Measurement of reference bubble velocity vector for a local 4-sensor probe using orthogonal high speed cameras

S. Pradhan, G. Lucas, X. Zhao
University Of Huddersfield

ABSTRACT

In recent years, there has been an increase in the level of interest shown in making flow rate measurements in multiphase flow. This in part has been brought about by the metering requirements of the oil and natural gas industries. Measuring the volumetric flow rate of each of the flowing components is often required and this is particularly true in production logging applications, where it may be necessary to measure the flow rates of oil and water down hole in vertical and inclined oil wells. Within the University of Huddersfield, work has been undertaken on the study of vertical and inclined multiphase flow. Previous work was based on the use of local, dual-sensor conductance probes to obtain the local axial velocity and volume fraction of the bubbles in multiphase flows. The purpose of this research presented in this paper is to investigate the accuracy with which a 4-sensor probe can measure bubble velocity vectors using two orthogonal high speed cameras.

The probe was manufactured from 0.3mm diameter stainless steel acupuncture needles due to their high level of rigidity. The acupuncture needles were mounted inside a stainless steel tube with an outer diameter of 4*mm*. A procedure was carried out whereby where all the readings are taken simultaneously from both the cameras and 4-sensor probe. The camera and DAQ setting are made such they were controlled by an external trigger signal that is achieved thought the same circuit that is been used for the probe signal. The velocity vector of the top plane, centre of gravity (COG) and bottom plane of the bubbles were measured using the high speed cameras and compared with the bubble velocity vector obtained from the probe signal. In this paper bubble velocity vector is quantified in term of a polar angle α an azimuthal angle β and a velocity magnitude v.

Nomenclature

α Polar angle (degrees)

β azimuthal angle (degrees)

v Velocity magnitude (m/s)

δt_{11} δt_{22} δt_{33} Time delays (s) calculated from the times at which the bubble surface contacts sensors 0, 1, 2 and 3 [3].

1 INTRODUCTION

As a part of a previous research project within the University of Huddersfield many dual and four sensor probes were built to measure the flow velocity of the bubbles in multiphase flow. This has relevance to many applications e.g. the oil industry, chemical industries and mineral processing.

The purpose of this research is based on the extensive research on sensitivity of 4 sensor-probes that were being used to measure the properties of multiphase flow. To be specific, these properties relate to local and mean axial velocity and local velocity vector of the dispersed phase.

Flows can be categorized in two types Single phase flow containing only a single substance and Multiphase phase flow where the flow contains several substances flowing at the same time. Understanding of these types of flow requires complex physics. Several combinations of flowing substances can be considered as multiphase flow e.g. gas-liquid flows, liquid-liquid flows, liquid-solids flows, gas-solids flows, and gas-liquid-solids flows etc.

According to its flow structure and pattern, a vertical multiphase flow can be generalized into four major different regimes known as bubbly flow, slug flow; churn flow and annular flow.

2 CONDUCTIVITY PROBE MANUFACTURE AND STRUCTURE

Background

Local measurement techniques for multiphase flow can be categorized as intrusive or non-intrusive methods.

1. Intrusive methods include:

Conductivity probes using needles, heat transfer probes, hot wire anemometers.

2. Non intrusive method

Methods where local flow properties can be measured where the equipment is not inserted into the flow include:
Light attenuation, electrical resistance tomography (ERT), photography and image analysis, laser Doppler anemometry, phase Doppler anemometry and Particle Image Velocimetry (PIV).

Within the University of Huddersfield local flow property measurements that are carried out include the intrusive method using a intrusive, four-sensor conductivity probe as described in [1]-[3].

3 THEORY

With the help of a local four-sensor probe we can measure various characteristics of the dispersed phase including the local volume fraction and the local vector velocity of an individual bubble. The bubble velocity vector is expressed in terms of the velocity magnitude v and the velocity direction, which in turn can be expressed in terms of a polar angle α and an azimuthal angle β. Based on the assumptions given in [1] a mathematical model was introduced [3] to calculate α, β and v, for a given bubble, from the time intervals δt_{11}, δt_{22} and δt_{33} calculated from measurements of the times at which each of the four sensors came into contact with the surface of the bubble.
In the work presented in this paper the probe dimensions x_i, y_i and z_i are assumed to be known, where x_i, y_i and z_i define the coordinate of the ith rear sensor relative to leading sensor allowing α, β and v to be calculated form the measured time interval δt_{11}, δt_{22} and δt_{33} using the equations as discussed in [1]-[4].

