Boundary layer measurement of a vessel sailing over the sea

Shoko OHTA[1*] , Akinari SHIGETOMI[1], Yuji TASAKA[1], Yuichi MURAI[1],
Yasushi TAKEDA[1], Munehiko HINATSU[2] and Yoshiaki KODAMA[2]

[1] Graduate School of Engineering Hokkaido University, N13, W8, Kita-ku, Sapporo, Hokkaido 060-8628 Japan (*Corresponding author, e-mail: shoko-o@ring-me.eng.hokudai.ac.jp).

[2] National Maritime Research Institute, 6-38-1, Shinkawa, Mitaka-shi, Tokyo 181-0004, JAPAN

Friction drag of a large ship accounts for 80 % of the total drag, and hence drag reduction caused by bubbles is expected because of less environmental impact and easy installation. As a method to assess the bubble-originated alternation of the boundary layer structure beneath actual moving ship, we have designed a ship-mounting type of ultrasound probe and applied for ultrasound velocity profiler (UVP). The measurement performance is examined by a 50m-long flat bottom ship in NMRI 400m-long towing tank. After the measurement system is verified and improved for high-speed seawater environment, the system is applied to the measurement of the boundary layer beneath a moving vessel on the sea around Japan for five days. The vessel is 127 long and the local seawater velocity profiles at three position of the vessel are measured. With the results, the alternation of the profiles due to injection of bubbles is detected by the present UVP instruments.

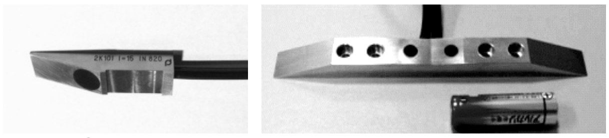
Keywords: ship engineering, drag reduction, turbulent boundary layer, velocity profile

1 INTRODUCTION

Energy-saving is severely requested for recent jump in oil prices. The merchant service is also affected with it considerably. Around 80% of the fuel for a large ship is consumed only for the friction drag that the ship receives on the sea. Thus the drag reduction has been a long and hot topic in this area. In particular the use of bubbles is expected at present as the most feasible way to reduce the friction drag because of less negative impact to the sea environment, and easy installation to existing ships[1][2]. A great deal of laboratory scale experiments[3] has been carried out to date to have confirmed the great effect of bubble-provided drag reduction. Now the stage is moving to the examination on the sea so that the practical usefulness is directly evaluated.

In Japanese NEDO-grant project, our UVP[4]-team is assigned to the measurement of the velocity profiles at plural positions around the ship under the sea. Several demands must be satisfied for the ultrasonic transducers in the high-speed natural seawater environment, which is available for long days. To this end, we design and manufacture a number of transducers in various points of view. Fig. 1 shows two samples of the transducers among them, which are actually employed for the measurement.

In this paper, we report on the design of the transducers, the examination by mounting them on 50m-long flat bottom ship at NMRI 400m-long towing tank, and also the application to 127m-long vessel moving on the sea. In addition, the effect of bubble injection on the turbulent velocity profiles is focused on as the measurement results are discussed.



(a) Single Beam Type (b) Double Beam Type

Figure 1: Ultrasonic Transducers Employed for Ship

2 TOWING SHIP TEST

2.1 Design of transducer

The ultrasonic transducer that we newly designed for the ship is shown in Fig. 1.

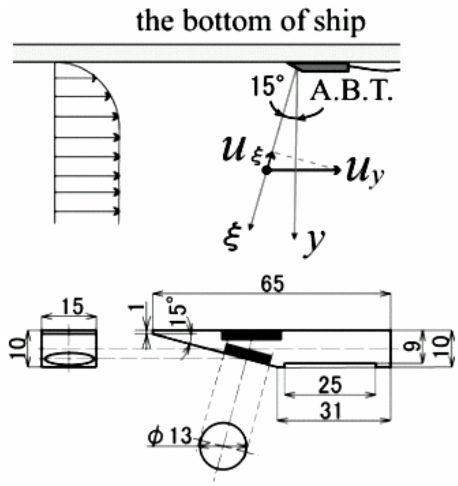


Figure 1: Angled Beam Transducer (2MHz)

