A novel idea of methodology for evaluating spatial propagation characteristics of ultrasound pulse-echo

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Ultrasonic transducers have individual specificities on the spread width, emission angle, valid length, and more. Especially in the specificities, the emission angle accuracy of ultrasonic pulse-echo is crucial in ultrasonic measurements of velocity profiling techniques. In this study, with the combination of optical and ultrasonic measurements, we established an experimental methodology for evaluating the propagation characteristics of ultrasound pulse-echo. A stereo-vision system was utilized to obtain three-dimensional particle dispersion coordinates as the ultrasonic measurement reference values. As an application example, an ultrasonic transducer with an active element and a circular-stainless casing was used. This methodology could calibrate propagation characteristics of the ultrasonic transducers, such as the actual axis and spread width of the ultrasound pulse path. The method realized a highly-accurate evaluation of the tilt angle of the pulse emission against the transducer casing axis within O(0.01°) thanks to vast amounts of data of randomly-dispersed particles in water. Sound pressure measurement using a hydrophone sensor, a representative example of previous research, would not realize this data density.

Keywords: Ultrasound propagation, Alignment, Calibration, Stereo vision

1. Introduction

Ultrasonic velocity profiling technique has more highly been developed in recent years as a multidimensional velocity vector measurement method; for example, Yoon et al. presented the "instantaneous velocity-vector profile" method, which can measure the two-dimensional vector components utilizing a combination of three ultrasonic sensors [1]. Kikura et al. developed a two-element ultrasonic transducer for measuring two-dimensional velocity profile [2]. Shoji et al. updated the technique for measuring three-dimensional velocity distribution by a single transducer having multiple elements [3]. For these techniques measuring flow rate measurement or velocity vector, the actual emission angle of the ultrasonic wave is particularly essential in ensuring its accuracy.

A typical ultrasonic transducer is mechanically structured by casing, backing, active element, and wear plate. Individual specificity of the transducer is confirmed in angular or dimension errors of the active elements to a greater or lesser extent. Especially calibrating the misalignment of the transducer casing axis and the actual axis of the ultrasound path is the most experimentally important because transducers are generally installed according to the jig hole axis. Such assembling issues must be experimentally measured as numerical simulation cannot predict them.

For calibrating the propagation characteristic of transducers, experimental methodology should have the capability measuring three-dimensional propagation characteristic. However, only a few studies have been reported evaluating the ultrasonic pulse's propagation characteristics. Among the visualization techniques for ultrasound propagation, the Schlieren method is a well-known example for visualizing the sound pressure field [4,5]. This method can visualize the pressure field but has a technical limitation: pressure distribution projected on two-dimensional space can only be measured. Another example of experimentally evaluating sound field is using a multi-point hydrophone; Inoue et al. developed a system to measure a three-dimensional sound field using a hydrophone [6]. Although this method is robust, evaluating the alignment angle of the ultrasonic beam path with higher accuracy up to $O(0.01°)$ has never been attained because of requiring many spatial measurement points and the spatial resolution of the sensor position in three dimensions.

In this study, we develop a novel methodology to evaluate spatial propagation characteristics of ultrasound pulse-echo from reflectors. For evaluating the characteristics of the ultrasonic pulse, the methodology aims to obtain the individual specificities of the ultrasonic transducer, such as the propagation width, the emission angle, valid length of the propagated ultrasound. Here, a spherical particle was used as a tracer to visualize the ultrasound pulse propagating in water. The ultrasound pulse-echo profile was simultaneously obtained with the optical measurement of three-dimensional coordinates. A stereo-vision system with a pair of cameras realized the evaluation of three-dimensional coordinates. The efficacy of the established methodology is checked by applying velocity profiling, as discussed finally.

2. Experimental setup

The experimental setup is shown in Fig. 1(a). The experiments used an acrylic rectangular open box with 200 mm on the inner side. Tap water with dispersed spherical particles (Amberlite XAD1600N, Organo Co. Ltd.) as a visualizing agent for light and ultrasound is filled up in the box. The water used was sufficiently degassed to prevent the adhesion of air bubbles to the particles, inner walls of the vessel, and the transducer. These particles are white translucent beads of polymeric adsorbent and are 400 ± 50 μm in harmonic mean diameter, 1.25 in uniformity coefficient, and 1.015 to 1.025 in Specific gravity. Due to the difference in density between water and particles, all the particles settle in a few minutes. Therefore, it is necessary to keep stirring the water in the container with an L-shaped vane installed at the upper corner of the water bath, as shown in Fig. 1(a). A micro control unit (Arduino) controls it with a 90° reciprocal motion.

