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Parallel resonant frequency tracking based on the static capacitance online measuring for a piezoelectric transducer

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ABSTRACT

Piezoelectric transducers working series resonant frequency (SRF) may suffer damage due to the overheat of the piezoelectric device caused by the large current. It is especially severe when the load value is large and changes fast. On the other hand, it is proved that a transducer enjoys a load-based self-adjustable output power when operating under its parallel resonant frequency (PRF). To take advantage of such feature and avoid the damage at SRF, a method of PRF tracking was proposed based on the online measurement of static capacitance. First, the relationship between the output power and load was derived based on the parallel equivalent circuit. Then, a target impedance value was defined and tracked as the flag of PRF. It shared the same changing rules as that of total equivalent impedance with respect to working frequency. The variable-step frequency sweeping method was improved to find PRF in less than 1 s and the error is less than 1 Hz. The proposed method monitored the static equivalent capacitance in real time since the capacitor always changes irregularly with the working condition. Also, the self-unlock mechanism was added to eliminate local optimum. The experimental results based on the proposed methods agreed with the theoretical analysis, which indicated the potential of the proposed method in practice.

1. Introduction

Transducers often work at the series resonant frequency (SRF) to take advantage of the largest vibration in practice. So researchers mainly focus on the tracking of SRF when they try to improve the performance of a transducer [1–4] However, parallel resonant frequency (PRF) is a better choice when the load is large and the changes fast, such as in ultrasonic welding. First, at SRF, device temperature increases when the current is much larger due to smallest impedance. The over-heat may damage the transducers when the piezoelectric properties change [5]. Second, the output power at PRF increases linearly with the value of load [6]. Such feature guarantees the transducer enough power for the load and avoids excessive power when working without load.

To find out the relationship of PRF with the equivalent impedance of a transducer, a parallel resonant equivalent circuit (PREC) was built. Based on the PREC, the function of the parallel equivalent impedance (PEI) was derived based on the static and dynamic electric equivalent parameters. Furthermore, the static equivalent capacitance is sensitive to temperature. Unfortunately, it is difficult to quantify the influence of temperature rise on the device, since the temperature effects concern multiples factors such as the shape of the transducer, heat dissipation condition, ambient temperature, and working time. In such case, the static capacitance asks for an online detection because it often varies irregularly with temperature.

PRF is found at the point of maximum PEI when PEI is calculated based on the accurate value of static capacitance. Generally, PRF is tracked based on the phase-locked loop (PLL) method according to the principle that the impedance phase is zero at PRF [7]. A voltage-controlled oscillator is often used to keep the phase difference between the voltage and current at zero. The matching inductance has to be changed manually for there is a chance that the lock may lose control under heavy load. Besides PLL, B. Mortimer et al. [8] eliminated the problems of phase measurement error and non-ideal modeling by measuring the transducer output power instead of the phase difference. A hill-climbing system of an admittance locking loop was designed according to the phenomenon that the power transferred to the medium reaches the peak at the maximum admittance point. Since ultrasonic wave cov-

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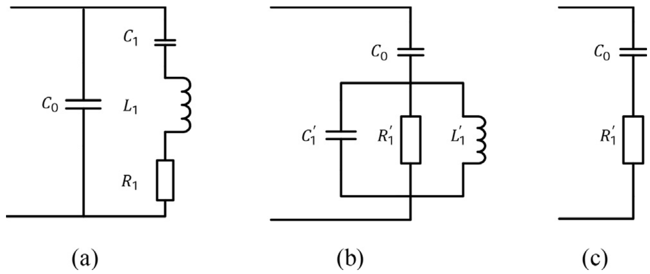

Fig. 1. Different equivalent circuits of a piezoelectric transducer. (a) SREC (b) pseudo-PREC (c) simplified pseudo-PREC at PRF.

ers a range of 20 kHz to 500 MHz, the research carried out under 25 kHz is not enough to verify the effectiveness of the proposed method. Zhu Wu et al. deduced that the transducer was equivalent to a pure capacitor under the action of the third harmonic of the resonant frequency [9]. Since the measured frequency based on such principle is much larger than the common operation frequency, the proposed method imposed a challenge on the design of hardware equipment when trying to switch fast between the online measure and steady operation.

The self-unlock frequency sweeping method is proposed in this paper. The control system adapts the frequency within the predefined range to reach the impedance maximum. Also, a self-unlock trick is added into the sweeping program to avoid local optimum. The desired frequency is found within less than 1 s thanks to the self-adaptive sweeping steps. The proposed method call for less serious demands on the hardware and is easy to realize since the iterate control algorithm only relates to PEI.

