Acoustic characterization of cavitation intensity: A review

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ABSTRACT

Cavitation intensity is used to describe the activity of cavitation, and several methods are developed to identify the intensity of cavitation. This work aimed to provide an overview and discussion of the several existing characterization methods for cavitation intensity, three acoustic approaches for charactering cavitation were discussed in detail. It was showed that cavitation noise spectrum is too complex and there are some differences and disputes on the characterization of cavitation intensity by cavitation noise. In this review, we recommended a total cavitation noise intensity estimated via the integration of real cavitation noise spectrum over full frequency domain instead of artificially adding inaccurate filtering processing.

1. Introduction

Cavitation usually refers to the generation of cavities and the subsequent dynamic behaviors when a liquid suffers from a sufficient pressure drop [1]. Due to high temperature and pressure [2-5], micro jet [6-8], shock wave [9-11], light emission [12-14] and derived biochemical effects [15-17] in the process of cavitation, cavitation has been widely used in many fields, such as sonochemistry [18-21], environmental engineering [22-25], biomedical engineering [26-28], material science [29-32], food processing [33-35], and so on. To estimate the cavitation effects and monitor the conditions of cavitation processes, cavitation detection and intensity characterization are desired.

Seventy years ago, cavitation intensity, as a self-evident concept, has appeared in the literature [36]. However, for a long time, a common and clear definition of cavitation intensity is rarely found, although chemical method [37-39], acoustic method [40-43], optical method [44-48], mechanical method [49-52], electrochemical method [53], hybrid method [54-60] have been used to measure the cavitation intensity.

Recently, Wu et al. [61] proposed a common and clear definition of cavitation intensity, that is, the energy released by cavitation bubbles per unit time and space. As shown in Fig. 1, Wu et al. found even if the existing methods in which different effects of cavitation are taken into account to characterize the cavitation intensity, the results are correlated with each other via the state variables of cavitation introduced by Wu et al. in a previous paper [1]. In theory, if the state variables of cavitation are accurately measured, the cavitation intensity will be determined accordingly. However, it is difficult to measure the state variable of cavitation accurately. Though some methods are hopeful to be used for measuring the state variables of cavitation, for example, the direct observations via high resolution photographic device. However, the equipment is inconvenient to be implemented in industrial applications.

For industrial cavitation applications, such as ultrasonic cleaning, real time and convenient measurement methods and associated equipment are needed. Mechanical methods, for example, inserting an aluminum foil into a cavitating liquid and measuring the distribution of pin holes on the foil caused by cavitation erosion, may be the easiest way among the existing methods. However, this mechanical method could not get the real-time results, and will interfere with the measured cavitation field itself. Chemical methods are usually used to give the results of time-space accumulation, which is difficult to reflect the temporal and spatial distribution of cavitation activity. Optical methods require light transmission characteristics of media, and the experimental systems are usually inconvenient to implement in industrial applications. Acoustic methods, for example, spectrum analysis of cavitation noise measured by a hydrophone, is time-consuming and little interfered to the cavitation field itself. Therefore, acoustic methods have already been widely used in ultrasonic cleaning and other ultrasonic liquid treatment.

However, due to the complexity of cavitation noise spectra, despite variety researchers have developed various methods to estimate the cavitation intensity via noise spectrum analysis, a well-recognized and unified method is still needed. Therefore, in this review, we try to sort out various acoustic methods to characterize cavitation intensity, briefly...
describe the basic principles of these methods, figure out their advantages and disadvantages, and then explore the key scientific problems and possible solutions of acoustic methods to characterize cavitation intensity.

2. Three acoustic approaches for charactering cavitation intensity

According to the way the detector receives signals from the cavitation field, there are three types of acoustic approaches for charactering cavitation: the first is the active cavitation detection (ACD); the second, passive cavitation detection (PCD); while the third, self-sensing cavitation detection (SSCD), as shown in Fig. 2.
In this technique, a transducer sends ultrasonic wave to the cavity field, and the transducer or another one receives ultrasonic reflection from the cavitation bubbles. R A Roy et al. [63] used the ACD to measure the threshold of transient cavitation generated by short high-frequency ultrasonic pulses. The signal processing of backscattered waves was used to monitor cavitation activities. However, due to focusing and size constraints, the ACD may be difficult to realize in industrial applications [62,64]. It is worth to note that there are some modified versions of active cavitation detection which based on the frequency shift signal generated by the Doppler effect caused by rapid expansion and collapse of cavitation bubbles [65]. These techniques might be more sensitive than traditional PCD, and they could provide information about bubble distribution. For increasing the spatial coverage of cavitation detection, ACM(Active cavitation mapping)[66,67] has been developed based on ACD by using a linear array instead of a single transducer. ACM can provide high sensitivity and spatial-temporal resolution, but it is time-consuming and limited to real-time cavitation mapping during ultrasonic processing or other industrial monitoring processes.

