Characterization of output signal from hollow cylindrical cavitation sensor

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1. Introduction

Recently, acoustic cavitation generated by high-pressure ultrasound has been investigated for medical therapeutic applications such as medication and gene therapy by sonoporation [1,2]. Meanwhile, cavitation can damage healthy cells in the human body. Therefore, it is necessary to control cavitation to ensure its suitable use in the medical field. However, there is currently no quantitative method for measuring the amount of generated cavitation required for the control. Therefore, ensuring the safety of the cavitation for the human body is a serious problem.

In the field of sonochemistry, several applications that exploit the effect of cavitation have been proposed. For example, cavitation has been investigated for producing advanced materials such as carbon nanotubes [3] and for dispersing nanometer sized diamond particles [4]. In the future, it is expected that industrial applications of sonochemistry will be developed. However, the lack of a quantitative technique for measuring the amount of generated cavitation has hindered the development of such applications.

Previously, the generation of cavitation by sound pressure, as typified by the mechanical index (MI), has been investigated in medical field [5]. However, it is necessary to measure the amount of cavitation generated both for highly accurate investigations on the effect of cavitation on the human body for medical applications and for technical advances in sonochemistry. Therefore, it is important to develop a technique for measuring the amount of generated cavitation.

We have been studying the quantitative measurement of acoustic cavitation. Zeqiri et al. in National Physical Laboratory (UK) proposed a method that employs a hollow cylindrical cavitation sensor [6–8]. To enable this method to be used in practical applications it is important to consider the relationships between the output voltage from the sensor, the cavitation generation conditions, and the secondary effects of the cavitation. In this work, we investigated the characteristics of the output voltage from a hollow cylindrical cavitation sensor by using the dissolved oxygen (DO) level of distilled water and sonochemical luminescence.

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2. Experimental method

2.1. Measurement system

Figure 1 shows the basic structure of the cavitation sensor used in this study. Construction of the hollow cylindrical cavitation sensor is described in Refs. [7] and [8]. A 110-μm-thick polyvinylidene fluoride (PVDF) film was used as the piezoelectric material and a 5-mm-thick closed-cell sponge was used as the acoustic isolator. The hollow cylindrical cavitation sensor has a three-plie structure. The outermost material of the sensor was acrylic resin. The sponge was attached to the inner surface of the acrylic resin by epoxy resin. In addition, the PVDF film, acting as a passive acoustic receiver, was attached to the inner surface of the sponge.

The ultrasound exposure system used a stainless-steel vibrating disk with a Langevin-type transducer (HEC-45402, Honda Electronics). The output signal from a function generator (AFG310, Sony Tektronix) was amplified by a power amplifier (75A250, AR) and was applied to the transducer. The operating frequency was 150kHz. The vibrating disk was placed on the bottom of a water tank (190 mm long, 190 mm wide, and 120 mm high). Distilled water was added to the tank to a height of about 100 mm. The cavitation sensor was placed at the center of the tank, approximately 40 mm above the vibrating disk. The output signal from the cavitation sensor was sent to a digital oscilloscope (TDS2012B, Sony Tektronix). 2.2. Signal processing of the output voltage from the hollow cylindrical cavitation sensor

The output signal was measured using the hollow cylindrical cavitation sensor as shown in Fig. 1. High-frequency components (i.e., in the megahertz range) of the output signal from the sensor were analyzed. These high-frequency components originate from shockwaves caused by the collapse and vibration of bubbles produced by acoustic cavitation [9,10]. The high-frequency components in the output signal were converted into Broadband Integrated Voltage (BIV) [7,8]. BIV was calculated by integrating the high-frequency components in the megahertz range. BIV is defined by the equation:

\[
BIV = \int_{f_1}^{f_2} V(f)df,
\]

\[
V(f) = \int_{-\infty}^{\infty} v(t)e^{2\pi if}dt,
\]

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where $v(t)$ is the output signal from the cavitation sensor. $V(f)$ represents the frequency spectrum. In this paper, the frequency limits of integration are taken to be $f_1 = 1$ MHz and $f_2 = 5$ MHz [6–8].

### 3. Results and discussion

The relationship between BIV and the DO level of distilled water was investigated. The DO level was measured by a dissolved oxygen meter (ID-100, Iijima Electronics). The results are shown in Fig. 2. BIV increased with increasing amplitude of the applied voltage to the transducer at DO level of about 8.3 mg/l. BIV increased rapidly above amplitude of an applied voltage of about 60 V. We noted the slope of BIV at voltages above about 60 V. In the case of DO level of about 2.3 mg/l, there was only a small change in BIV with applied voltage. The number of bubbles generated by acoustic cavitation is known to be affected by DO level: a higher DO level results in more bubbles being generated. Therefore, it was considered that BIV increased above 60 V because the amount of cavitation generated was higher at DO level of 8.3 mg/l. By contrast, there was little variation in BIV with increased voltage at DO level of 2.3 mg/l because the number of bubbles generated by cavitation was small.

Next, the relationship between amount of $\text{OH}^\bullet$ generated by acoustic cavitation and BIV was investigated. Generation of $\text{OH}^\bullet$ was measured by Electron Spin Resonance (JES-FA200, JEOL). The results are shown in Fig. 3. The DO level was about 8 mg/l. BIV has a strong positive correlation with generation of $\text{OH}^\bullet$ by cavitation. Finally, the relationship between BIV and sonochemical luminescence in the water tank was investigated. The sonochemical luminescence is the chemical reaction between luminal anions and $\text{OH}^\bullet$ produced by acoustic cavitation. The intensity of sonochemical luminescence increases with increased generation of $\text{OH}^\bullet$. The amount of generated $\text{OH}^\bullet$ was proportional to the amount of generated cavitation as shown in Fig. 2. Therefore, the sonochemical luminescence intensity is proportional to the amount of cavitation generated. Figure 4 shows the sonochemical luminescence at DO level of about 8 mg/l. The intensity of sonochemical luminescence was measured with a photomultiplier (R585, Hamamatsu Photonics) and a photon-counting unit (C9744, Hamamatsu Photonics). The vertical scale of Fig. 4 shows the charge pulse number of sonochemical luminescence per second. The charge pulse number was proportional to the intensity of sonochemical luminescence [11]. As a result, there was a positive correlation between BIV and the sonochemical luminescence generated by the cavitation.

From the results shown in Figs. 2–4, it is thought that BIV is amount proportional to the amount of acoustic cavitation generated.

### 4. Summary

We have investigated a method for quantitatively measuring acoustic cavitation. In this paper, the characteristics of BIV calculated from the high-frequency components (in the megahertz frequency range) of the output voltage of a hollow...
cylindrical cavitation sensor were investigated. The results revealed that BIV was dependent on the DO level. In addition, a strong correlation was found between BIV and the sonochemical luminescence. This indicates that BIV has the potential to be used as an index of the amount of acoustic cavitation generated.

In the future, we intend to perform a detailed investigation of the relationship between BIV and active oxygen species in detail. Also, we hope to investigate the ultrasound systems such as ultrasonic cleaning systems by using this BIV method.

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References


