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Resonance tracking and vibration stablilization for high power ultrasonic transducers

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ABSTRACT

Resonant frequency shift and electrical impedance variation are common phenomena in the application of high power ultrasonic transducers, e.g. in focused ultrasound surgery and in cutting. They result in low power efficiency and unstable vibration amplitude. To solve this problem, a driving and measurement system has been developed to track the resonance of high power transducers and to stabilise their vibration velocity. This has the ability to monitor the operating and performance parameters of the ultrasonic transducers in real time. The configuration of the system, with its control algorithm implemented in LabVIEW (National Instruments, Newbury, UK), ensures flexibility to suit different transducers and load conditions. In addition, with different programs, it can be utilised as a high power impedance analyser or an instantaneous electrical power measurement system for frequencies in the MHz range. The effectiveness of this system has been demonstrated in detailed studies. With it, high transducer performance at high power can be achieved and monitored in real time.

1. Introduction

Ultrasound is widely used in clinical applications in surgical and medical instruments for biological tissue cutting, ablation and dissection [1–3]. Most of these systems work in the low frequency range, 20–100 kHz, and at high power, utilising a vibrating metal probe to contact the target tissue and achieve the desired effects. During such high power ultrasound operations, it is critically important to drive the transducer at its resonant frequency, as the highest power conversion is achieved at this point. However, the resonant frequency of an ultrasonic transducer is subject to significant variations during operation, from causes such as self-heating and variations in input power and acoustic loading conditions. Driving ultrasonic transducers at frequencies other than resonance results in poor power conversion and increased self-heating. The problem is exacerbated when the mechanical quality factor of the transducer, Q_M, is high, which is usually the case for high power ultrasonic transducers, as the magnitude of the electrical impedance changes rapidly at frequencies near its resonance [4]. Therefore, it is important to achieve resonant frequency tracking, and also to keep the vibration velocity of the transducer stable or controllable to achieve consistent results [5].

To date, various electrical systems have been reported to track the working frequency around the resonant frequency of ultrasonic transducers [4–8]. These reports detail the theoretical background, in which the analogue phase-locked loop (PLL) [4,6,7] is the most commonly used method. This is based on the principle that tuned ultrasonic transducers are resonant when the impedance phase is zero. The current and voltage in the driving circuit are sampled to calculate the phase difference, which is then used to control a voltage-controlled oscillator (VCO). The VCO adjusts the driving frequency to keep the phase difference zero. Alternatively, Mortimer et al. [8] uses maximum admittance as an indicator of resonance of a tuned transducer. An automatic 'hill-climbing system' is used to lock the input admittance of the transducer to be the maximum to achieve maximum power transfer from the transmitter to the medium. However, the working frequency of this system is below 25 kHz, which limits its application at higher frequencies.

The methods which have been reported are still not able to control the ultrasonic transducer to perform with constant vibration amplitude because of the change of impedance magnitude following changes in the resonant frequencies and the acoustic load [9]. When the electrical impedance at resonance increases, the voltage has to be increased to deliver more power to the transducer to compensate for the additional impedance so that the vibration amplitude can keep stable [5]. Although commercial driving systems for high power ultrasonic transducers are available, each driving system is matched to only limited, specific transducers and changes in the transducer require complicated calibration procedures by the supplier.

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This paper presents the development and characterisation of a new driving and measurement system for high power ultrasonic transducers, which can track transducer resonance and stabilise the vibration velocity amplitude at the same time. Unlike the conventional driving systems, which are normally based on complicated electric circuits, the controllers of our system are realised in LabVIEW graphical programming software, which ensures its potential to implement advanced control algorithm or adjust the controller parameters conveniently when necessary. With this configuration, the flexibility of the system is greatly improved and the function of the system can be easily extended by simple software modification. For example, the system can be utilised as a high power impedance analyser to characterise the performance of a transducer at high power drive conditions. Although the system has been developed for high power ultrasonic transducers for cutting applications, its flexibility and wide bandwidth (up to 5 MHz) allows its use in other ultrasound applications, such as the instantaneous electrical power measurement of sources for focused ultrasound surgery [10]. During operation, the voltage, current, vibration amplitude, impedance magnitude and phase can be monitored in real time.

2. Dynamic behaviour of ultrasonic transducers

2.1. Tuning of the capacitance

A piezoelectric transducer at frequencies near resonance can be modelled as a simple equivalent circuit, as illustrated in Fig. 1 [4], which can be considered as two arms. The electric arm has two components, C_0 and R_0, which are the capacitance of the clamped transducer and the dielectric loss resistance, respectively. As R_0 generally has a much higher value than the other parallel components, it is neglected in this study. The mechanical arm consists of a mechanical compliance, C_1, a mass component, L_1, and a mechanical loss resistance, R_1. All these parameters can be determined experimentally from the characteristic curves of the electrical impedance of the transducer [11].