2.2. Passive cavitation detection (PCD)

The PCD is based on the spectrum estimation of cavitation noise emitted by cavitation bubbles. Plenty of studies have shown that cavitation intensity has a strong correlation with cavitation noise. Fifty years ago, Branson N G invented an instrument for measuring cavitation intensity in a liquid [68], the main principle of the instrument was using a piezoelectric hydrophone to measure the noise signals above 1 MHz, and the invention seems to be practical for cavitation detection in the field of ultrasonic cleaning. Later, B.Niemczewski [69-71] conducted series of experiments in which a cavitation intensity meter manufactured by Branson Incorporated (USA) was used to measure the so-called cavitation intensity on the principle of measuring ‘white cavitation noise’. However, the reason why the noise signals above 1 MHz can be used to characterize cavitation intensity of is unclear. Actually, cavitation noise is very complex, and it contains fundamental component, harmonics, sub-harmonics and broadband noise. As a result, it is very difficult to obtain the “pure” or “real” cavitation noises from the total signals collected by a hydrophone.

To separate the cavitation noise, Vijayanand S. Moholkar et al. [41] proposed a method for characterizing the spatial distribution of cavitation intensity in an ultrasound bath, using water (cavitating media) and silicon oil (non-cavitating media), the cavitation intensity was obtained by subtracting the acoustic emission spectrum of non-cavitating media from that of cavitating media. However, from an operational point of view, viscous non cavitating media may increase damping and cause ultrasonic attenuation [72], also different liquid medium usually have different acoustic impedance, which may change the frequency and intensity distribution of the sound field, although the ultrasonic transducer settings remain the same.

In another way, J.Frohly et al. [64] proposed taking the cavitation noise spectral integral as a criterion to characterize the cavitation activity. Zhaofeng Liang et al. [73] put forward another spectral analysis strategy based on the processing technique of Frohly et al., and divided the cavitation noise spectrum into continuous spectrum and line spectrum to characterize transient cavitation and stable cavitation respectively. Chao Li et al. [74] proposed that the integration of broadband noise spectrum can also be used to characterize the hydrodynamic cavitation intensity. Since then, various researchers [42,59,60,75-80] used cavitation noise to characterize cavitation intensity through different specific strategies, as shown in Table 1, especially in the field of biomedical engineering, the PCD [81-83] and its upgraded method PCM (passive cavitation mapping) [84-87] have almost become conventional methods.

Recently, International Electrotechnical Commission [88] issued a technical standard for measuring of cavitation noise in ultrasonic baths and ultrasonic reactors. It specified the cavitation measurement at 2.25 f0 in the frequency range 20 kHz to 150 kHz, and the cavitation measurement by extraction of broadband spectral components in the frequency range 10 kHz to 5 MHz. In the above-mentioned IEC document, the acoustic pressure spectrum was shown schematically as Fig. 3, and divided into three types of frequency component: the largest peak in the vicinity of f0, which was ascribed to the direct field (shown in blue); smaller peaks, which were ascribed to stable cavitation (shown in yellow); broadband noise between the peak, which was ascribed to transient cavitation (shown in red).