A liquid-crystal display (LCD) projector (EB-2065, Seiko Epson Corp.) is used to optically visualize the particles dispersed in water, generating color gradation illuminations. The LCD projector can make a light beam with an image of a pixel dot pattern with three colors (red, green, and blue). The color information in the projected light is utilized for the stereo-matching process of particles photographed in each camera. The focal point of the projector light was adjusted at the intermediate of the water bath. On the side wall opposite entering the light of the LCD projector, a 4 MHz ultrasonic transducer with 5 mm in active element diameter is fixed and contacted with the tap water directly. The 4K5I (Japan Probe) used in this study is a linear beam-type transducer with a disk-shaped element made of piezoelectric composite material. A cylindrical stainless-steel casing surrounds the element with a diameter of 8 mm. Since the wavelength of 4 MHz ultrasound, 0.25 µm, is sufficiently smaller than the representative diameter of the dispersed spherical particles, the ultrasonic wave is well reflected. The light path region is adjusted so that the ultrasound path is overlapped as much as possible, although the light axis does not necessarily have to correspond to the axis of the ultrasound path. As illustrated in Fig. 1(a), the diameter of entering color light from the LCD projector is approximately 10−15 mm, which is much larger than 5 mm in the diameter of the active element of the ultrasonic transducer. A darkroom environment is required for the experiment to sufficiently capture the reflected light of small particles.

A stereo-vision system consisting of two CMOS cameras (DFK33UP1300, The Imaging Source Asia Co., Ltd) is used to track the illuminated particles dispersed in a three-dimensional coordinate. The stereo-vision principle is based on a method of typical binocular vision for perceiving depth using “stereo disparity”, which is the same as the function of both eyes of a human. The light axis of both cameras is fixed, having 100 mm in distance between them with a degree of 18.9° at the water bath center. Known as a baseline, the longer the distance between cameras is, the better depth accuracy is. The baseline length should be shorter than the half-side length of the water bath to avoid the influences from the refraction and reflection. The stereo vision method used in this study can be referred according to previous study [7]. Images in each camera showing the stereo-matching result are shown in Fig. 1(b). The stereo-matched particle images and the cross-correlation coefficient V_{cp} calculated from each particle image are placed in the Fig. 1(c).

A pulser-receiver instrument (JPR-10CN, Japan Probe, Co., Ltd) was used to generate a 4 MHz ultrasound pulse with four cycles and to receive ultrasonic echo simultaneously. The ultrasound pulse generation is triggered by the timing of the function generator (Agilent 33220A, Keysight Technologies). A square-wave pulse with 50 Hz

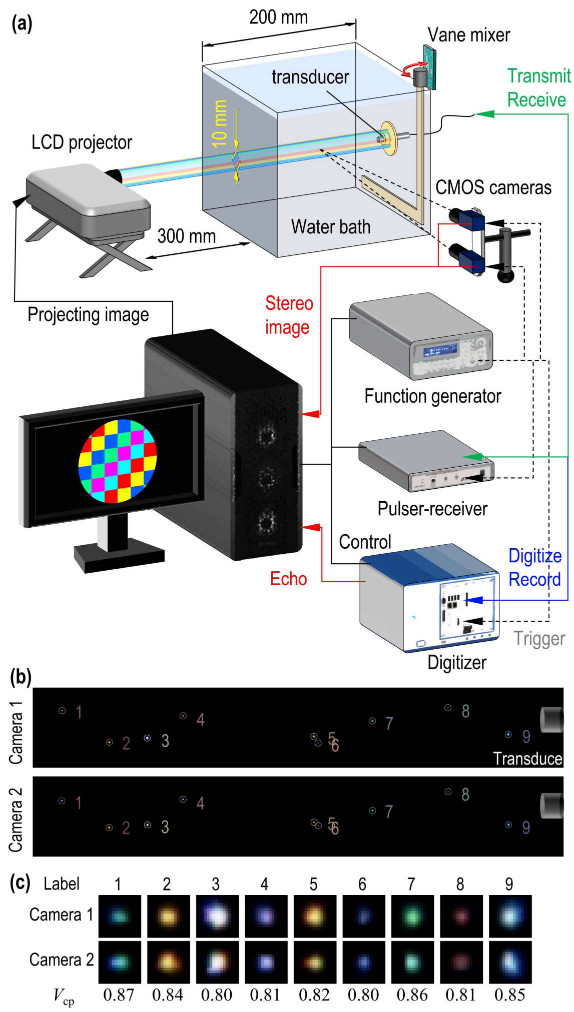

Figure 1: (a) Schematic of the experimental setup, (b) particle detection and stereo matching in images of each camera, and (c) the enlarged view of the detected particles and its direct cross-correlation values V_{cp} in each pair of the images.

