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A model for measuring the velocity vector of bubbles and the pierced position vector in breaking waves using four-tip optical fiber probe, Part I: Computational method

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ABSTRACT

A dual-tip optical fiber probe has been attempted to make measurement of bubble size in breaking waves, especially for the violent and aerated bubble plumes presented immediately after breaking in laboratory and field. However, the performance of field measurement based on such probe is not satisfactory due to the measurement error produced by the large numbers of escaped and missing bubbles. The objective of the present study and its companion are to evaluate the errors of bubble size measurement in breaking waves using a dual-tip optical fiber probe, and the errors were grouped as oncoming bubble errors, receding bubble errors and missing bubble errors in terms of the bubble motion relative to the probe. The study on errors shows that the incomplete velocity vector of bubble and missing pierced position vector where the tips contact the bubble are the major reasons for errors. In order to make error correction, this paper proposes a four-tip optical fiber probe to obtain these two vectors and other required parameters. The mathematical model of the recommended probe is derived, which enables the bubble velocity components in the *x*, *y* and *z* directions and the pierced position vector is the unique functions of several time intervals and probe's spatial distribution relationship. The optimized algorithm is suggested to calculate the velocity vector, the pierced position vector and other required parameters from time intervals taken from the output signals of the proposed probe. The model and algorithm claim that the velocity vector of bubbles and pierced position vector can be obtained as long as the time intervals can be captured by four-tip optical fiber probe. Verification and validation of the model is presented in the accompanying paper.

1. Introduction

The size distribution of the entrained bubbles in breaking waves have been of great interest to engineers and oceanographers as they have great impacts on many geophysical processes, including the generation of sea-surface sound (Loewen and Melville, 1991), production of marine aerosols (Cipriano and Blanchard, 1981), and enrichment of the sea-surface microlayer (Blanchard, 1989). In order to quantify the influence of air entrainment on these processes, many studies have been focused on the bubble size measurement by breaking waves in both the laboratory and field, and the results show that the size distribution of the entrained bubbles is a controlling factor in these processes, and the size distribution may be described by the bubble size distribution (BSD) or chord length distribution (CLD). BSD may be represented either in terms of the equivalent diameters BSD (deq) or in terms of the bubble major axis BSD(a), which is used to the actual size distribution (Besagni et al., 2016; Besagni, 2017), and the CLD refers to the size distribution with a set of random chord length values rather than equivalent diameter or major axis. In general, Non-intrusive techniques (i.e., image analysis) are generally preferred over intrusive methods (i.e., probes) for BSD measurement, and the probes are well known to provide CLD.

The techniques used in existing investigations on the bubble size distribution generated by breaking waves in both the laboratory and ocean are classified as acoustic (Medwin, 1970; Vagle and Farmer, 1998; Czerski et al., 2011), photographic (Stokes and Deane, 1999; Leifer et al., 2003; Geißler and Jähne, 1995), and probe (Serdula and Loewen, 1998; Rojas and Loewen, 2007; Blenkinsopp and Chaplin, 2007). Photographic technique is commonly used to investigate the BSD from the images

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collected by different types of underwater imaging system. Deane and Stokes teams have made invention and improvement on a waterproof camera placed in the interior of the bubble plumes generated by breaking waves, and collect BSD data (Stokes and Deane, 1999). They find that the bubble density is proportional to the bubble radius to the power of $-3/2$ for small bubbles (radius less than 1.0 mm) and the smallest bubbles can be collected as small as 200 μm. Such camera has been also deployed in a shore-based configuration (data and power supplied via shore-connected cables) as well as an autonomous device in the open sea with its own power supply and data storage, which have been used in ASCOS (the Arctic Summer Cloud-Ocean Study) (Leifer et al., 2003), DOGEE (the Deep Ocean Gas Exchange Experiment) (Geißler and Jähne, 1995), SEASAW (the Sea Spray, Gas Flux and Whitecap study) (Norris et al., 2011) and HiWASE (High Wind Air-Sea Exchanges) (Brooks et al., 2009) to examine the bubble formation mechanisms. Acoustic techniques are also used to measure the void fraction and BSD in bubble plumes generated by breaking waves both in the ocean and laboratory. For example, Medwin and co-workers (Medwin, 1970; Vagle and Farmer, 1998; Farmer et al., 1998; Czerski et al., 2011) developed the acoustical resonator in order to make much more detailed measurements inside oceanic bubble plumes; Farmer et al. made improvements on the original resonator design and carried out a theoretical analysis of its operation. Since then, resonators have been used regularly to measure the size distributions of bubbles with radii between 16 and 300 μm (Vagle and Farmer, 1998; Czerski et al., 2011). Moreover, Farmer and co-workers extended the bubble population measurement to smaller radius (less than 16 μm) using improved acoustical resonator with higher frequency (Czerski et al., 2011). In summary, photographic technique is commonly used to investigate the BSD and bubble shapes because of its non-intrusive nature. It has been verified that this method is suitable for analyzing void fraction up to 5% (Besagni et al., 2017), but this technology is not suitable for the dense bubble plume and large fraction. Active acoustic techniques for estimating oceanic BSD require relatively large dimensions for the instrument (i.e, acoustic doppler velocimetry and acoustical resonator), and may significantly disturb the flow resulting in frequent unreliable noisy data, especially on the laboratory scale. Moreover, the studies of this two techniques mainly focus on the subsequent periods after formation stage (it is suggested that the life of a plume can be divided into four main phases: formation, injection, rise, and senescence (de Leeuw and Leifer, 2002)), the bubble with large size and high void fraction during the formation stage can not be detected in acoustic and photographic methods, and the large bubbles produced in the formation stage make a significant contribution to the air–sea gas transfer velocity and the rapid degassing of the bubble plume after wave breaking (de Leeuw and Leifer, 2002). Therefore, it is necessary to measure the BSD inside these dense bubble plumes so as to quantify the influence of air entrainment on these geophysical processes more accurately. In comparison with the aforementioned techniques, the intrusive probe technique is much simpler and has a highly comparable accuracy in dense bubble plumes measurements of void fraction and velocity.