From the circuit in Fig. 1, the admittance of the ultrasonic transducer is

$$Y = \frac{R_1}{R_1^2 + \left(2\pi f L_1 - \frac{1}{2\pi f C_1}\right)^2} + i\left[2\pi f C_0 - \frac{2\pi f L_1 - 1/2\pi f C_1}{R_1^2 + \left(2\pi f L_1 - \frac{1}{2\pi f C_1}\right)^2}\right] \quad (1)$$

in which f is the frequency. From Eq. (1), the conductance G and susceptance B can be deduced to be

$$G = \frac{R_1}{R_1^2 + (2\pi f L_1 - \frac{1}{2\pi f C_1})^2} \quad (2)$$

$$B = 2\pi f C_0 - \frac{2\pi f L_1 - 1/2\pi f C_1}{R_1^2 + \left(2\pi f L_1 - \frac{1}{2\pi f C_1}\right)^2} \quad (3)$$

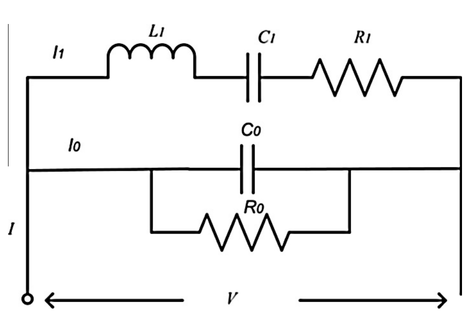

Fig. 1. An electrical model for ultrasonic transducers operating near resonance.

From Eqs. (2) and (3), we obtain:

$$\left(G - \frac{1}{2R_1}\right)^2 + (B - 2\pi f_s C_0)^2 = \left(\frac{1}{2R_1}\right)^2 \quad (4)$$

where f_s is the mechanical resonant frequency, the series resonance of the circuit in Fig. 1.

The locus of the conductance and susceptance in the region of the transducer's resonant frequency can be represented as a circle, as shown in Fig. 2, where f_s is characterised by maximum conductance, f_m is the frequency of maximum admittance (minimum impedance), and f_r is the resonance of the whole system, with zero phase. The highest performance of the transducer can be obtained when these three resonant frequencies equal each other, as the impedance is lowest and purely resistive. However, because of the existence of C_0, the whole circle is moved upwards from the G-axis by $B = 2\pi f_s C_0$. This makes f_s, f_m and f_r differ from each other, with the difference increasing with frequency and C_0. When working with low admittance transducers, the value of $2\pi f_s C_0$ may be greater than the radius of the admittance circle. Thus the transducer has no zero-phase frequency and an inductor is needed to compensate for the capacitance C_0. When connected in parallel with the transducer, the value of the inductance is

$$L_0 = 1/4\pi^2 f_s^2 C_0 \quad (5)$$

Fig. 3 shows the admittance circle of an ultrasonic transducer with and without tuning the capacitance. After tuning, the admittance circle is symmetrical about the G-axis and f_s, f_m and f_r are equal to each other.

2.2. Resonant frequency shift and impedance variation

During operation, the value of C_0, which is directly related to the dielectric properties of the piezoelectric elements of the transducer, remains approximately constant. However, the values of R_1, L_1 and C_1 will change considerably according to excitation power level, self-heating and acoustic load variation [12,13]. Variation of L_1 and C_1 will result in shifting of the resonant frequency while changes in R_1 will lead to variation in the electrical impedance at the resonant frequency. The electrical impedance of a commercial ultrasonic transducer with a tuning inductance is shown in Fig. 4. To illustrate the effect of acoustic load, results are shown for both air and water media. When changing to water, the resonant frequency changes from 78.75 kHz to 78.62 kHz and the impedance magnitude at resonance changes from 48 Ω to 730 Ω. To address this variation, the frequency of the driving signal should track this change to maintain resonance, and the amplitude of the driving signal has to be adjusted correspondingly to maintain constant vibration amplitude.

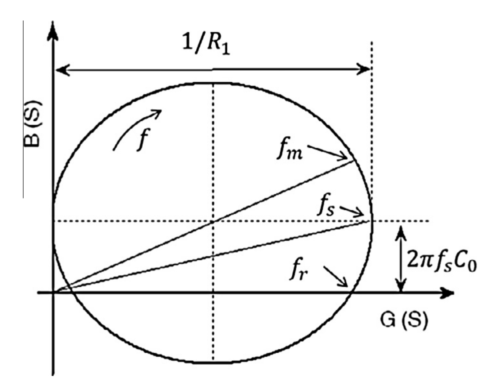

Fig. 2. The locus diagram of admittance of an ultrasonic transducer near resonant region.