in frequency (20% duty cycle) is used as the triggering signal. This signal controls the recording devices of both optical and ultrasonic measurements simultaneously; the pulser-receiver, a digitizer (NI-5122, National Instruments Co.), and two CMOS cameras. The digitizer receives echo data measured by the pulser-receiver and can record the data with 10 ns in sampling rate. When 20,000 points of ultrasound echo data are sampled, the maximum measurable distance from the transducer is 299 mm in the case of speed of sound, 1,496 m/s. The speed of sound in water is estimated by using a micro-stage.

3. Methodology for measuring propagation characteristics of ultrasonic pulse

3.1 Particle identification between optical and ultrasonic measurement

An analytical procedure for identifying the detected particles by optical and ultrasonic measurements is explained below. As a basic concept, the information of three-dimensional coordinates (x_p, y_p, z_p) acquired by the stereo-vision system is used as the reference for identifying the particles detected by the ultrasound pulse-echo. The three-dimensional coordinates of the emission point of the ultrasound

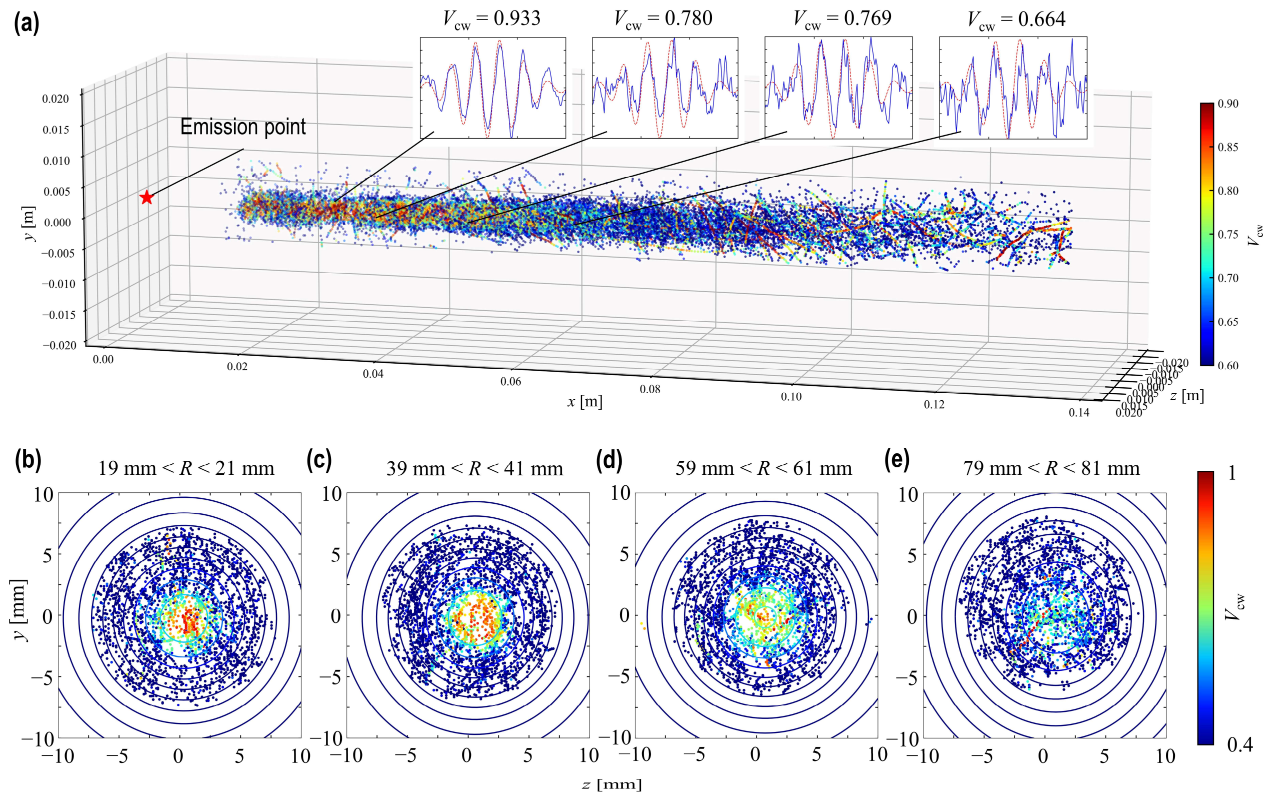

Figure 2: (a) Three-dimensional coordinates of the particles with color gradation representing the correlation value V_{cw}, where examples of template matching results between a beat-signal wave and the extracted wave in an echo profile, where the vertical axis indicates the echo amplitude normalized by the maximum within the extracted wave, and (b)−(e) two-dimensional distributions extracted from the three-dimensional particle distribution in (a), representing the four R ranges shown above.

pulse are determined by the stereo-vision system from the transducer coordinates. The distance R from the emission point (x_0, y_0, z_0) to each particle center can be calculated by positional relation, $R = [(x_0 - x_p)^2 + (y_0 - y_p)^2 + (z_0 - z_p)^2]^{1/2}$. The R is physically the same as the time-of-flight of the ultrasound pulse, L, if the speed of sound is constant in the propagated media.

When the distance L is determined by template matching for the obtained ultrasound pulse-echo as the center of the template wave, the particles minimizing $\Delta G = |R - L|$ at the same measurement frame are searched. Then, the particle data of both optical and ultrasonic measurement is identified if $\Delta G < 0.5$ mm as a result of the searched particle. From 100,000 frames (50 fps; 2000 s) of images and ultrasound pulse-echo profiles, three-dimensional coordinates of the particles, including