

Ultrasonic Measurement of Velocities in Multiphase Flow

Vinh Phan

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Introduction:

The purpose of this work was to investigate the use of ultrasonic methods for phase velocity measurement. The experiments were composed of three parts. In the first part, continuous phase velocity measurement was performed in single phase water flow and the sound transmission method was used to measure the velocity of the water. In the second and third parts, the dispersed phase (bubble gas) velocity was measured in static and flowing water respectively using the sound reflection method. The results demonstrated that the ultrasonic technique can be used for accurate measurement of the continuous and dispersed phase velocities in two-phase bubble flow situations.

Ultrasonic approach:

In two-phase bubble flow situations, previous work references pointed out that the continuous phase ranges from 80 to 100 percent of the total volume (in our experiment we used water as the continuous phase). The dispersed phase may be gas or oil (we used gas for the experiment) and the purpose is to measure the velocities of both bubbles and water using ultrasonic waves.

The ultrasonic wave is a material wave. It travels faster along the direction of flow and slower in the opposite direction. The faster the flow, the smaller the downstream transit time and the larger the upstream transit time. The transit times are recorded by the electronic device to calculate the water velocity. The dispersed phase velocity is measured using reflection properties of the ultrasonic waves. Due to the difference in impedance of the dispersed phase (bubble) and the continuous phase (water), sound is reflected from the bubble at Doppler-shifted frequencies caused by the bubble motion and thus contains information about the bubble velocities. Having measured these frequencies, we can determine the bubble velocities.

Downhole tool description:

The equipment used for these experiments included a mass flow meter, prototype downhole ultrasonic tool, and PT 868 transport meter. The mass flow meter was used for cross-checking the water velocity measured by the downhole tool. The downhole tool contains three sections lined up vertically. The lowest is the “sound speed” section and has two pairs of transducers used to measure speed of sound in the fluid. Right above the sound speed section is the “transmission” section containing four pairs of transducers spaced 90 degrees apart around the circumference of the tool. The continuous phase velocity measurement is performed by this section. The purpose of spacing four transducers 90 degrees apart along the circumference is to obtain better average velocities of flowing phases. The “reflection” section is located at the top and also contains four pairs of transducers spaced 90 degrees apart around the circumference. The bubble velocities are measured using this section. The PT 868 transport meter is an electronic device used to obtain the signals from the transducers and analyze them based on the program stored in the device.

1. Transmission experiment:

Theory:

Each transducer can work in both modes as transmitter and receiver. Sound waves emitted from the transmitter travel through fluid and are reflected from the wedge surface toward the pipe wall. From the wall, the wave is reflected back toward the other side of the wedge and finally the wave reflected by this wedge is obtained by the receiver. The transmission path for water flow velocity calculation is shown in Figure 1. Downstream transit time and upstream transit time are recorded by the PT868 to calculate the water velocity by the following formulas:

$$T_d = \frac{2L}{C + V_f} + \frac{L'}{\cos(\alpha)(C + V_f \cos(\alpha))} \quad (1)$$

$$T_u = \frac{2L}{C - V_f} + \frac{L'}{\cos(\alpha)(C - V_f \cos(\alpha))} \quad (2)$$

T_d and T_u are the downstream and upstream travel times.

C is the speed of sound in water.

L is the vertical path of sound traveling in fluid(1.25 inches)

L' is the distance between two reflection points on the wedge(1.50 inches).

α is the angle of the wedge(60 degrees).

V_f is the fluid velocity.

Operating procedure:

1. Fill the water reservoir up to approximately submerge the WATER label. The equipment diagram is shown in Figure 2. A hose can be used for this purpose.
2. Making sure all valves are open, run the pump to circulate water through out the system to clean up the inside surfaces.
3. Close all valves (valve 1, 3, and 4) except for the one connected directly in front of the mass flow meter (valve 2).
4. Turn on the PT868 and load the parameter program SITE0 to start the measuring.
5. Record the mass flow rate on the mass flow meter and compute the actual water velocity based on water density and cross section area of the tube.
6. Compare the actual velocities to the measured velocities displayed on the PT 868.
7. At the end of the experiment, switch off the pump and the PT868 transport. Let all water drain down into the reservoir and empty the reservoir using the submersible pump.

