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Power-saving device for air bubble generation using a hydrofoil to reduce ship drag: Theory, experiments, and application to ships

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ABSTRACT

We have developed a new power-saving device to reduce the drag of a ship's hull using small bubbles. The device reduces the energy required for bubble generation. The device, which consists of angled hydrofoils with air introducers, uses the low-pressure region produced above the hydrofoil as the ship moves forward to drive atmospheric air into the water. We describe the device principles obtained from simple fluid dynamic theory, and, through experiments performed in a small towing tank, show the fundamental air entrainment and bubble generation processes for the flow behavior around a hydrofoil beneath a free surface. We also present a semi-empirical scaling process for practical application to full-size ships to estimate the net drag reduction achieved by this device. Finally, the results of a series of full-scale tests are reported and show that, with correct operation, our device can produce a net power saving of 5–15% for ships.

1. Introduction

Over the past few decades, the mechanism of air lubrication has been investigated for reduction of the friction drag on a ship's surface and to reduce CO_2 emissions. Three physically different air lubrication techniques have been identified: air cavity, air film, and small bubble methods. The classification of the working principle in these different drag reductions was explained by Ceccio (2010). The small bubble method, which utilizes functions of micro- to sub-millimeter bubbles, has an advantage over the air cavity and air film-based methods in that it reduces friction without requiring any change in the form of the ship's hull. Another advantage is its large impact to the drag reduction ratio per void fraction supplied into the boundary layer. The impact is ordinarily larger than unity, and reaches 100 on ideal conditions as reviewed by Murai (2014). Researchers in this field use the term "microbubble drag reduction" as they expect turbulence modification realized by eddy-suppressing small bubbles inside turbulent boundary layer. Practical application of microbubble method to ship drag reduction has been actively studied in recent years because of the potential energy savings and the environmental benefits in terms of marine pollution. Kodama et al. (2008) reported approximately 10–15% saving of the total energy consumption for an experimental ship. Mizokami et al. (2010) also succeeded in about 10% fuel saving as bubbles were injected below a vessel with wide flat bottom surface. Their ships of air lubrication system are already in commercial uses. For challenging further improvement of drag reduction, Mäkiharju et al. (2012) proposed high-void fraction type of air-layer drag reduction and estimated its usefulness to large tankers. Jang et al. (2014) also reported 5–6% net power-saving estimated for a bulk carrier as they scaled their towing model ship experiments considering the power for bubble injection.

One of concerns toward further improvement of microbubble method is the fact that the energy required to supply air bubbles using conventional bubble generators is quite significant, and it occupies 3–10% of the total energy consumption of a ship dependent on the depth of bubble generation. This explains that the required power for bubble generation in worse operations cancels out the power saved by drag reduction. For example, the theoretical estimate of the energy loss due to the adiabatic compression of air, i.e., the ratio of the internal energy increase ΔU to the work done in the adiabatic compression of air L_{total}, is given by

$$\frac{\Delta U}{L_{total}} = \left(\frac{K-1}{K}\right)\frac{C_V}{R}, \quad (1)$$

where C_v, R, and κ are the heat capacity at constant volume, the gas constant, and the heat capacity ratio, respectively. From Eq. (1), the energy loss due to the adiabatic compression of air is approximately 71% at 20 °C (R=287 J kg^{-1} K^{-1}, C_v=718 J kg^{-1} K^{-1}, and

Abbreviations: WAIP, winged air induction pipe; AIP, air induction pipe

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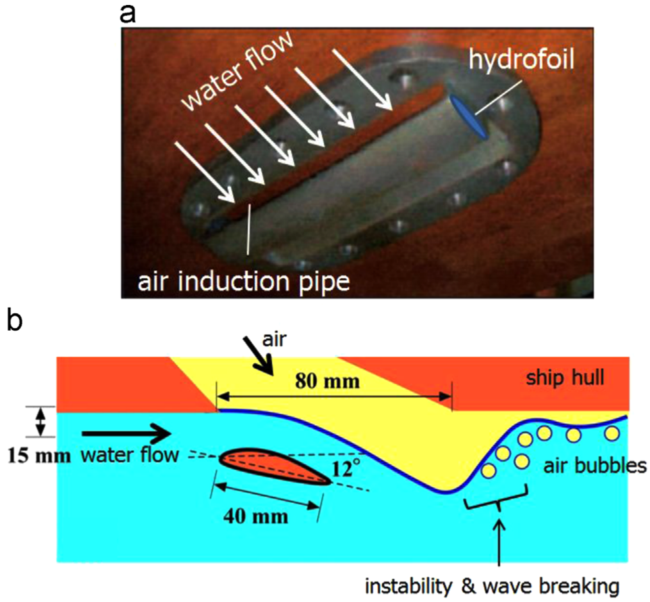

Fig. 1. Winged air induction pipe (WAIP): (a) photograph; (b) schematic drawing of the WAIP cross-section. The hydrofoil is a NACA 65_3-618 (chord length of 40 mm, span-wise length of 240 mm, and angle of attack $\theta = 12°$).