3A THEORY FOR IMAGE PROCESSING

In this section a model is developed which enables us to find the reference velocity vector of a single bubble that crosses the 4-sensor probe from images obtained from 2 orthogonal high speed cameras. The analysis presented in this section is applied to images taken in the x-z plane and the y-z plane (see fig 3). The analysis given below is for the x-z plane only. A similar process is undertaken for the y-z plane. The centre of gravity (COG) is assumed to be the centre point of the longest chord of the bubble. This chord is also considered as major axis, assuming the bubble to have the shape of two semi ellipse with a common major axis.
Assuming A(x_1, z_1) and B(x_2, z_2) are the two coordinates of the longest chord.

$$\text{COG } (x, z) = \frac{(x_2 - x_1)}{2}, \frac{(z_2 - z_1)}{2} \quad (1)$$

$$\text{Slope of major axis } (m_1) = \frac{(z_2 - z_1)}{(x_2 - x_1)} \quad (2)$$

The minor axis of the semi ellipse forming the top half of the bubble is perpendicular to the slope of the major axis and is given by eqn. 3.

$$\therefore m_1 m_2 = -1 \quad (3)$$

Where m_2 is the slope of the minor axis.

From the calculated value of m_2 we can now initially assume that the semi ellipse for the top half of the bubble passes through point Xa where the coordinates of Xa are the intersection of the line of slope m_2 (which passes through the centre of the major axis) and the upper boundary of the bubble image. Using Xa we may now make an initial guess for b_T, the length of the semi minor axis for the ellipse defining the top of the bubble. We may also define a parametric equation for the semi ellipse, which defines the upper half of the bubble boundary as

$$x = (a_T \cos(t)\cos(\phi) + b_T \sin(t)(-\sin(\phi))) \quad (4)$$

$$z = (a_T \cos(t)\sin(\phi) + b_T \sin(t)(\cos(\phi))) \quad (5)$$

Where a_T is the length of the semi major axis.

We may use a similar procedure to define the semi ellipse forming the lower half of the bubble in the y-z plane.

3B. MODEL FOR CALCULATING A DISTANCE FROM CENTRE TO POINT IN ELLIPSE DETERMINED WITH THE SLOPE OF POINT INSIDE/OUTSIDE ELLIPSE

As shown in figure 2 the semi ellipse created from the above equation does not necessarily cover all the boundary points of the top half bubble, so it is necessary to use curve fitting using the least square method to minimize the distance of the boundary points in the bubble image from the calculated bubble boundary. This curve fitting is carried out using the $\hat{x}, \hat{z}$ coordinate system, where origin is at COG of the bubble, and where $\hat{x}$ coincides with the major axis and $\hat{z}$ coincides with the minor axis. Let us define a point X which lies on the boundary of the upper half of the image of the bubble. Point X has the coordinate $(\hat{x}_i , \hat{z}_i)$. We may also define a line from the centre O of the ellipse to X which has a gradient m_i . This line intersects the boundary of the calculated ellipse at point A $(\hat{x}'_i , \hat{z}'_i)$, and we may calculate the point $\hat{x}'_i , \hat{z}'_i$ as shown below.

$$\left(\frac{\hat{x}'^{2}_i}{a_T^{2}}\right) + \left(\frac{\hat{z}'^{2}_i}{b_T^{2}}\right) = 1 \qquad (6)$$

Or $$\hat{x}'^{2}_i b_T^{2} + \hat{z}'^{2}_i a_T^{2} = a_T^{2} b_T^{2}$$

Or $$\hat{x}'_i = \sqrt{a_T^{2} b_T^{2} / \left(b_T^{2} + m_i^{2} a_T^{2}\right)} \qquad (7)$$