Results:

actual mass flow rate(lbm/min)	actual velocity (ft/sec)	measured velocity (ft/sec)
154.0	0.2098	0.21
137.7	.1876	.19
100	.136	.14
77.8	0.105	0.10
67.0	0.091	0.09

The results are plotted in Figure 3.

2. Reflection experiment (static water):

Theory:

The principle idea used in this section is the Doppler shift effect. Due to the difference in acoustic impedance of the bubble and water (the impedance of bubble is much less than that of water), the sound wave is reflected at the bubble boundary. The reflection path for bubble velocity is shown in Figure 4. If the bubble is in motion, the reflected wave will have a different frequency from the incident wave. The frequency of the sound wave is shifted at the moving bubble and the magnitude of the difference carries information about the bubble velocity by the following equation :

$$V_b = C \left(1 - \frac{F_i}{F_r}\right) \quad (3)$$

V_b and C are bubble velocity and speed of sound in water respectively.

F_i and F_r are the frequencies of incident and reflected sound wave at the bubble respectively.

Knowing speed of sound C , incident frequency F_i , and reflected frequency F_r , we can compute the bubble velocity. In the reflection experiment, the PT868 analyzes signals coming from the transducers to obtain the values of the reflected frequency. The Reflection mode for measuring bubble velocity is set by setting keyword "FLOW DIRECTION" to OFF.

Operating procedure:

1. Fill the water reservoir up to approximately submerge the WATER label. The equipment diagram is shown in Figure 2. A hose can be used for this purpose.
2. Making sure all valves are open, run the pump to circulate water through out the system to clean up the inside surfaces.
3. Rotate the tool so that one of the four pair of transducer is opposite the bubble port to ensure the bubble stream will cross the ultrasonic wave path.
4. Tape the ruler on the tube parallel to the reflection section.
5. Gradually close all valves (valve 1, 3, and 4) except for the one connected directly in front of the mass flow meter (valve 2).
6. Wait until water fills up the vertical tube and the flow stabilizes. Turn off the pump and immediately close the last open valve (valve 2). So we have a static column of water.
7. Adjust the air control valve to obtain a stabilized bubble stream going up. A fine adjusting air valve is recommended.
8. Turn on the PT868 and load the parameter program SITE1 to start the measurement.
9. Switch on the video camera and focus on the reflection section. Ensure a proper contrast by observing the picture on the monitor and set the camera clock resolution down to one hundredth of a second. Record the experiment corresponding to each flow velocity for about 20 minutes.
10. Wait until the measurement stabilizes and then record the measured bubble velocity on PT868. Sometimes the device locks itself to a particular velocity and is not able to update itself. In this case, switch it off and then on again.
11. Play back the tape and perform two successive pauses. For each pause, record the time and the position of the bubble on monitor to obtain the travel time and the travel distance of the bubble. The best approach is to use the VCR that can play back frame by frame
12. Adjust the air control valve to obtain different bubble velocities. Note that to achieve a straight and stable bubble path, we can only obtain up to a certain maximum bubble velocity.

13. Compare the actual velocities measured by video camera to the measured velocities displayed on the PT 868.

Results:

Travel distance (inch)	3.5	4.1	2.56	Actual velocity (ft/sec)	Measured velocity (ft/sec)
Travel time (second)	0.35	0.42	0.25		
Velocity (ft/sec)	0.833	0.813	0.853	0.83	0.89
Travel distance (inch)	3.0	4.125	2.2	Actual velocity (ft/sec)	Measured velocity (ft/sec)
Travel time (second)	0.27	0.38	0.20		
Velocity (ft/sec)	0.926	0.905	0.917	0.91	0.96
Travel distance (inch)	3.2	4.3	2.3	Actual velocity (ft/sec)	Measured velocity (ft/sec)
Travel time (second)	0.26	0.35	0.19		
Velocity (ft/sec)	1.026	1.024	1.008	1.02	1.01
Travel distance (inch)	3.0	3.94	2.5	Actual velocity (ft/sec)	Measured velocity (ft/sec)
Travel time (second)	0.24	0.34	0.19		
Velocity (ft/sec)	1.04	0.966	1.096	1.03	1.04

3. Reflection experiment (moving water):

Theory:

The approach is the same as in the case of static water. The higher the speed of water the higher the bubble velocity and thus the higher the reflected frequency from the approaching bubble.

