Numerical analysis of optical fiber probing by ray tracing method

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Abstract Ray tracing numerical analysis of optical fiber probing, which is one of practical measurement techniques of bubbles and droplets dynamics, has been developed as a reliable method to analyze signal patterns. The analysis is applicable to bounded surfaces of flat planes, cylinders and ellipsoids as well as objects of constant refractive indexes in three dimensions. The rays’ energy in reflection and refraction processes is calculated repeatedly in the surfaces considered with polarization. The light source is assumed as linear polarized light with random fluctuations simulating a laser source. Three phenomena were analyzed by using the numerical model and experiment; (1) light emission trajectories from sensing edge, (2) piercing a bubble and (3) piercing an air-water free surface. We have obtained the following from the results; (1) the optical fiber probe emits almost straight light which angle is around 10° in water phase, (2) the reflected light from the frontal and rear surfaces of the bubble is considered to cause the “pre-signal,” which often appears in the case of the probe piercing the center area of a bubble, and (3) the signal will have the second peak signal just after piercing the frontal surface of the bubble if the surface does not deform, however, the second peak will disappear if the surface forms a meniscus.

1. Introduction

Optical fiber probing is one of reliable measurement techniques especially in gas-liquid flows with a high-concentration dispersed phase. It can detect not only the gas-liquid phase fraction but also the bubbles’/droplets’ diameters and velocities.

The left of figure 1 shows the basic structure of the optical fiber probe. The material of the fiber is plastic or glass, the sharply-ground edge forms a sensing point for detecting a gas or liquid phase and the other edge is optically connected to a laser diode (LD) and a photo detector (PD). The PD detects whether the sensing edge is in the air or water phase based on the amount of the returned beams reflected at the sensing edge by Snell's law.

The right of figure 1 shows a typical signal pattern at detection of a bubble. When the sensing edge is in water phase, the signal voltage is low (Figure 1 (1)). When the sensing edge pierces the bubble
frontal surface, the signal rapidly increases (2). While the sensing edge is positioned in the air phase, the signal keeps a high voltage (3). When the sensing edge is back into the water phase, the signal level rapidly decreases (4).

The right of figure 2 shows another type of signal. This type of signal includes “pre-signal” just before the sensing edge pierces the bubble frontal surface. The conventional analysis neglects the pre-signal and uses only the burst signal. However, the raw signal includes a lot of important information or a potential greatly improving the optical fiber probing. In particular, the pre-signal appears only when the probe pierces the central region of the bubble and is very useful to judge the pierce position. However, the mechanism is still unclear. Hence, we have developed a numerical analysis in order to understand the mechanism of the promising signals.

Fig. 2 A typical high-speed video image and a signal pattern of piercing a bubble

2. Ray tracing method

The ray tracing method is well known algorithm in making 3D computer graphics. It simplifies continuous light wave as discrete ray segments. This method is applicable to an optical analysis, if the waveguide media is enough larger than a light wavelength. The probe diameter (230µm) in the present study is considered to be enough larger than the source light wavelength (500-650nm).

Fig. 3 Algorithm of the ray tracing method

(1) Definition of the light field; materials' refractive indexes and their interface shapes and positions.
(2) Irradiation of the input/output edge by several ray segments simulated as random linear polarization laser.
(3) Iteration of the refraction and reflection while under-calculating ray segment's energy is higher than preset residue.
(4) Sum up returned ray segments' energy.
Figure 3 shows the algorithm of the ray tracing method. (1) Definition of the light field, which contains optical materials’ refractive indexes and their interface shapes and positions; the optical fiber probe is assumed as step index type, and the current model assumes all surfaces is smooth and neglects diffusing. (2) Irradiation of the input and output at the edge by a number of ray segments simulated as random linear polarization laser beams. (3) Iteration of refraction and reflection while under-calculating ray segment's energy is enough high; the energy ratio of refraction \((T)\) and reflection \((R)\) is described by the following equations depending on each polarization of parallel \((R_p, T_p)\) and perpendicular \((R_s, T_s)\). (4) Summation of the returned ray segments' energy; the numerical signal level is defined as the ratio of the total energy of returned ray segments and input ray segments.