From the equation of straight line with gradient m_i we get;

$$\hat{z}'_i = m_i \sqrt{\left(a_T^{2} b_T^{2} / \left(b_T^{2} + m_i^{2} a_T^{2}\right)\right)} \qquad (8)$$

The distance from O to A is S_i and the distance from O to X is r_i

Where

$$r_i = \sqrt{(\hat{x}_i)^2 + (\hat{z}_i)^2} \qquad (9)$$

And

$$S_i = \sqrt{(\hat{x}'_i)^2 + (\hat{z}'_i)^2} \qquad (10)$$

We define an error term E_i and that $\mathrm{E}_i = (S_i - r_i)^2$

We wish to minimize the quantity E .

Where $$\mathrm{E} = \sum_{i}^{n} (\mathrm{E}_i)^2$$

And that $\mathrm{E} = \sum_{i=0}^{n} (S_i - r_i)^2$ for the entire boundary points in the upper half of the bubble. In this way we can find b_T the length top half of the bubble in the x-z plane. We may follow a similar procedure to find the length b_B of the minor axis of semi ellipse for the bottom half of the bubble in the x-z plane. The whole procedure is repeated for the y-z plane.

With the help of two cameras places placed orthogonally in x-z and y-z plane and parallel to x, y and z axis of water tank as shown in figure 3, we can again calculate local velocity vector velocity, magnitude v polar angle α and an azimuthal angle β .

From xz frame we can calculate $Vx = \frac{\delta x}{\delta t}$ and $Vz_x = \frac{\delta z_x}{\delta t}$ in the same way from yz frame we are able to calculate $Vy = \frac{\delta y}{\delta t}$ and $Vz_y = \frac{\delta z_y}{\delta t}$. At same frame Vz_x should be equal to Vz_y, therefore we let the actual velocity in the Z direction $Vz = \left(Vz_x + Vz_y\right) / 2$.

Where $Vx, Vy \, and \, Vz$ are the velocities in each direction and $\delta x, \delta y, \delta z_x \, and \, \delta z_y$ is defined as the distance traveled from one frame to another frame, thus enabling us to calculate magnitude v, polar angle α and an azimuthal angle β using the equation listed below.

$$v = \sqrt{\left(Vx^2 + Vy^2 + Vz^2\right)} \quad \text{------------------ (i)}$$

$$\alpha = \tan^{-1}\left(\frac{\sqrt{x^2 + y^2}}{z}\right) = \cos^{-1}\left(\frac{z}{\sqrt{x^2 + y^2 + z^2}}\right) \quad \text{----------------------- (ii)}$$

$$\beta = a\tan\left(\frac{y}{x}\right) \quad \text{-------------------------------- (iii)}$$

4 RESULTS

The experimental apparatus was set up as shown in figure 3.A series of experiments were performed to take a data of air-in-water flows using local-four sensor probe, of which the dimension are listed below in table 1, and two orthogonally placed high speed cameras. For the purpose of getting only one bubble signal that hit the probe, a mid-trigger approach was carried out for both cameras as well as the data acquisition board acquiring the probe signals. The conductance data were acquired at the rate of 10 kHz frequency using high speed pc-based data acquisition system. From the conductance data, (signal shown in fig 4) the time interval $\delta t_{ii} \left(ii = 1,2,3\right) \, where \, \delta t_{ii} = \delta t_{ia} + \delta t_{ib} - \delta t_{0b}$ were calculated, which were used in the probe dimension to calculate α , β and v using equation and model described in [1]-[4], table 2.

High speed camera images were also taken during the time of acquiring the data from the conductance probe , thus obtained images were rectified to find out the bubble that hit the probe at the same time, this process was been made easy by using the mid trigger method. The trigger signals were received from the same circuitry that was made for acquiring the data of conductive probe.

From the captured image the numbers of frames were calculated for the frame where the bubble just touches the front senor and the frame where the bubble has just left the whole probe, after the processing as described in section 3a and 3b (output as shown in fig 5) the distances traveled in x, y and z axis were calculated.