Operating procedure:

The procedure is the same as in the case of static water. The only difference is that we have to adjust the valves to obtain different flow rates of water.

Results:

Travel distance (inch)	2.875	3.4	2.2	Actual bubble velocity	Measured bubble velocity	Water velocity
Travel time (second)	0.25	0.29	0.19	(ft/sec)	(ft/sec)	(ft/sec)
Velocity (ft/sec)	0.96	0.977	0.965	0.97	0.98	0.09
Travel distance (inch)	3.0	3.7	4.1	Actual bubble velocity	Measured bubble velocity	Water velocity
Travel time (second)	0.24	0.31	0.33	(ft/sec)	(ft/sec)	(ft/sec)
Velocity (ft/sec)	1.04	0.995	1.04	1.02	1.01	0.1
Travel distance (inch)	2.8	3.4	4.0	Actual bubble velocity	Measured bubble velocity	Water velocity
Travel time (second)	0.23	0.28	0.33	(ft/sec)	(ft/sec)	(ft/sec)
Velocity (ft/sec)	1.01	1.01	1.01	1.01	1.06	0.14
Travel distance (inch)	3.2	3.8	4.2	Actual bubble velocity	Measured bubble velocity	Water velocity
Travel time (second)	0.23	0.28	0.31	(ft/sec)	(ft/sec)	(ft/sec)
Velocity (ft/sec)	1.16	1.13	1.13	1.14	1.12	0.16
Travel distance (inch)	3.4	3.85	2.6	Actual bubble velocity	Measured bubble velocity	Water velocity
Travel time (second)	0.21	0.24	0.16	(ft/sec)	(ft/sec)	(ft/sec)
Velocity (ft/sec)	1.35	1.34	1.354	1.35	1.27	0.19

The results of both static and moving water reflection experiments are plotted in Figure 5. As we can see, there exists a constant deviation between the actual and measured bubble velocities. This problem can be solved by tool calibration. The intercept and slope of the tool calibration is obtained by the least square method to be 0.23ft/sec and 0.7786 respectively.

Program parameters for PT868 in transmission experiment.

This program was stored in the PT868 as SITE0.

System Parameters

Energy Option = Off
System Units = English
Volumetric Units = Gal/Min
Totalizer Units = Gallons

I/O Parameters

Analog Out = Off
Error Handling = Hold last value
Zero Cutoff = 0.000ft/sec

Communication Parameters

Baud Rate = 9600
UART Bits = 8 data, no parity

Pipe Parameters

Transducer Number = 291
Pipe Material = Steel
Steel = Carbon steel
Pipe OD = 6.0 inches
Pipe Wall = 0.25 inches
Lining = No
Fluid Type = Water
Water = Normal Water
Water Temperature = 68.000 deg F
Reynolds Correction = Off
Calibration Factor = 0.913
Depth of Reflector = 50 percent

Setup Parameters

Set Up = Signal
Signal Low Limit = 40
Signal High Limit = 85

Velocity Low Limit	=	-40.000 ft/sec
Velocity High Limit	=	40.000 ft/sec
Transmitter Voltage	=	High Voltage
Gain Setting	=	High Gain
Flow Direction	=	Upstream
Rep Period 1	=	100 μ s
Rep Period 2	=	800 μ s
Xmits Per Reading	=	10000
Weak Signal Threshold	=	20
Code Length	=	16 pulses
Filter Width	=	48
Averaging Factor	=	5

Program parameters for PT868 in reflection experiment.

This program was stored in the PT868 as SITE1.