\[
R_p = \frac{\tan^2(\theta_i - \theta_r)}{\tan^2(\theta_i + \theta_r)} \\
R_s = \frac{\sin^2(\theta_i - \theta_r)}{\sin^2(\theta_i + \theta_r)} \\
T_p = \frac{\sin(2\theta_i)\sin(2\theta_r)}{\sin^2(\theta_i + \theta_r)\cos^2(\theta_i - \theta_r)} \\
T_s = \frac{\sin(2\theta_i)\sin(2\theta_r)}{\sin^2(\theta_i + \theta_r)}
\]

3. Results and discussions

3.1 Light emission from the sensing edge

To validate the numerical analysis basically, the light emission trajectories from the sensing edge of the probe were investigated by both of experiment and the numerical analysis. Figure 4 shows the experiment of the microscopic visualization. The light source was a laser diode, which had a random linear polarization. The fiber was single mode step index and the refractive indexes of the core and the clad were 1.47 and 1.40, respectively. The outer diameter of the fiber clad and the core were 230\(\mu\)m and 220\(\mu\)m, respectively. The sensing edge was grounded by 35\(^\circ\). The light trajectories were investigated in both of air phase and water phase. To figure out the light trajectory, a tracer of a drop of milk was diluted into the water in the water phase case. The numerical model assumed the same condition of the experiment in three dimensions.

![Microscopic visualization of light emission trajectories from the sensing edge](image_url)
Figure 5 summarizes the results. The left column shows the numerical model and the right does the microscopic images. The top row shows the water phase condition and the bottom does the air phase. The numerical model results seem to well simulate the microscopic images.

We have to pay attention at the water phase cases. They emit almost straight light of which angle is around 10°, as contrasted to the air phase cases emitting three dominant diffusing lights. This phenomenon is caused by the difference of the refractive indexes of the air and water. The semi-straight light is estimated to cause the pre-signal in figure 2. The details will be discussed in next section.

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<th>Microscope</th>
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**Fig. 5** Light emission trajectories from the sensing edge of the optical fiber probe

### 3.2 Signal pattern of the fiber piercing a bubble

To validate the numerical analysis, the signal pattern of the fiber piercing a bubble was investigated by both of experiment and the numerical analysis.

The optical set up of the experiment was same as Figure 1. The light source and the fiber condition were same as the previous section. A photo diode was applied for light detection. It was connected to the fiber optically and to a data recorder electronically. A digital high-speed video camera was applied for visualization. The camera was synchronized to the data recorder to figure out the signal time and the position of the bubble.

The bubble was injected from the bottom of a water pool. The bubble’s size and rising velocity were characterized from the visualization images. The major axis was 2.44mm, the minor axis was 1.34 mm and the rising velocity was 0.22 m/s.

The numerical model’s optical assumption was same as the experiment except for the returned light detection. The numerical signal level was defined as the ratio of the total energy of returned ray segments and input ray segments. The bubble was approximated to be an ellipsoid, which major axis and minor axis were same as the experiment. The center axis of the bubble agrees with the
fiber axis. The current model assumes a solid surface model. It means the probe piercing does not deform the bubble surface.

The experimental result is showed in Figure 2 and the numerical result is in Figure 6. Figure 6 also shows characteristic patterns of (1) - (3). (1) Most rays are scattered away if the bubble is far from the sensing edge. (2) Some ray segments are returned into the sensing edge by reflecting on the frontal and rear surface of the bubble if the bubble is positioned enough closely to the sensing edge. This phenomenon is considered as the dominant mechanism of the pre-signal. (3) Many ray segments are returned into the sensing edge by reflecting on the frontal surface of the bubble if the sensing edge pierced a central area of the bubble. However, this second peak never appears in the experimental result. This difference is considered to be caused by surface deformation. The details will be discussed in the next section.