Optical fiber phase detection probe is first used by Miller and Mitchie (1970) and described in detail by Cartellier and Achard (1991). Following their pioneering work, the optical fiber probes with single-tip or dual-tips have been extended to investigate the natural multiphase flow, such as gas-liquid two-phase flows that occur at the air–sea interface when bubbles are entrained by breaking waves (Serdula and Loewen, 1998; Rojas and Loewen, 2007; Blenkinsopp and Chaplin, 2007, 2010, 2011). Loewen and co-workers have compared the BSD and void fraction using the single tipped optical fiber probes with video image data in a unidirectional flow cell using a specialized flow cell system and in laboratory wave channel, respectively. It is found that the optical fiber probes could be used to obtain fairly accurate estimates of the void fraction in dense bubble plumes (Serdula and Loewen, 1998; Loewen, 1998; Rojas and Loewen, 2007). Blenkinsopp and Chaplin follow the work of Loewen and co-workers, they make more detailed measurements of the BSD in a laboratory wave channel, including the influence on bubble size and void fraction produced by different types of water, effect of scale on air entrainment by different breaking wave types (Blenkinsopp and Chaplin, 2007, 2010, 2011), it is concluded that the influence of water type may be relatively insignificant, but the effect of scale may impact interpretation of the results.

The laboratory measurement of bubble size using optical fiber probes discussed in above studies confirm that the optical fiber probe technique can be used to make reasonable estimates of BSD in the dense bubble plumes entrained immediately beneath breaking waves. However, probes usually record chord lengths of bubbles rather than bubble vertical diameters or true bubble size. The BSD is derived from the chord length distribution (CLD) by using statistical algorithms. Hence, another aim for these studies is to derive BSDs from measured CLDs using reasonable algorithms, it is concluded that a correlation between the bubble shape and size is essential for these process and the aspect ratio take a vital role in CLD to BSD algorithms. Giorgio Besagni proposed the aspect ratio correlation derived from the image analysis of dense plume, the different aspect ratio correlation have been proposed according to the major axis of the bubble (Besagni et al., 2016). Furthermore, the experimental error of the optical probe produced by three effects should be considered.

- improper dewetting at the probe tip (the blinding effect)
- alteration of bubble trajectory prior to or during the piercing process (the drifting effect)
- bubble deformation and/or deceleration at the probe tip (the crawling effect).

The relative influence of these effects on the final residence time estimates, as well as their absolute magnitude is not yet clear. However, the drifting effects was widely estimated in non-perpendicular piercing experiments beneath breaking waves in laboratory, where the probes are layed with variation of the impact angle rather than oriented at 90° or at 0° in existing experiments, the results showing the drifting effects may be qualified by the impact angle. Furthermore, an extra single-tip optical fiber probe or a dual-tip optical fiber probe (D-OFP) is deployed in order to carry out an independent measure of the angle between the probe axis and bubble motion direction, but it is capable of measuring the lager bubble rather than the angle between the probe axis and bubble motion direction (Blenkinsopp and Chaplin, 2010).

The present article considers the inaccuracy of the optical probe technique in dense bubble plumes. The first objective is to find proper parameters for correcting the errors produced by probes with one or two tips in the non-perpendicular piercing experiments. The second objective is to find the solution of estimated the proposed parameters that are responsible for inaccuracies in the CLD. The outline of this paper is as follows. In Section 2, we outline the basic measurement principle of an optical fiber probe with two tips. The measurement error of this probe is analyzed in Section 3. Mathematical model of improved probe for making correction of error is presented in Section 4. Section 5 provides a detailed description of bubble parameters algorithm in the proposed model. The conclusions are given in Section 6. Verification, validation and the performance of the recommended model of the method are reported in the accompanying paper.

2. Bubble measurement principle of D-OFP

This section describes the measurement principle of optical fiber probe with two tips. Although the probes used in existing measurement have been equipped with only one tip, the amount of probes is to be one or two in the same point. The maximum number of tips employed in current studies is up to 2. It means that the researchers have attempted to use probes with more tips to make more accurate measurement for bubble size. Hence, this study focuses on the bubble measurement theory of D-OFP.

The measurement principle of optical fiber probes used for bubble