System Parameters

Energy Option = Off
System Units = English
Volumetric Units = Gal/Min
Totalizer Units = Gallons

I/O Parameters

Analog Out = Off
Error Handling = Hold last value
Zero Cutoff = 0.000ft/sec

Communication Parameters

Baud Rate = 9600
UART Bits = 8 data, no parity

Pipe Parameters

Transducer Number = 291
Pipe Material = Steel
Steel = Carbon steel
Pipe OD = 3.96 inches
Pipe Wall = 0.000 inches
Lining = No
Fluid Type = Water
Water = Normal Water
Water Temperature = 68.000 deg F
Reynolds Correction = Off
Calibration Factor = 1.0
Depth of Reflector = 60 percent

Setup Parameters

Set Up = Signal
Signal Low Limit = 40
Signal High Limit = 85

Velocity Low Limit	=	-40.000 ft/sec
Velocity High Limit	=	40.000 ft/sec
Transmitter Voltage	=	High Voltage
Gain Setting	=	High Gain
Flow Direction	=	Off
Rep Period 1	=	100 μ s
Rep Period 2	=	800 μ s
Xmits Per Reading	=	10000
Weak Signal Threshold	=	20
Code Length	=	16 pulses
Filter Width	=	48
Averaging Factor	=	5

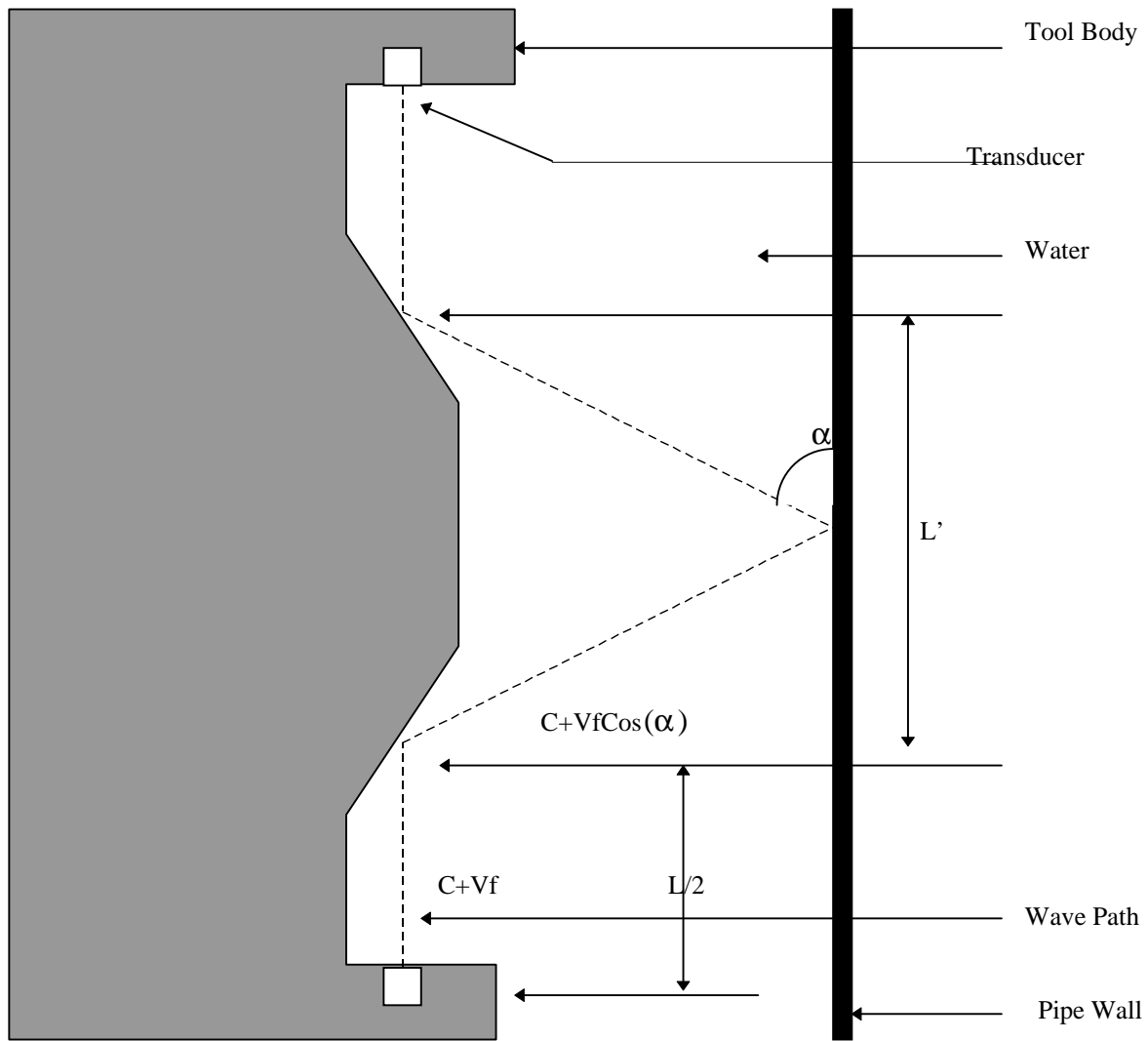


Figure 1: Transmission path for water flow velocity calculation.