The paper is organized as follows. Section 2 demonstrates the adjustable output power of transducer working at PRF. Section 3 introduces the target impedance as an alternative tracking of PRF and presents the online measurement of the static capacitance. The key technology to guarantee the accuracy and efficiency of the tracking and control are presented in Section 4 after the sketch of the entire control system. Then, the experiments are introduced in Section 5 to verify the flexibility of the proposed method. Finally, the results of the experiments are discussed in comparison with the former theoretical analysis.

2. Transducer's adjustable output power at PRF

Generally, a piezoelectric device at 1st order modal is expressed by a series equivalent circuit (SREC, Fig. 1) to characterize the electric properties of piezoelectric vibrations [10]. However, such equivalent circuit poses a huge challenge on the calculation of PRF. In the light of this problem, a pseudo-parallel resonant equivalent circuit (pseudo—PREC, Fig. 1b) was designed for n explicit expression of PRF. The electric parameters of the proposed circuit were calculated from SREC under the following assumptions:

1) The total impedance of pseudo-PREC and SREC is the same.
2) The electric properties are expressed by the static and dynamic parameters separately.
3) An independent static capacitor is necessary to demonstrate the capacitive characteristic of a piezoelectric transducer.
4) The dynamic branch is the simplest combination of capacitors, resistors, and inductors that express the dynamic characteristics of the piezoelectric transducer.

According to assumption 1, we have:

$$Z_p = Z_s \tag{1}$$

where Z_p is the total impedance of PREC, Z_s is the total impedance of SREC.

When Z_1 and $Y_1^{'}$ are defined as the impedance of the dynamic arm in SREC and the admittance of that in pseudo-PREC respectively, we have:

$$\begin{cases} Z_1 \overset{\text{def}}{=} R_1 + j\omega L_1 + \dfrac{1}{j\omega C_1} \\ Y_1^{'} \overset{\text{def}}{=} \dfrac{1}{R_1^{'}} + \dfrac{1}{j\omega L_1^{'}} + j\omega C_1^{'} \end{cases} \tag{2}$$

where $\omega = 2\pi f$ is the angular frequency of the simulated signal with a frequency of f.

Substitute (2) into (1), we have:

$$\frac{1}{j\omega C_0 + \frac{1}{Z_1}} = \frac{1}{j\omega C_0} + \frac{1}{Y_1^{'}} \tag{3}$$

Solute the real and imaginary parts of (3) respectively, we have:

$$\begin{cases} R_1' = \dfrac{1}{\omega^2 C_0^2 R_1} \\ C_1' - \dfrac{1}{\omega^2 L_1'} = \omega^2 C_0^2 L_1 - C_0^2\left(\dfrac{1}{C_1} + \dfrac{1}{C_0}\right) \end{cases} \tag{4}$$

According to the definition of PRF, we have:

$$f_p \overset{\text{def}}{=} \frac{1}{2\pi\sqrt{L_1 \frac{C_0 C_1}{C_0 + C_1}}} = \frac{1}{2\pi\sqrt{L_1^{'} C_1^{'}}} \tag{5}$$

where f_p is the parallel resonant frequency of the transducer.

In this way, the pseudo-PREC can be simplified into Fig. 1(c) at the PRF condition. In the case that the load can be regard as the resistor R_L connected in series with the dynamic resistor $R_1^{'}$, the power of transducer working at f_p with load is calculated to be:

$$P_T = \frac{U^2}{R_1^{'}} = U^2 \omega_p^2 C_0^2 (R_1 + R_L) \tag{6}$$

where P_T is the power of transducer, and ω_p is the angular frequency of f_p. As in (6), the power of transducer at f_p changes synchronously with the load value, namely the self-adjustable power. This phenomenon is particularly beneficial to the situation when the load suffers serious fluctuation such as welding processing. To take advantage of such property, the tracking of PRF is investigated.

3. PRF tracking

3.1. Target impedance tracking for PRF

The target impedance Z_t is introduced to exclude the impact of the static capacitor C_0. It is defined below.

$$Z_t \overset{\text{def}}{=} \left|Z_p^{'}\right| - \left|\frac{1}{j\omega C_0}\right| \tag{7}$$

where $Z_p^{'}$ is the total impedance of the pseudo-PREC which can be calculated from the operating voltage and current.

The equation of $\frac{dX}{d\omega} = 0$ is solved for the relationship between the maximum of Z_t and ω, we have:

$$\omega = \omega_p\sqrt{k} = 2\pi f_p\sqrt{k} \tag{8}$$

where

$$k = \frac{2R_1' C_1' + \sqrt{k_1 + k_2}}{R_1'\left(C_0 + 2C_1'\right)} \tag{9}$$