It has inclined head relative to the flow-perpendicular direction at angle of 15 degree. We call this angled beam transducer (ABT) in this paper. The head of ABT constitutes of hundreds of vibrating semi-conductor elements, i.e. composite type transducer, being adjusted to have 2MHz in resonance frequency. A thin sheet of ultrasonic absorber is inserted on the backside of the head to avoid the internal multiple reflection. In addition, the wire connected with the transducer is covered with electromagnetic double shield to prevent from noise inclusion through 100m-long transfer. The streamwise velocity profile along the measurement line is obtained as

$$u_y(\xi,t) = u_\xi(\xi,t)/\sin\theta\,. \quad (1)$$

2.2 Experimental conditions

The towing ship test is carried out in NMRI(National Maritime Research Institute of Japan)'s 400m-long towing tank that is 18m in width and 8m in depth. The towing ship of 50m in total length runs at constant velocity for around 10s. In this towing ship, ABT is mounted at 27.5m from the ship head. The sampling frequency, the spatial resolution in the beam direction, the velocity resolution, and the depth of the measurement of UVP are, 9ms, 1.5mm, 7.9mm/s, and 130.6mm, respectively. Bubbles are injected from the bottom of the ship at mean diameter of around 0.5 to 2.0mm. The towing speed is varied from 1.0m/s to 7.2m/s(14knowt), stepwise. The UVP measurement is conducted twice for the same speed to compare the velocity profiles that change with the bubble injection.

2.3 Experimental Results

As shown in Fig. 2, ultrasound reflects on the first bubble interface near the transducer. Thus it cannot transmit further to measure the flow beyond the bubble. This is because bubble size is larger than the effective diameter of the ultrasound beam. At near the first bubble position, UVP outputs locally low velocity. This does because a local standing wave is formed within a half-length of the pulsed ultrasound from the gas-liquid interface when it reflects on the interface. As the result, Doppler shift disappear near the bubble interface to provide very low velocity locally. With this principle, the bubble position that is located near the ship wall is measured, and the velocity of liquid and the bubble distribution are measured from the single data set of UVP measurement.

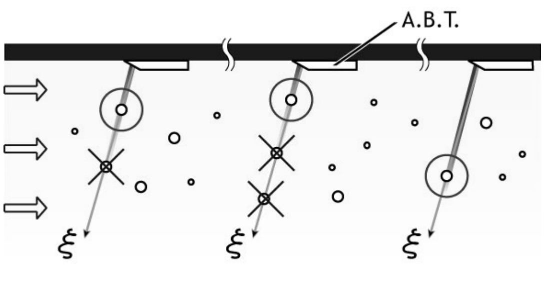


Figure 2: Ultrasonic beam reflection on nearest bubble

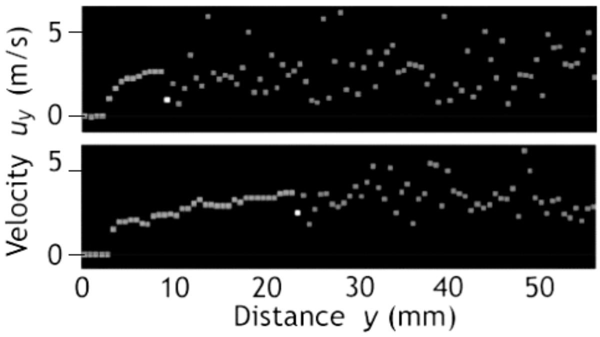


Figure 3: Instantaneous velocity profiles including bubbles: White point corresponds with position of bubble

3 APPLICATION TO ACTUAL SHIP

3.1 Improvement of transducer

In the application of UVP to actual ship, a coupled type of ABT is designed and manufactured so that the full information of turbulent flow characteristics in the boundary layer[6] is captured. The details are shown in Fig. 4. Since two ultrasonic beams form a Y-shape for measuring velocity vector profiles, we call this Y-type angled beam transducer (YABT). Depending on demands for UVP in measuring different location of the ship, three types of YABT are made as listed in Table 1.