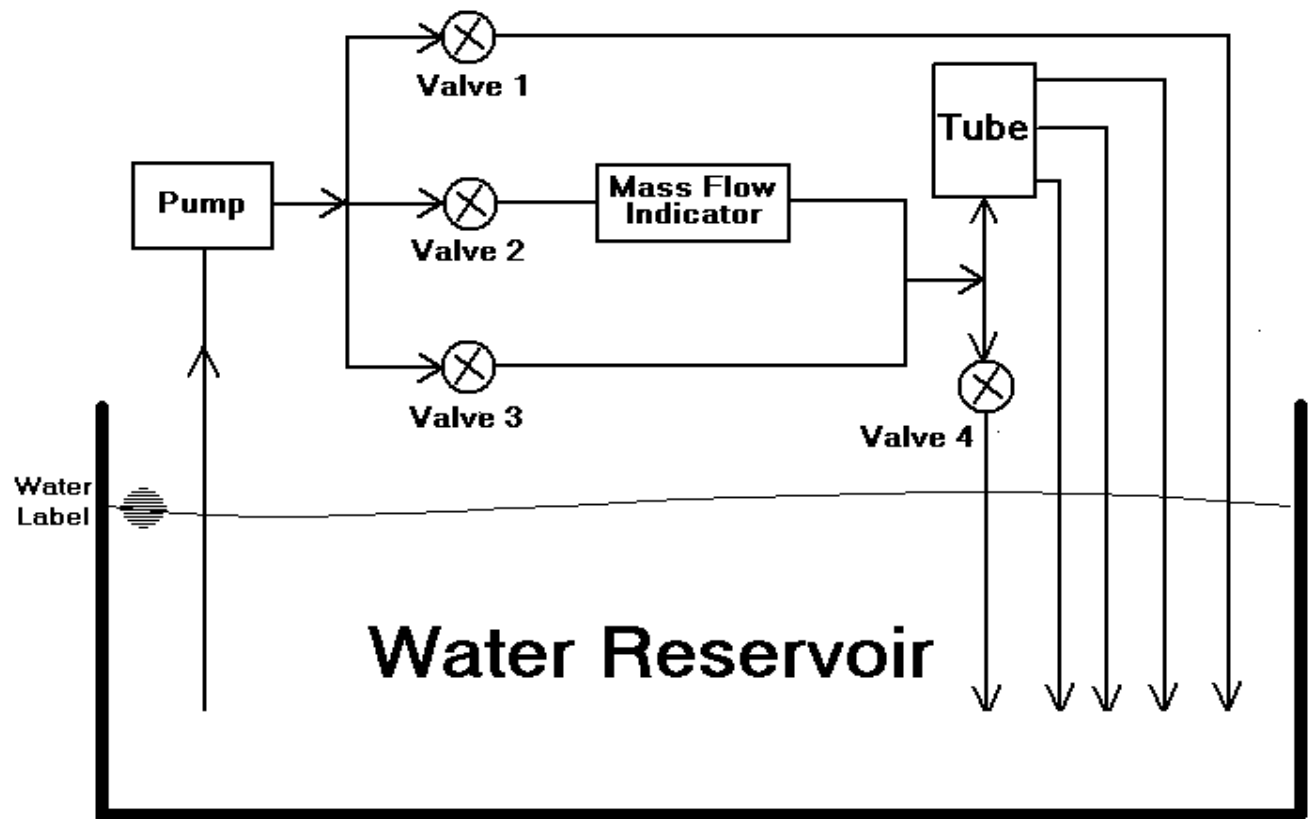


Figure 2 : Equipment Diagram