From the obtained distance traveled $\delta x, \delta y, \delta z_x \, and \, \delta z_y$ and the time taken to travel that distance, and as frames were taken at 250 frame per second giving the time for each frame as 4mS, magnitude v polar angle α and an azimuthal angle β were calculated using equation (i),(ii) and (iii) of which the results are shown in table 3.

5 CONCLUSIONS

From the results we can see that the velocity vector of the measured bubble from both cameras and that of the probe are similar except in the case of the alpha angle. This may be caused due to the slowing effect of the bubble due to the probe. Also due to the errors as described in [5].

After extracting every frame captured by the camera for a single bubble it shows that bubbles are not flowing in a straight path, also the bubbles gets deformed in every frame. For a single bubble it takes 0.01s to travel from tip of the front sensor to the tip of the rear sensor. This is 2.5 times longer then that of a single frame. Analysis of the frames shows that the bubble is continually deforming as it moves from the front to rear sensor. This makes the polar and azimuthal change as the bubble moves over the probe. In the mean time the fact cannot be ignored that there is always a strong possibility of initial deformation of the bubble when it hits the front sensor.

REFERENCES

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	X (um)	Y(mm)	Z(mm)
Sensor 1	314 (x_1)	63.60 (y_1)	2240.68 (z_1)
Sensor 2	-68.8 (x_2)	-409.1 (y_2)	2108.890 (z_2)
Sensor 3	-316.3 (x_3)	-152.3 (y_3)	1873.93 (z_3)

Table 1 measured dimensions of 4-sensor probes.

beta	118.8466
alpha	6.0575
mag_v	0.2600
AX_vel	-0.0600
AZ_vel	9.93e-004
rad_vel	0.0274

Table2. Probe results

Measurements	COG	TOP	BOT
Vx	-0.0168	-0.0562	0.0393
Vz_x	0.2358	0.0281	0.2415
Vy	0	0.073	-0.1011
Vz_y	0.2023	0.1966	0.2135
alpha_deg	1.835	4.3255	2.149
beta_deg	270	248.1981	234.4629
v	0.2119	0.1073	0.2253

Table 3 results from camera images

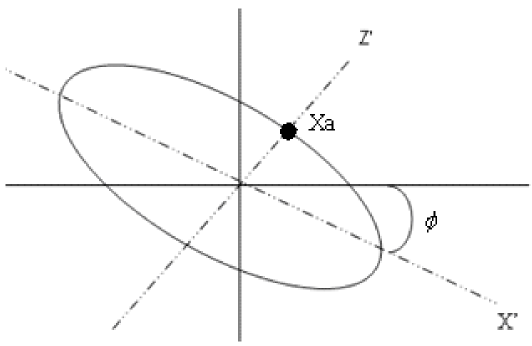

Figure 1. Ellipse being plot using equation (5) and (6)

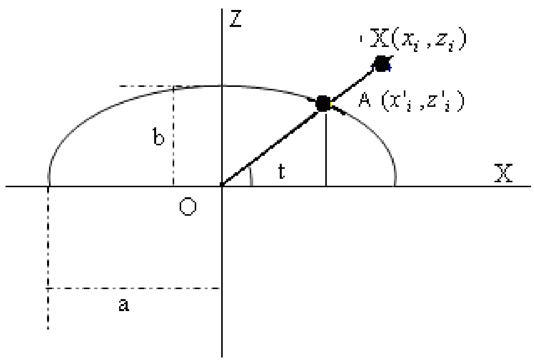

Figure2. Model determining the slope of point inside/outside ellipse.