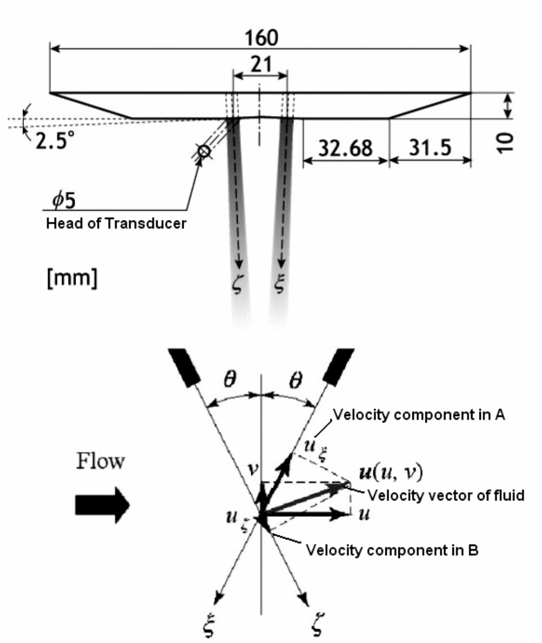


Figure 4: Y-type Angle Beam Transducer (2MHz)

Table 1: Specification of YABT

Basic Frequency	f_0	[Hz]	1	0.5	2
Wavelength	l	[mm]	1.53	3.06	0.765
Oscillator Diameter	D_0	[mm]	10	20	5
Measuring Range	X	[mm]	958.3	1916.7	479.2
Spatial Resolution	Dx	[mm]	3.06	6.12	1.53
NF length	X_{NF}	[mm]	8.170	16.340	4.085
Spread Angle	g_0	deg	4.475	4.475	4.475

The YABT is fabricated as a single unit in which a pair of transducers is tightly fixed with metal matrix. The relative angle of them is rigidly determined so that the velocity vector is obtained accurately despite to a narrow angle that is set so for handing high-speed flow conditions. When the velocity component of u_ξ , u_ς are measured with each transducer, not only the time averaged velocity vector but also Reynolds shear stress is obtained by the next equation[5]. Therefore, the process of drag reduction caused by bubbles is deduced as well.

$$-\rho\overline{u'v'} = \rho\frac{u_{\xi}'_{rms} - u_{\varsigma}'_{rms}}{2\sin\theta} \qquad (2)$$

3.2 Experimental conditions

The flow around actual moving ship [Pacific Seagull, Azuma Shipping Co.ltd., see Fig. 5] is measured for five days in January 2008, around the mainland of Japan. The ship is 127m in total length and runs at around 13knot (6 to 7m/s). The measurement conditions are classified into two cases; ballast and loaded conditions of liquid cement. The measurement positions are as shown in Fig. 6. Here YABT(1MHz) near the bow is for measuring the ship velocity relative to seawater, YABT(2MHz) at the center of the ship is for visualizing the boundary layer structure, and YABT(0.5MHz) at the stern is for investigating the inflow velocity profile upstream of the screw.


Figure 5: Experimental vessel “Pacific Seagull”

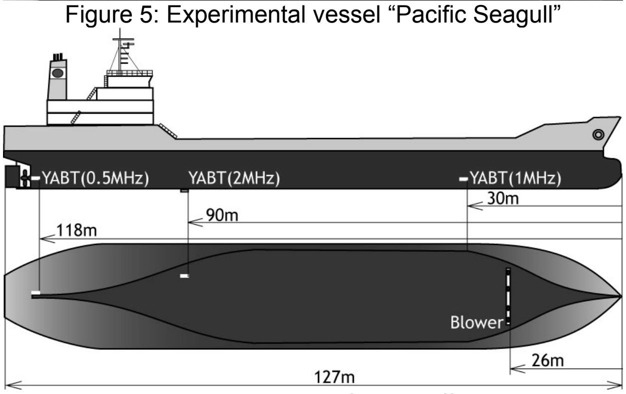
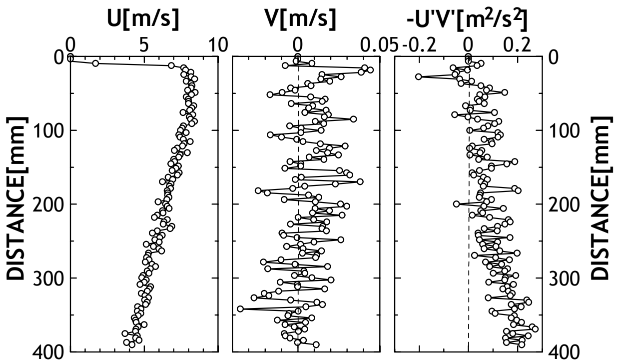


