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Single-transducer dual-frequency ultrasound generation to enhance acoustic cavitation

Hao-Li Liu [a,b,*], Chao-Ming Hsieh [a]

[a] Department of Electrical Engineering and Biomedical Engineering Center, Chang-Gung University, 259 Wen-Hwa 1st Road, Kwei-Shan, Tao-Yuan 333, Taiwan
[b] Devision of Medical Engineering Research, National Health Research Institute, Miaoli 350, Taiwan

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ABSTRACT

Dual- or multiple-frequency ultrasound stimulation is capable of effectively enhancing the acoustic cavitation effect over single-frequency ultrasound. Potential application of this sonoreactor design has been widely proposed such as on sonoluminescence, sonochemistry enhancement, and transdermal drug release enhancement. All currently available sonoreactor designs employed multiple piezoelectric transducers for generating single-frequency ultrasonic waves separately and then these waves were mixed and interfered in solutions. The purpose of this research is to propose a novel design of generating dual-frequency ultrasonic waves with single piezoelectric elements, thereby enhancing acoustic cavitation. Macroscopic bubbles were detected optically, and they were quantified at either a single-frequency or for different frequency combinations for determining their efficiency for enhancing acoustic cavitation. Visible bubbles were optically detected and hydrogen peroxide was measured to quantify acoustic cavitation. Test water samples with different gas concentrations and different power levels were used to determine the efficacy of enhancing acoustic cavitation of this design. The spectrum obtained from the backscattered signals was also recorded and examined to confirm the occurrence of stable cavitation. The results confirmed that single-element dual-frequency ultrasound stimulation can enhance acoustic cavitation. Under certain testing conditions, the generation of bubbles can be enhanced up to a level of five times higher than the generation of bubbles in single-frequency stimulation, and can increase the hydrogen peroxide production up to an increase of one fold. This design may serve as a useful alternative for future sonoreactor design owing to its simplicity to produce dual- or multiple-frequency ultrasound.

1. Introduction

It is well known that ultrasound can enhance bubble activity or the so-called acoustic cavitation. Acoustic cavitation, which is defined as the acoustically induced activity of gas-filled cavities [1–3]. The acoustic cavitation effect can be classified into stable and inertial cavitations [4,5]. In stable cavitation, the radius of bubbles oscillates around an equilibrium value over a considerable number of acoustic cycles without the generation of bubble collapse. In inertial cavitation, bubbles grow rapidly within one or two acoustic cycles before they collapse violently. Bubble activity enhanced by acoustic cavitation may have practical benefits and potential applications in industrial manufacturing, cleaning, welding [6], emulsifying, smashing, degasifying, promoting chemical reactions [7], enhancing sonoluminescence [8], and facilitating medical treatments such as transdermal drug transport [9].

Recent studies showed that dual- or multiple-frequency ultrasound excitation can extensively enhance the acoustic cavitation effect. Carpenedo et al. found that a large increase in the generated luminescence intensity is obtained under dual-frequency ultrasound irradiation in comparison to single-frequency ultrasound irradiation [10]. Barati et al. showed that with equal energies, the combination mode of sonication helped in generating a fluorescence intensity that was approximately 1.5 times higher than that the algebraic sum of the intensities of 150-kHz and 1-MHz irradiations and also 3.5 times higher the intensity due to single sonication alone [11]. The experimental results obtained from the studies in sonochemistry also verified that the extent of cavitation generated by multi-frequency ultrasound irradiation is higher than that generated by single-frequency irradiation [8,12–14]. The most acceptable mechanism was that the resultant field in dual- or multiple-frequency sonication covers a set of the frequencies with a range considerably wider than the sum of the spectra of the individual fields, and this leads to an increase in the size range of the

* Corresponding author. Address: Department of Electrical Engineering and Biomedical Engineering Center, Chang-Gung University, 259 Wen-Hwa 1st Road, Kwei-Shan, Tao-Yuan 333, Taiwan. Tel.: +886 3 2118800x5677; fax: +886 3 2118026.
E-mail address: haoliliu@mail.cgu.edu.tw (H.-L. Liu).

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bubbles involved in the cavitation process and an increase in the total number of cavitating bubbles [8]. Some experimental reports also support that the bubbles generated at higher frequency act as nuclei for lower frequency cavitation and thus enhance the acoustic cavitation activity [15–17]. Sonicating two or more frequencies simultaneously could disturb the sample solution to a greater extent than single-frequency ultrasound and may contribute to more cavitation nuclei generation in the solution [11].

Thus far, all the dual- and multiple-frequency ultrasound excitation methods proposed in the literature use separate piezoelectric transducers to individually generate single-frequency ultrasonic waves that interfere spatially [11,13,18,19]. This also includes a commercial device in which two ultrasonic transducers are arranged, namely, Orthoreactor® (Undatim Ultasonics, Belgium). However, it can be easily found that most of the piezoelectric crystals show more than one resonant frequency. It is hypothesized that dual- or multiple-frequency ultrasonic wave irradiations are possible to be generated from a single crystal once the driving frequency matches the characteristic frequency of the transducer.