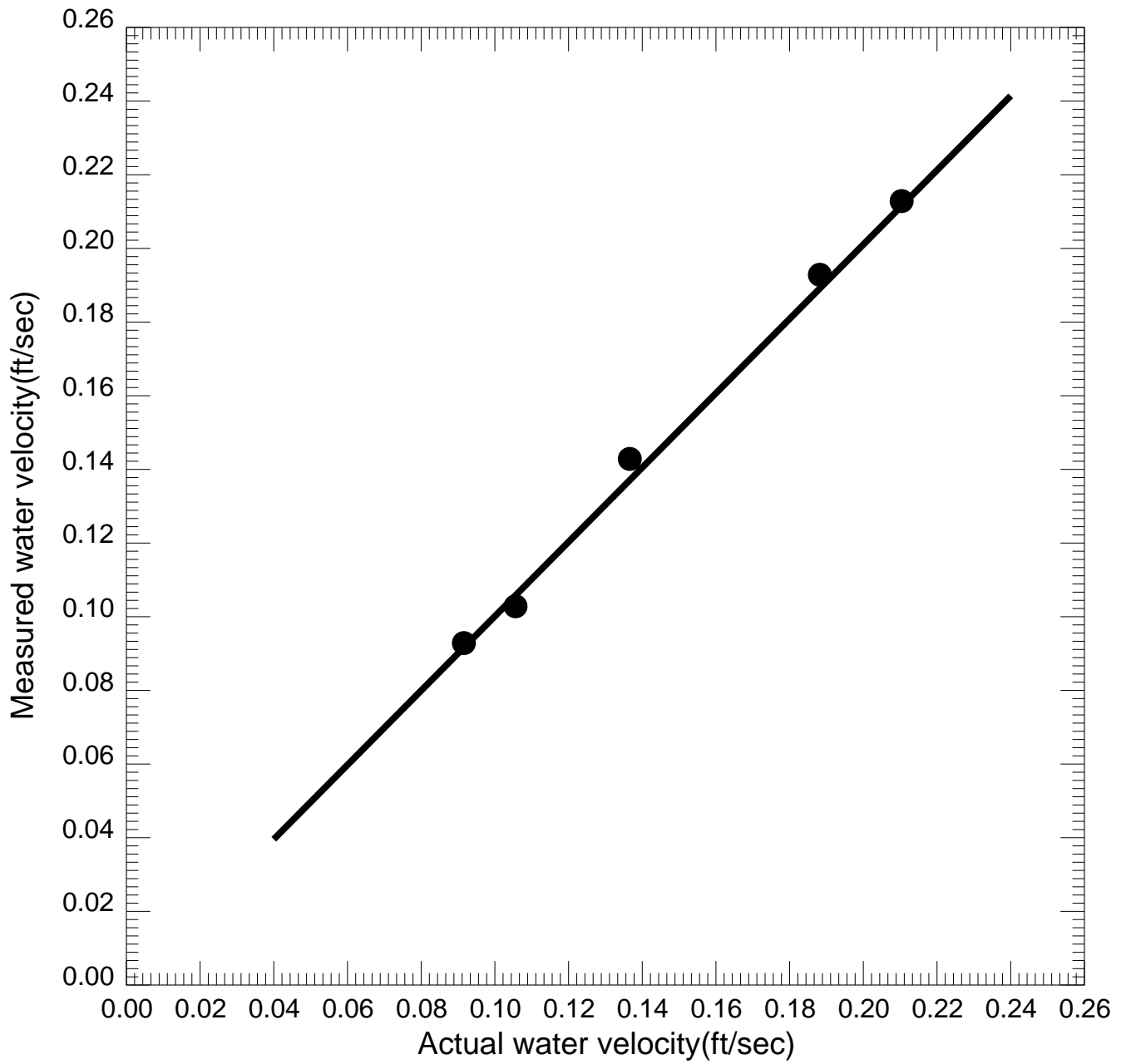


Figure 3

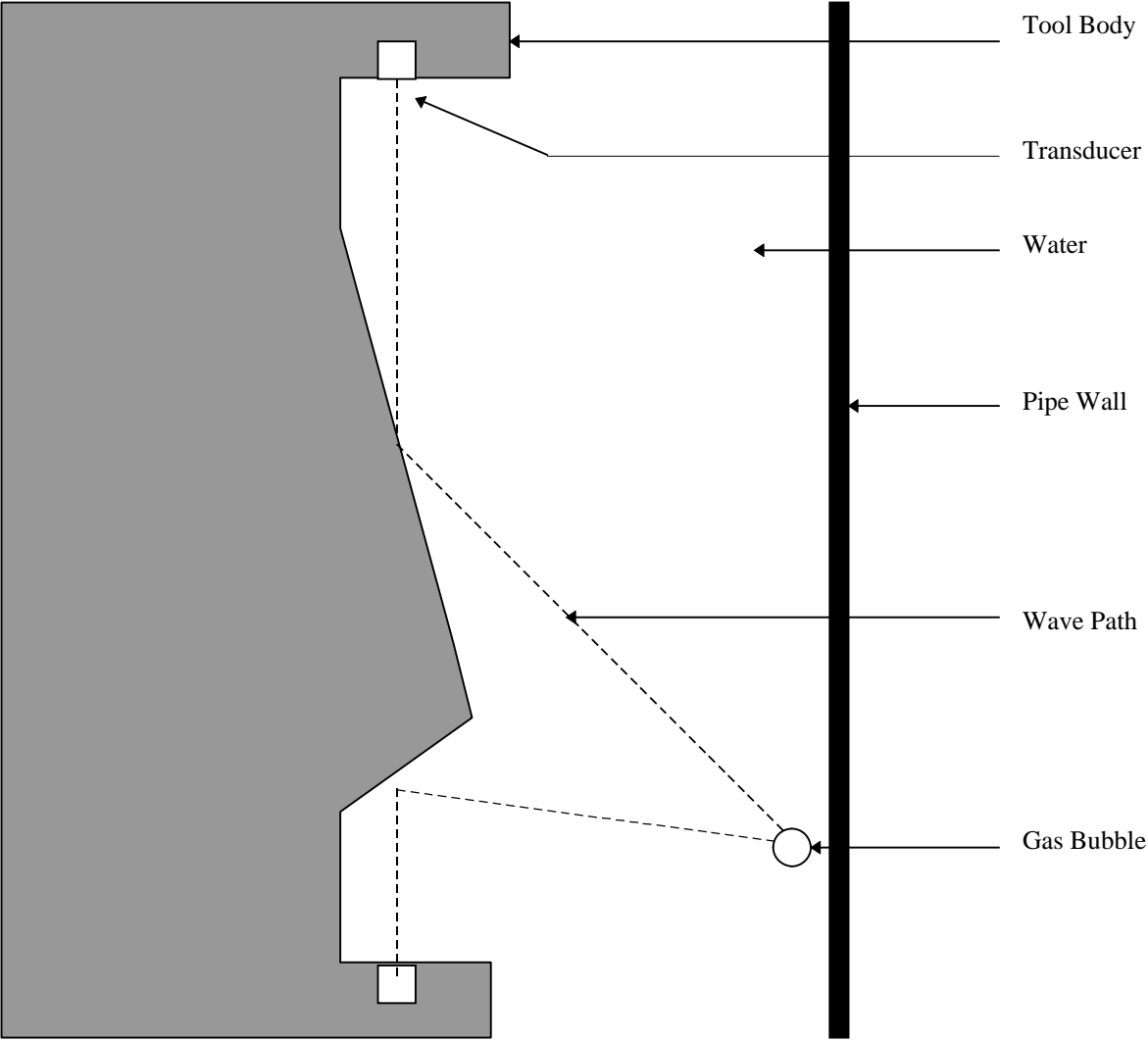


Figure 4: Reflection path for bubble velocity calculation.