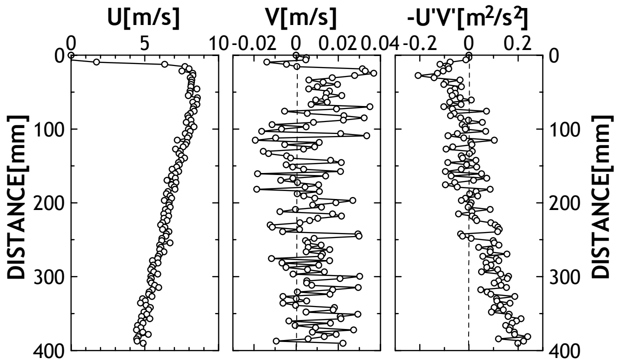
Figure 6: Mounting position of three different YABTs

3.3 Measurement results and discussion

The tracer of the present UVP measurement is naturally included contamination in the sea, but not intentionally mixed. In the case of ballast experiment, small bubbles created by the breaking surface at the bow are suspended long under the ship to be the tracer of UVP. Contrary, no significant echo is obtained in the loaded experiment due to deep distance from the seawater surface. The results shown below are limited to the ballast conditions.

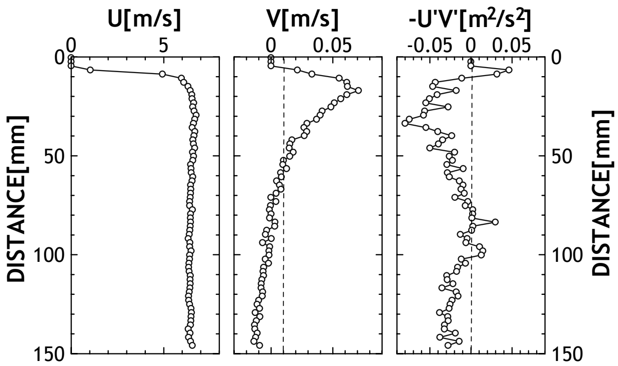


(a) Velocity profile in the case without bubble

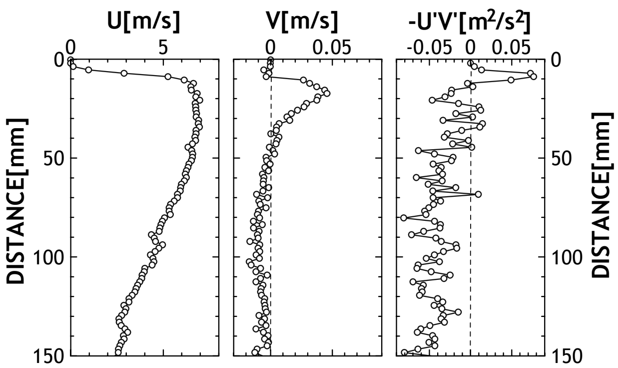


(b) Velocity profiles in the case with bubbles

Figure 7: Velocity profiles (YABT-1MHz) at bow



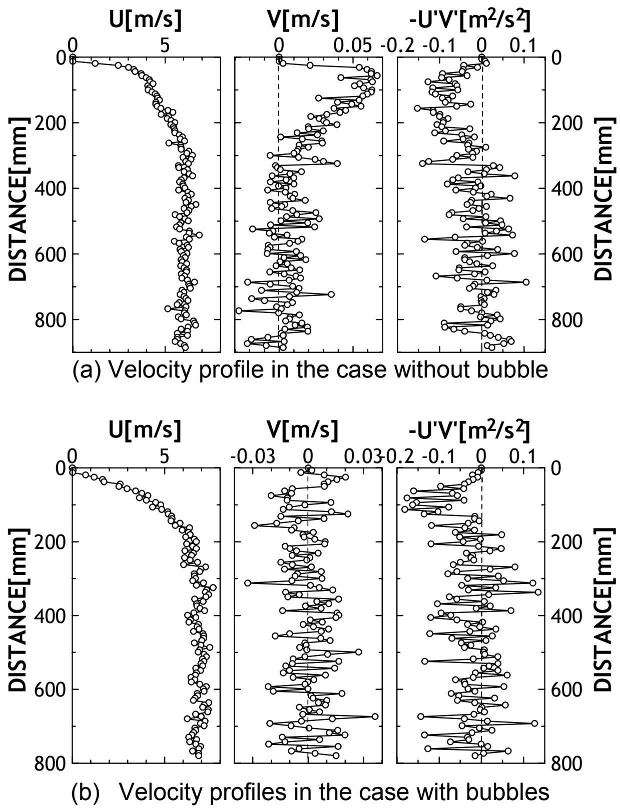
(a) Velocity profile in the case without bubble



(b) Velocity profiles in the case with bubbles

Figure 8: Velocity profiles (YABT-2MHz) beneath the ship

Figure 7 shows the velocity profiles measured by YABT near the bow of the ship. The thickness of boundary layer is found to be around 15mm, matching well the one estimated by the boundary layer theory. The main flow velocity profile has the highest velocity at 20mm and decreases with the distance from the wall to have a gentle negative velocity gradient. This is because the fluid exclusion effect downstream the bow remains there. In terms of bubble injection effect, there is no significant alternation seen in the results. This is explained by the fact that the flow near the measurement position does not interact with bubbles.



(a) Velocity profile in the case without bubble

(b) Velocity profiles in the case with bubbles

Figure 9: Velocity profiles (YABT-0.5MHz) at stern

Figure 8 shows the same set of results measured in the central part where bubbles can migrate through. The injection of bubbles changes the main flow velocity profile to be dumped at the far region from the wall (y>50mm). This change is caused by the reflection of ultrasound on densely suspended bubbles within y<50mm, but not the alternation of liquid velocity. However