![Figure 6](image.png)

**Fig. 6** Signal pattern of piercing a bubble (Numerical analysis)

### 3.3 Signal pattern of the fiber piercing an air-water free surface

To figure out the difference of the Figure 6 (3) signal peak, the signal patterns of the fiber piercing an air-water free surface were investigated by both of experiment and the numerical analysis. The optical and electronic set up of the experiment were same as the previous section. The left of Figure 7 shows the captured image by the synchronized high-speed camera just before the probe piercing the surface from air into water. A robot arm held the fiber and pierced the surface slowly. The moving velocity was 0.0014 m/s.

The numerical model approximated the meniscus as an axial symmetrically rounded surface with constant radius. This assumption simulates a static meniscus struck by a needle or a thin line. Figure 8 shows the visualized images of the experiment and numerical analysis. It shows the close up images around the sensing edge just piercing the surface from water into air. It is difficult to measure the meniscus radius in experiment, so it was assumed to be ranged from 0.0mm (flat surface) to 0.4mm in the numerical analysis.
Fig. 7 Experiment (left) and numerical analysis (right) of piercing an air-water free surface

Fig. 8 Visualization of a probe just piercing the air-water surface; numerical model and experiment

Figure 9 shows the returned light levels of the experiments and the numerical analysis. In the cases of the fiber piercing from air into water, the numerical model seems good accordance with the experiment. However, the cases of the fiber piercing from water into air show a big difference between the experimental result and the numerical result of assumed flat surface (R=0). I.e., just after the fiber edge contacting the free surface, the experimental signal declines sharply but the numerical signal continues to increase. The numerical increase is considered to be caused by the surface reflection, same as figure 6’s second peak. As discussed in the section 3.1, the light emit almost straight in water phase. Therefore, the reflection light is considered to be stronger than air phase case. This phenomenon is considered to let the surface deformation strongly affect to the signal pattern. To improve the accuracy of the numerical analysis, the model assumed the simple static meniscus model to simulate the surface deformation. As the result, the signal pattern seems a good accordance with the experimental signal in case of the meniscus radius to be assumed as 0.2mm.
4. Conclusions

Ray tracing numerical analysis of optical fiber probing has been developed as a reliable method to analyze signal patterns. The analysis assumed objects as constant refractive indexes bounded with smooth surfaces in three dimensions. The rays' energy in reflection and refraction processes is calculated repeatedly in the surfaces considered with polarization. The light source is assumed as linear polarized light with random fluctuations simulating a laser source. Three following phenomena were investigated by using the numerical model and experiment:

(1) The light emission trajectories from the sensing edge of the optical fiber probe.
   The microscopic visualization was applied for the experiment. As the result, the numerical analysis seemed a good accordance with the experiments. In addition, it was found that the optical fiber probe emits almost straight light which angle is around 10° in water phase.

(2) The signal pattern of the fiber piercing a bubble.
   The synchronized high-speed video camera visualization was applied for the experiment. As the result, the numerical analysis could simulate well the pre-signal, which often appears in the case of the probe piercing the center area of a bubble. The pre-signal is considered to be caused by the reflected light from the frontal and rear surfaces of the bubble.

(3) Signal pattern of the fiber piercing an air-water free surface.
   The synchronized high-speed video camera visualization was applied for the experiment. From the result, the surface deformation was found to affect strongly to the signal pattern. To improve the accuracy of the numerical analysis, a simple static meniscus model was applied to simulate the surface deformation. The numerical signal seems a good accordance with the experiment in case of the meniscus radius to be assumed to 0.2 mm.

5. Future research

The current numerical model assumes a trivial meniscus model. We will develop surface tension balance model into the numerical model for rigid analysis.
References


