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Study on Ultrasonic Echo Measurement for Vertical Pipe Gas-Liquid Multiphase Flow Containing Large Bubbles

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For the effective operation of airlift pump, the method to achieve the flow state of upward liquid-gas multiphase flow in a pipe by ultrasonic measurement is investigated. In this study, echo measurement data taken from two different air-lift experiment systems are analyzed. Extracting one indicator from echo map on each ultrasonic emission and calculating the feature information of flow by machine learning is conducted. As feature information, flow pattern is chosen and applying a flow pattern identification model made in one experiment into another experiment is tried. As a result, a model scored high accuracy in one experimental system marked lower, but high to some extent accuracy in another system. It is implied that with the more quality and quantity of training data, the constructed flow pattern identification model can be converted to unknown experimental system.

Keywords: Ultrasonic Echo, Gas-Liquid Interface, Vertical Pipe Flow, Large Bubbles, Machine Learning

1. Introduction

In the depths of Japan's exclusive economic zone (EEZ), ranging from around 1000 to 6000 meters below the sea surface, significant deposits of valuable metals, including cobalt-rich crust and REY-rich mud, have been discovered. These abundant resources are found on the seabed. As an effective pumping method, an airlift pump is attracting the attention. It operates by introducing air into a vertical pipe, creating a difference in density between air and water, which induces upward flow. Airlift pumps are particularly advantageous due to their straightforward design, enabling equipment to be conveniently gathered on a ship. They have been successfully employed in extracting manganese nodules from depths close to 5000 meters [1].

The pumping process in an airlift pump involves gas-liquid multiphase flow within the pumping pipe, which exhibits different flow patterns, directly affecting pumping efficiency. While significant knowledge exists regarding changes in flow patterns in two-phase air-water flows, our understanding of flow patterns in gas-liquid phase flows in huge length of pipe (up to 6000 m), especially when the liquid phase is non-Newtonian or when gas-liquid-solid three-phase flow occurs due to the presence of mud and solid particles during pumping, remains insufficient. Actually, in 200 m length airlift experiment, gas-liquid flow shew deviation from known flow pattern map [2]. Thus, it is crucial to continuously observe the flow state during the pumping process.

In this study, ultrasonic measurement is used as the observation method. Ultrasonic measurement offers several advantages, such as its suitability for opaque fluids and its non-invasive nature. The objective of this study is development of flow observation method for ascending gas-liquid multiphase flow in a pipe using ultrasonic measurement .

2. Experiment

In this study, data from two airlift experimental systems are used. In both system, cases with air-water two-phase flow are analyzed. Measurements are conducted on measurement section consisting of a vertical pipe made of transparent PMMA to allow flow visualization. An TDX is used to emit ultrasonic pulses and to receive the echo (ultrasonic intensity).

2.1 Experimental system 1

First system is constructed in the University of Tokyo. An overview of the apparatus is shown in Fig.1. The pipe inner diameter in the measurement section is 40 mm and the wall thickness is 5 mm. One ultrasonic transducer (TDX) is installed within a water jacket with inclination angle 5º in the measurement section and one high-speed camera taking images of the same point as the TDX, and the ultrasonic measurements and camera recording are synchronized. Emitted ultrasonic pulses consists of 4 waves with the frequency 4.17 MHz, and the repetition frequency is 3998 Hz. The distance between the TDX and pipe outer wall is roughly 20 mm, in the calculated far-field area of the ultrasonic wave. The flow rate of each phase is controlled by pump and mass flow controller. The flow rates vary in gas phase from 20 to 80 L/min, and in liquid phase from 15 to 75 L/min. The flow pattern map made on the basis of research by Taitel et al.[3] is shown in Fig.2.

2.2 Experimental system 2

As the second system, data from an airlift experiment conducted jointly by the University of Tokyo, Hokkaido University and National Maritime Research Institute (NMRI) in 2021 are used. The pipe inner diameter in the measurement section is 26 mm and the wall thickness is 2 mm. The gas flow rate is controlled by mass flow controller and the consequential liquid flow rate is measured by an electromagnetic flow meter. Flow rates vary in gas phase from 32 to 255 L/min. The flow pattern map is shown in Fig.2. Three TDXs are attached to one pipe within water jackets, which ensure the far-field area distance (30 mm) and all the measurement is synchronized with high speed video camera. TDX2 measures the same point as camera, and other TDXs measures vertically distant points, which can observe locational variations of the flow structure. Additionally, TDX3 is set on the opposite direction with others, which can check the variation of flow structure by direction. In this study, however, 3 TDXs are used at the same time simply to make the amount of echo data achieved in one experiment larger. The setting of ultrasonic emission is the same as system 1.

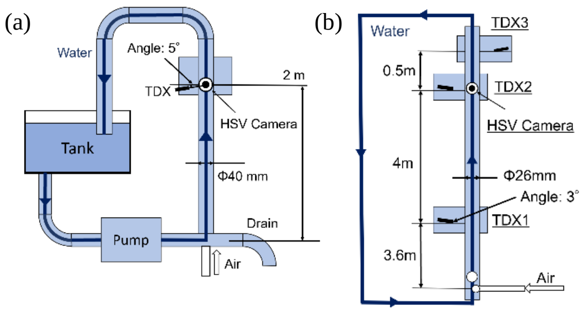

Figure 1: Experimental system in system 1 (a) and 2 (b).