we can see an increment of the velocity near the wall in the case with bubbles. This is consistent to the general knowledge, i.e. the velocity gradient of logarithmic layer increases when drag reduction occurs with bubbles[6]. On the other hand, Reynolds shear stress increases near the wall. This means that bubbles generate additional turbulence in the boundary layer while total drag is reduced mainly by the wall-contact area of bubbles. This is known as bubble-covering effect that is similar to air-film method of drag reduction. In fact, the mean bubble size estimated from the bubble's echo signal ranges from 15mm to 25mm. This range of bubble has no function to damp the turbulence of liquid phase but rather activate the momentum transfer. Consequently the present data well describe the actual situation of drag reduction provided by large bubbles[7].

Figure 9 shows the same results measured at the stern of the ship. This point is located inside the wake region of the ship and the flow is affected by the long friction from the bow. Thereby the main flow velocity decreases thickly from the wall. In the case of bubble injection, the main flow velocity increases due to reduced average density before the screw. In the NEDO project, the influence of bubbles on the screw performance is also investigated, which is reported in another publication.

4 SUMMARY

In order to understand how the boundary layer is altered with injection of bubbles in actual moving ship on the sea, we have designed and utilized several types of ultrasonic transducers that are applicable to seawater environment. The final form of the transducer we applied for it is Y-type angled beam transducer (YABT) that can capture the velocity vector profile as a function of the distance from the ship wall. In the stage of towing ship test, bubble distribution is measured from the first bubble reflection in the direction of the ultrasonic beam. The application of the YABTs to three positions around the ship reveals for the first time that the seawater velocity in the logarithmic layer is accelerated with presence of bubbles.

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