$Z_{input}(\omega) = Z_C(\omega) \| Z_{f_1}(\omega_1) \| Z_{f_2}(\omega_2) \dots Z_{f_i} \| (\omega_i) \quad \text{for } i = 1, 2, \dots, n \tag{1}$$

$$Z_C(\omega) = 1/j\omega C$$

$$Z_{f_i}(\omega_i) = R_i + Z_{L_i}(\omega_i) + Z_{C_i}(\omega_i) = R_i + j\left(\omega_i L_i - \frac{1}{\omega_i C_i}\right) \quad \text{for } i = 1, 2, \dots, n$$

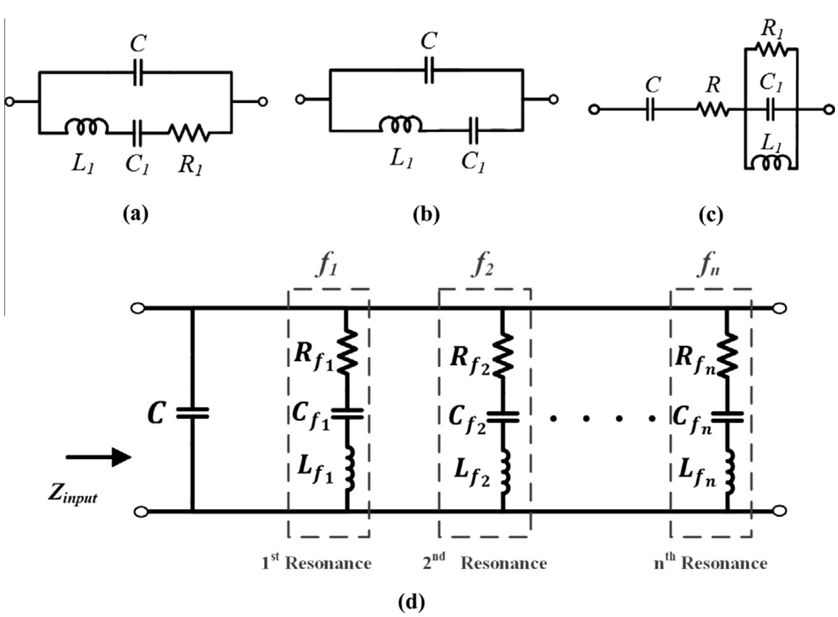

Fig. 2. Electrical model of an ultrasound transducer (a) Van Dyke model [12]. (b) Sherrit model [12]. (c) Easy model [17] and (d) extended Van Dyke model for a device with multiple resonance frequencies.