This study proposes an ultrasound system design by exciting a single piezoelectric transducer to generate dual-frequency sonication. A prototype system was designed and proposed. Wave pressure distributions were measured and compared with theoretical estimations. An optical imaging approach was used and hydrogen peroxide production was measured to detect and quantify macroscopic bubble generation, and the backscattered signals were analyzed to identify the acoustic cavitation activity. Water samples with different levels of distillation and different values of applied power were also tested to verify the enhancement in cavitation. The spectrum obtained from backscattered signals was also recorded to characterize the bubble activity.

2. Method

2.1. Experimental setup

Fig. 1 shows the experimental setup. A water tank was constructed (200 × 200 × 600 mm). The transducer is connected to the circuit and then fixed to the bottom of the tank. A PVDF-type hydrophone (Onda, Sunnyvale, California, USA; calibration range: 50–20 MHz) was positioned on the transducer axis to record the ultrasonic signals and the generated harmonics due to acoustic cavitation activity. The hydrophone was connected to an oscilloscope and then to the computer through the GPIB interface for the measurement and observation of the spectrum. In order to optically detect the visible bubbles generated during ultrasonic energy stimulation, a CCD camera (pixel number = 3264 × 2448 per image frame) was positioned perpendicular to the transducer axis with a light source (tungsten filament, power = 50 W) on the opposite side. Other than the windows for CCD camera and light source, the surroundings of the water tank were all paved with the ultrasound absorption material to reduce the reflection of waves and the generation of standing waves. The entire setup was also optically shielded by placing the equipment in a dark room to reduce the light scattered from other sources.

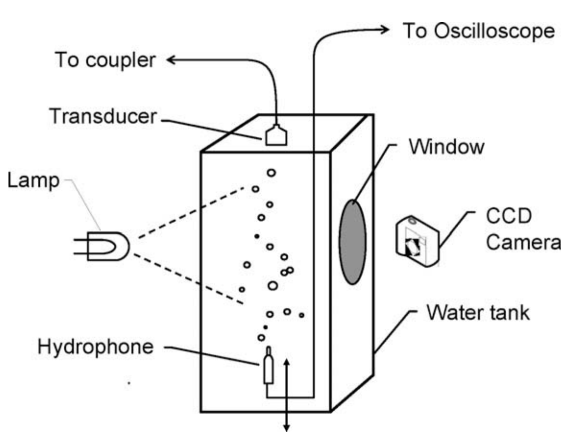

Fig. 1. Experimental setup.

Fig. 2 shows the conceptual electronics design. Two functional generators were used to generate sinusoidal signals (33220A, Agilent, Palo Alto, CA, USA), and the frequency of the output sinusoidal waves were selected to match one of the characteristic resonance frequencies of the planar transducer. Each sinusoidal signal is then fed to a power amplifier for signal amplification. The two amplified signals were then electrically matched to reduce the reflective power from transducer. The two matched/amplified signals were then mixed by using the magnetic coupling approach which has been commonly applied for radio-frequency signal heterodyning [20]. One toroid coil with a high magnetic flux capacity was used to couple the amplified signals and then output the mixed signal to the ultrasound transducer. The turn ratio of the two input ports (denoted by N1 and N2) and the output port (denoted as N3) was given to unity (i.e., N1:N2:N3 = 1:1:1) in order to mix the feed-in amplified signals without any further weighting and amplification. A planar piezoelectric element (PZT-4, diameter: 25 mm, thickness: 7 mm) was used in this study. The resonant frequency of this piezoelectric transducer was measured by using a spectrum analyzer (4395A, Agilent, Palo Alto, CA, USA). Fig. 3 shows the spectrum measurement and indicates that the characteristic frequencies locate at 83, 175, 241, and 271 kHz. The matching circuits were designed as a wideband transmission-line-type circuit (one is for the frequency range of 50–100 kHz and the other is for 150–300 kHz); these circuits could help the transducers to operate at the abovementioned frequency range with an acceptable power transmission efficiency (VSWR < 2; which corresponds to a return loss of approximately −9.5 dB and an efficiency of approximately 90%).

2.2. Measurement of gas concentration in test water samples

In order to easily observe the acoustic cavitation activity enhanced by the designed system, different water samples with varying distilled levels were employed rather than pure distilled water. A dissolved oxygen meter (OXI 330I, WTW, Weilheim, Germany; measured environment: atmospheric pressure = 960 mbar, temperature = 20 °C) was used for measuring the oxygen concentrations in the test water samples. In the degassed and the gassed water samples, the oxygen concentrations were measured to be 0.47 and 5.7 mg/l, respectively. The test water samples in the following experiments were then prepared by mixing degassed and gassed water in the following volume ratios: 1:0 (degassed water only), 2:1, 1:1, 1:2, 1:3, and 0:1 (gassed water only).

2.3. Measurement of ultrasonic pressure field

The ultrasonic pressure field was then measured and characterized. An acrylic water tank with a semiautomatic 3-D positioning system was used along with the transducer for conducting measurements inside the tank. The same hydrophone mentioned above was positioned to measure the pressure distribution along the transducer axis with a spatial resolution of 1 mm and a scanning distance of 500 mm. The pressure measurement was performed at low output power (1 W) and it was assumed that wave nonlinearity effect was not occurred at the whole power range we employed. The acoustic power output was also measured by using