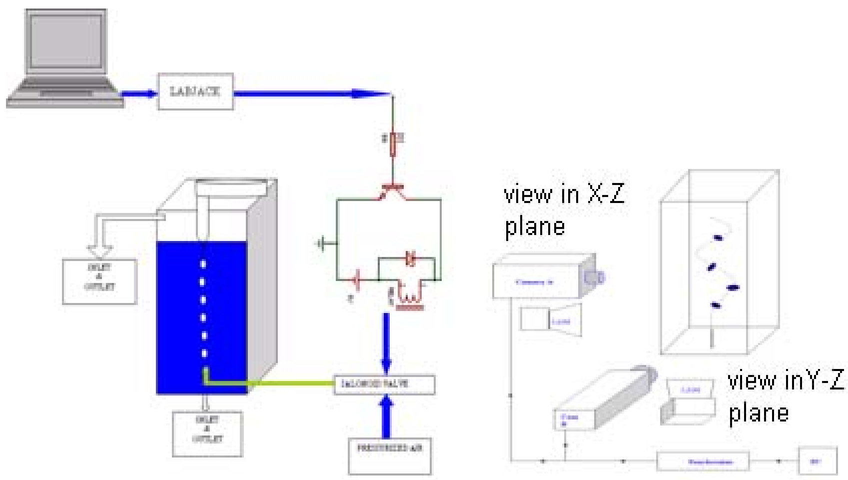

Figure 3 experimental set up

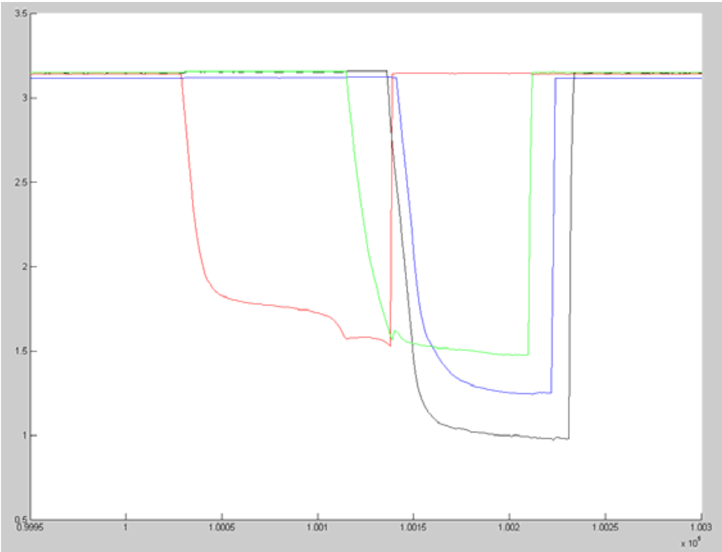

Figure 4 output signals from 4- sensor probe

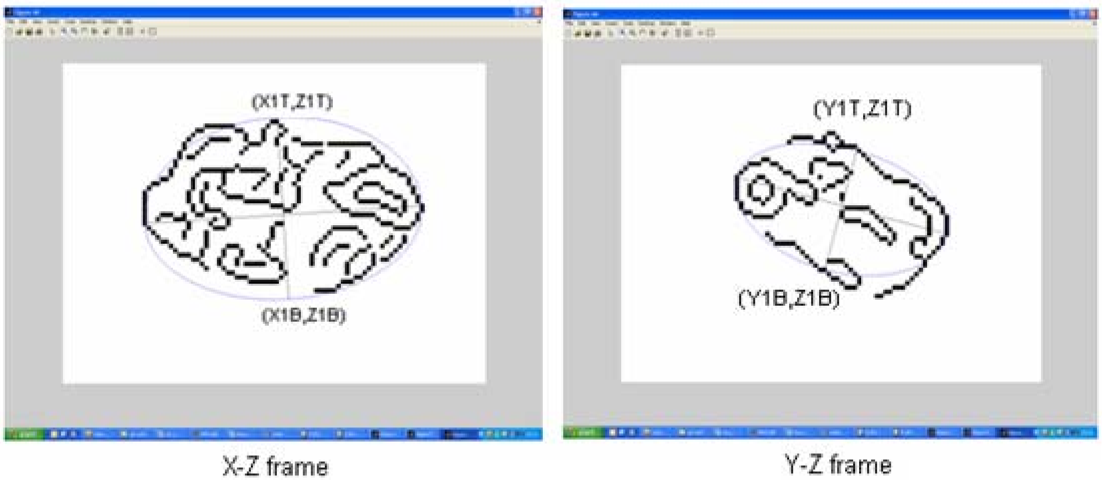

Figure4 Frames from X-Z plane and Y-Z plane from camera after image processing