### Table 1
Overview of the strategies used for characterizing cavitation intensity via noise spectrum.

| Authors / references | Detail strategies and main finds |
|----------------------|---------------------------------|
| Ohbin Kwon et al. [59] | • Photomultiplier tube and hydrophone were used to measure cavitation intensity synchronously; • Filtered acoustic signals at different cut-off frequencies were used to analyze inertial cavitation; • PMT output showed a similar trend as broadband acoustic emission. |
| R Balachandran et al. [75] | • Fluorescence spectroscopy, microelectrode based chronolamperometry, hydrophone pressure measurement was carried out at different acoustic frequencies to establish a correlation with hydroxyl radical production and characterize transient cavitation; • Numerical integration of broadband noise spectrum fitting curve was used as an index of transient cavitation intensity. |
| K.L. Tan and S.H. Yeo [42] | • The development and intensity of cavitation in microchannel under an ultrasonic horn were analyzed by using high-speed camera and hydrophone; • Subharmonic spectrum was used to character the cavitation intensity; • By introducing the micro channel, the transient cavitation effect could be extended. |
| Lukman Yusufa et al. [60] | • Cavitation intensity was measured by dual-perspective high-speed photography and PCD; • Subharmonics were used to analyze the cavitation activity. |
| I. Tzanakis et al. [76] | • The cavitation intensity was measured in liquid aluminum using a high temperature cavitation meter calibrated by National Physical Laboratory; • Integration of cavitation noise over frequency spectrum was used to character the cavitation intensity (more details of the noise spectrum analysis were not mentioned in the paper, readers might be referred to the paper [80]); • There was an optimal power setting, in which bubble structure and amplitude reach physical equilibrium and the cavitation intensity reaches the maximum. |
| V. Grosjean, et al. [77] | • Axial sound field was measured by a hydrophone; spectrum analysis of the measured signals was made to quantify the cavitation intensity; • The total power was obtained by integrating the spectrum up to 150 kHz, and the power of broadband noise is derived by subtracting the power of peaks from the total; • Increasing ultrasonic power promoted transient cavitation and stronger sound shielding. |
| Liu et al.[78] | • Cavitation intensity distribution in gaseous liquid was measured via a hydrophone; • The total energy was obtained by numerical integration of the noise spectrum over whole frequency domain, the power spectrum integral with a frequency range of f0 ± 2.5 kHz was used to represent the linear partial energy, the cavitation effect is approximately expressed by the difference between total energy and line energy; • Reducing the gas content to a certain extent could evidently promote the cavitation effect, while the gas content reached a certain value, continuing to reduce the gas content slightly weaken the cavitation effect. |
However, there are some confusion in the IEC’s representation as shown in Fig. 3. First, stable cavitation bubbles can also oscillate in the fundamental frequency $f_0$ and emit the fundamental acoustic signal [1], as a result, in the total noise spectrum, it cannot only ascribe the fundamental to the direct field. Second, in a high amplitude acoustic field, waveform distortion in nonlinear acoustic wave propagation may also cause the harmonics [89,90]. Besides, Jae Hee Song et al. [79] found that the subharmonic component can also be caused by periodic shock waves, which come from the subharmonic collapse of cavitation clouds driven by HIFU. Therefore, the transient (also called inertial) cavitation intensity measured using the conventional PCD may be relatively inadequate due to the lack of this sub-harmonic component caused by periodic shock waves. The PCD may also give either an overestimation of stable cavitation intensity due to the including of the harmonic components caused by non-cavitation factors or an underestimation due to the discarding of the $f_0$ component caused by stable cavitation.

2.3. self-sensing cavitation detection (SSCD)

In some applications, such as ultrasonic processing of molten metal [91], it is usually impossible to place conventional measuring sensors such as hydrophones in the high-temperature liquid. To provide the process monitoring, one strategy is to use high temperature measurement sensors [76], such as a high temperature cavitometer [80]; another strategy is to make full use of the present processing transducers in the work medium.

Fig. 3. Schematic representation of acoustic pressure spectrums [88]

Fig. 4. Cavitation intensity indicated by gray images and spectrograms [94]
Cavitation noises have strong correlation with cavitation intensity. The acoustic method especially using cavitation noise to characterize cavitation intensity has advantages in real-time measurements and easy to implement, which is suitable in industrial applications.

However, cavitation noise spectrum is too complex to clearly ascribe specific spectral features to the so-called stable or transient cavitation. In our view, the classification of cavitation as stable or transient (inertial) is binary and inadequate in some cases. In this review, we recommend a total cavitation noise intensity estimated via the integration of real cavitation noise spectrum over full frequency domain instead of artificially adding inaccurate filtering processing.

Therefore, further work should include in-depth analysis of cavitation noise spectrum and development of methods to separate real cavitation noise from total collected noise.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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