correlation value V_{cw} are determined as shown in Fig. 2(a). The V_{cw} is obtained by template matching of the ultrasound pulse-echo, which is represented by color scale. The total number of the detected particles is approximately 155,000. For ease of understanding of Fig. 2(a), the scatter plot of particles in the range of $V_{cw} > 0.6$ were not displayed. Furthermore, from the overall trend, the closer to the emission point the coordinates of the particle are, the higher the V_{cw} are, and vice versa. At the same time, the closer to the emission point the coordinates of the particle are, the narrower the dispersion of particles is. As one of the novelties in this study, it should be emphasized that this distribution represents a three-dimensional pulse-echo quality. There has never been a methodology evaluating pulse-echo because most previous studies are focused on measuring sound pressure fields to evaluate the propagation characteristics in ultrasound pulse.

In the region of $x > 0.1$ m, some particles with high correlation values V_{cw} were confirmed as some paths like a string. This occurrence of the paths would be caused by the deviation of diameter of the dispersed particles; the diameter of spherical particles generally has deviations with a Gaussian function, and the harmonic mean diameter and uniformity coefficient are 400 ± 50 μm and 1.25 as the catalog data, respectively. There would be specific criteria for detecting the size distribution of the dispersed particles. Only if the particle having a larger diameter than a certain level passes through the path of the ultrasound pulse, such particles having localized-high-correlation values are often detected.

3.2 Analysis for ultrasound propagation characteristic

By associating the obtained ultrasonic pulse-echo having relatively high V_{cw} with the three-dimensional coordinates in particle distribution, an analytical method to evaluate propagation characteristics in the ultrasonic pulse is presented below. The particle's data (over 150,000) was obtained from the pulse-echo profiles and stereo-vision images for 2000 s, as mentioned above. The vast amount of particle data over 150,000 is randomly-distributed in the measurement space and has sufficient density for evaluating the propagation characteristics, such as spread width and actual emission angle in ultrasonic pulse emitted from the transducer. As a prerequisite, the x-axis in world space is adjusted by a rotation matrix corresponding to the cylindrical axis of the transducer, which is obtained using a cross-laser-marking instrument.