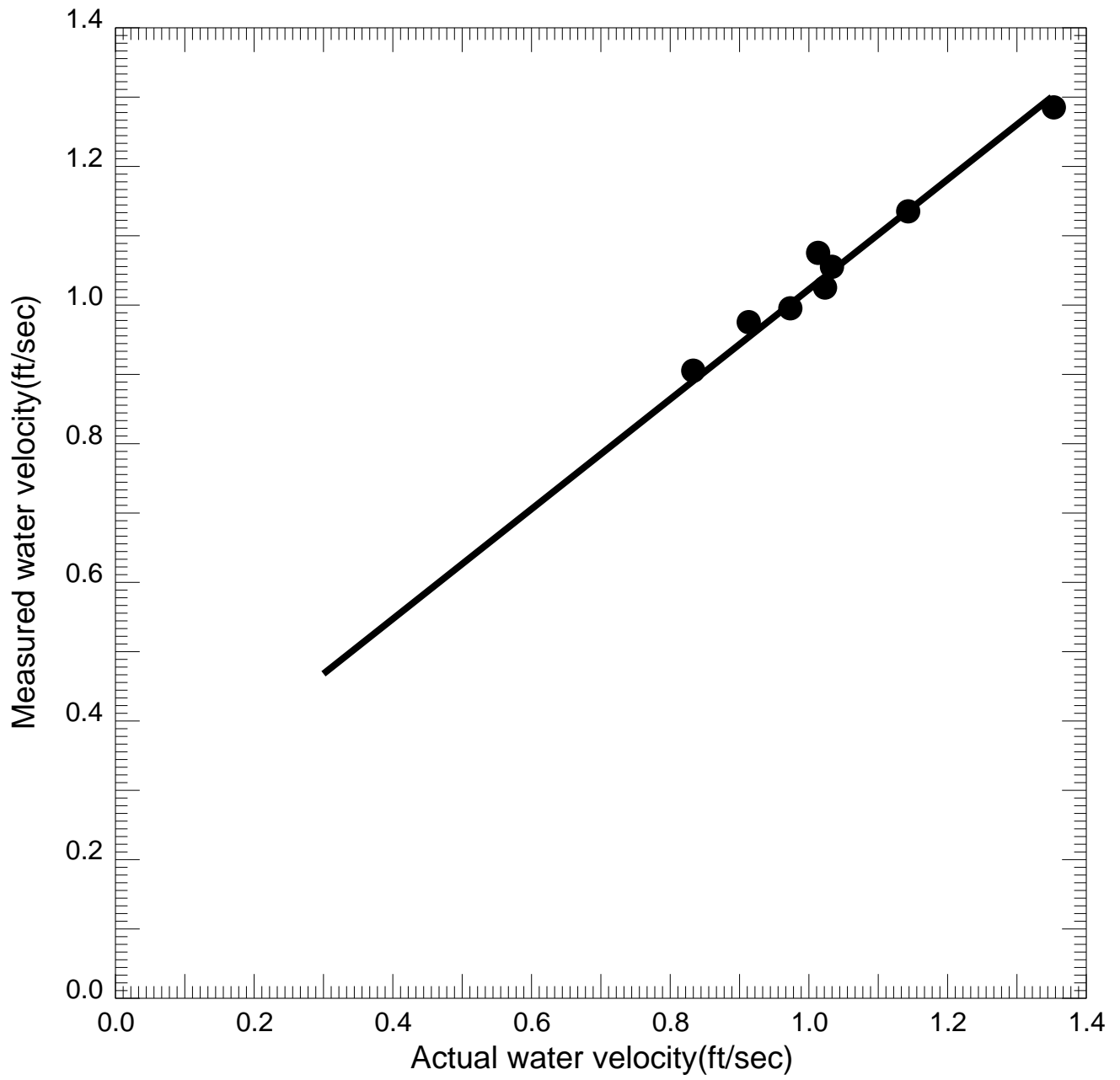


Figure 5