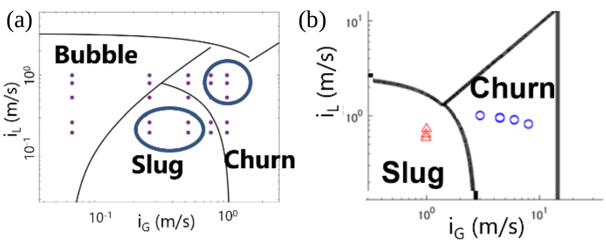

Figure 2: Flow pattern map in system 1 (a) and 2 (b).

3. Analysis Method

The ultrasonic measurement mechanism is conducted by emitting an ultrasonic beam towards the flow path and receiving the reflected wave by the same transducer. In this section, the reflection information is analyzed using the echo intensity technique [4]. This technique uses the extremely high ultrasonic reflectivity of the gas-liquid interface to locate the position of the gas-liquid interface. The visualization of the flow is in comparison with the camera image, in which each temporal variation of camera image and echo map is piled up along the timeline. An example of the visualization is shown in Fig.3.

In this study, identification by machine learning using the temporal variation of extracted echo property is conducted. Also, the efficiency of trained model conversion from one experimental system to another experimental system is examined. As the echo property, the "center of gravity", which express the echo distribution in distance direction is used (Fig.3). In order to check the efficiency of data extraction, identification using actual echo map data is also conducted and the accuracy is compared. The data is split with sampling time calculated by dividing constant converted length (3.75 m) with mixture apparent velocity i_T. The label is achieved from the flow pattern map.

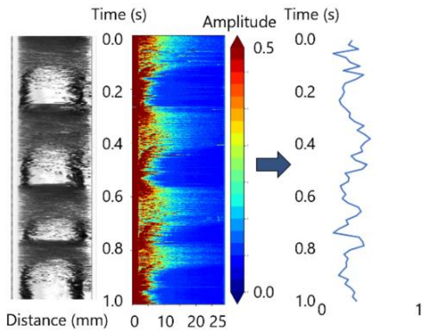

Figure 3: Example of comparison of processed camera image and echo map, and calculation of "center of gravity" of echo.

4. Result

In training, data taken from experimental system 1 are used. Flow pattern identification is conducted between slug flow and churn flow, using random forest algorithm with center of gravity data and convolutional neural network (CNN) with echo map data. As train data, 72 pieces are chosen from each flow pattern (144 pieces as a whole). Also, as test data 18 pieces are used from each and the slug/churn identification accuracy for all 36 pieces of test data is compared. As a result, the accuracy with center of gravity data is 0.92, which is higher than the accuracy with echo map data, 0.77. While the effectiveness of identification model with center of gravity data is demonstrated in experimental system 1, the convertibility of the model to another experimental system is examined. The identification model constructed in experimental system 1 is directly converted to the identification of slug/churn flow in experimental system 2 and the accuracy is checked. As test data, 13 pieces are used from each flow pattern. The accuracy with the test data (system 2) into the converted model (system 1) result in 0.69, which is lower than the accuracy with test data from system 1 (0.92). In this study, the conversion of flow pattern identification model constructed with data from one experimental system to another experimental system does not show as secure accuracy as in original experimental system.

Table 1: Accuracy of flow pattern identification model trained with "center of gravity" data from system 1 and tested with data from each system.

	System 1	System 2
Accuracy	0.92	0.69

5. Discussion

First, in flow pattern identification with echo data using machine learning, it is found that the appropriate data extraction makes training more efficient and improves the accuracy with limited train data. In this study center of gravity data is used, but there can be another effective data extraction. Second, the flow pattern identification model valid for experimental system 1 did not show the same degree of accuracy for system 2. Looking into the incorrectly identified cases, it turned out that in system 1 all of the incorrect cases are churn flow overestimated as slug flow, while in system 2 all the misidentified cases are slug flow overestimated as churn flow. In both incorrect cases the flow structure is ambiguous in terms of flow patterns and difficult to decide slug/churn flow even from the flow structure. Thus, the difference of accuracy can be attributed to the low distinctiveness of the flow itself, not the identification method. In flow pattern, which is artificially divided and for which there is no practical significance in strictly defining the boundaries, misidentifying cases seen in this experiment are difficult to solve and not so important. Therefore, for the development of practically important flow pattern identification system, train data and test data should be taken from more distinctive cases.

6. Summary

In this study, ultrasonic measurement to vertical pipe gas-liquid multiphase flow containing large bubbles is conducted in two experimental systems. With the echo intensity data as extracted "center of gravity" data, flow pattern identification between slug and churn flow using machine learning is tried. In a single experimental system, the identification model shows accuracy higher than 0.9, which confirms the efficiency of machine learning flow pattern identification with data extraction. Also, it is implied that an identification model constructed in one experimental system can be directly converted to identification in another system with echo data of good quantity and quality in view of distinctiveness of flow pattern, even if some size scales of the systems are different.

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