The coefficients of Gaussian function are optimized based on the least-square method, and the obtained optimal surfaces are superimposed on the scatter plots as isopleth lines shown in Figs. 2(b)–2(e). Processing this approximation to whole L at intervals of 2 mm, the distribution characteristics for L are evaluated as the variables of the Gaussian function. As shown in Fig. 3(a), the obtained results $\sigma/2$ are plotted with respect to L, which is calculated by $\sigma = (\sigma_y^2 + \sigma_z^2)^{1/2}$. The valid range of L in this experimental condition is determined as 16.9 mm < L < 96.4 mm, considering the approximation error of the Gaussian function. The propagation width of the ultrasound pulse emitted by a transducer with a circular cylinder can be estimated as $\sin(\theta/2) = ck/f_cD$, where k and D are the empirical coefficient and diameter of the active element, respectively. When k = 1.1, the propagation width of O(1%) in attenuation rate of sound pressure is shown as the red color dash line in Fig. 3(a), and element radius (2.5 mm) of the ultrasonic transducer is shown as the black color dash line in Fig. 3(a). The length of near field (dead time) in ultrasound pulse, $L_{NF} = D^2f_c/4c$, where L_{NF} = 16.71 mm in this experimental condition (c = 1,496 m/s). As seen in Fig. 3(a), the $\sigma/2$ has good accordance with the element radius in L < 60 mm and with spread width estimated by $\sin(\theta/2) = ck/f_cD$ when k = 1.1 in L > 60 mm, although the spread width is physically different from the $\sigma/2$ as it represents a threshold considering the attenuation of sound pressure intensity.

As shown in Fig. 3(b), the central coordinates δ in the obtained Gaussian function are plotted with respect to L, which is calculated by $\delta = (\mu_y^2 + \mu_z^2)^{1/2}$. The δ monotonically increases with respect to the length from ultrasound transducer L, where the slope φ in $\delta(L)$ is estimated as 0.67°, fitted by $\delta = \tan^{-1}(\delta)L$. This slope means the angled gap between the x-axis and the path axis of the ultrasound pulse. As the central axis of the transducer corresponds to the x-axis, the transducer has a tilt angle for the emission of ultrasound pulse as an individual specificity. The geometric relation of the propagation characteristics is explained as a schematic in Fig. 3(c). The error of the path and region of the propagated ultrasound is significant if the measurements of ultrasound pulse-echo are utilized as the velocity vector evaluation.

4. Summary

In this study, with the combination of optical and ultrasonic measurements, we established an experimental calibration methodology, which evaluates the propagation characteristics of pulse-echo in a typical ultrasonic transducer. A stereo-vision system was utilized to obtain three-dimensional particle dispersion coordinates as reference values of the ultrasonic measurement. As the application example, an ultrasonic transducer with an active element and a circular-stainless casing was used. This methodology could calibrate propagation characteristics of the ultrasonic transducers, such as the actual axis and spread width

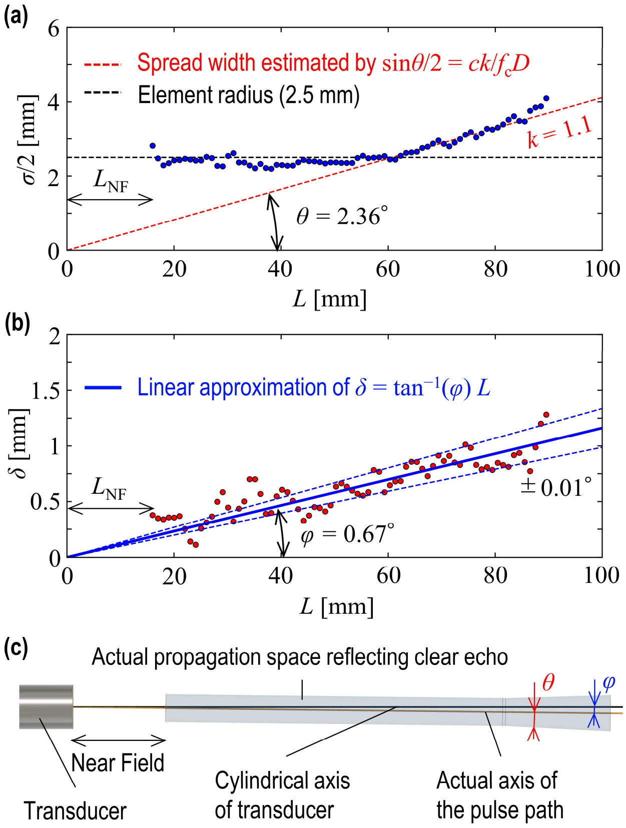

Figure 3: (a) The calculated results of $\sigma/2$ for L, (b) the central coordinates δ in the obtained Gaussian function, and (c) a schematic of actual propagation space for the ultrasound pulse emitted from the ultrasonic transducer.

of the ultrasound pulse path. As a result, this method realized a highly-accurate evaluation of the tilt angle of the pulse emission against the transducer casing axis within O(0.01°) thanks to vast amounts of data of randomly-dispersed particles in water. Here, ultrasound in the nearfield range is out of the scope of our method because the near field is a region where sufficient ultrasonic echoes cannot be measured.

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