$\kappa = 1.4$). To supply air bubbles at a specified water depth, the energy required includes the adiabatic compression energy, the energy required for the bubble generation procedure (e.g., the small air bubbles are generated by passing air through either a porous medium or capillary tubes) and the mechanical energy loss in the compressor. As a result, the net power saving declines to as little as 0–5%, which is a serious obstacle to the practical application of microbubbles in the shipbuilding industry (e.g. Kodama et al., 2008).

To overcome this obstacle, we invented a new bubble generation device suitable for its installation to ship (Takahashi and Murai, 2004; Murai and Takahashi 2008). Fig. 1 shows the new device, which is called a winged air induction pipe (WAIP). This device, which has an angled hydrofoil with an air introducer, provides the low-pressure region above the hydrofoil as the ship moves forward. The low pressure drives the atmospheric air to a critical water depth without significant air compression, depending on the flow conditions around the hydrofoil, the hydrofoil's shape, the angle of attack, and other factors. Interaction between the hydrofoil and upper deformable free surface was investigated by Duncan (1983). In our case, the hydrofoil is located at a small distance from the flat wall so that air and water join smoothly to flow out downstream. This device also generates small bubbles without the use of bubble fragmentation devices such as porous plates. We confirmed that the small bubbles are generated by the instability of the air–water interface, which is subject to a high shear rate along the surface of the hydrofoil. The number density of bubbles increases with the subsequent wave-breaking phenomenon which occurs just behind the hydrofoil (Kumagai et al., 2010). We installed WAIPs on a coaster and achieved a net power saving of 10–15% as being elaborated in Sections 4.3 and 4.4 in this paper.

Here, we describe the theory of the entrainment of air by a hydrofoil moving beneath an air–water interface and experimentally demonstrate the bubble generation processes in laboratory scales. We also show a semi-empirical scaling process for estimation of the total drag reduction for ships that can be achieved by installing the WAIP device; the scaling is based on experimental results from a circulating water channel. Finally, we report on full-scale sea trials to demonstrate how our device works in practical applications, which will provide information to optimize the device and lead to further improvements.

2. Theory

2.1. Threshold of air entrainment by a hydrofoil beneath a free surface

When the hydrofoil of a WAIP attached to a ship's hull moves at a constant velocity U, water flows over the hydrofoil surface; a low-pressure region is then produced over the upper surface of the hydrofoil (Murai and Takahashi, 2008). The magnitude of the negative pressure ΔP depends on the flow speed, type of hydrofoil, the angle of attack, and also the depth of the hydrofoil from the air–water interface. The atmospheric air is entrained when the magnitude of the negative pressure is higher than the hydrostatic pressure of the water at the depth of the WAIP installation (Murai et al., 2010):

$$\Delta P = C_P \tfrac{1}{2}\rho U^2 \geq (\rho - \rho_{air})gH \cong \rho g H, \tag{2}$$

where C_P, ρ, ρ_{air}, and g are the negative pressure coefficient of the hydrofoil, the density of water, the density of air, and the gravitational acceleration, respectively. Note that $\rho \gg \rho_{air}$. From Eq. (2), we can estimate the critical velocity for air entrainment $U = U_E$:

$$U_E \cong \sqrt{\frac{2gH}{C_P}}. \tag{3}$$

In this simple formula, C_P is not defined as a point wise value on the hydrofoil surface but is given by average value of local negative pressure coefficient distribution in the region between the hydrofoil and the outlet of air induction pipe (AIP). Thus, the WAIP is designed to provide strong negative pressure region between the hydrofoil and AIP so that the above-given critical velocity U_E is lowered as small as possible.

Fig. 2 shows an experiment that demonstrates the effect of the towing velocity on the air entrainment by the WAIP (Kumagai et al., 2010). When the towing velocity U was smaller than the

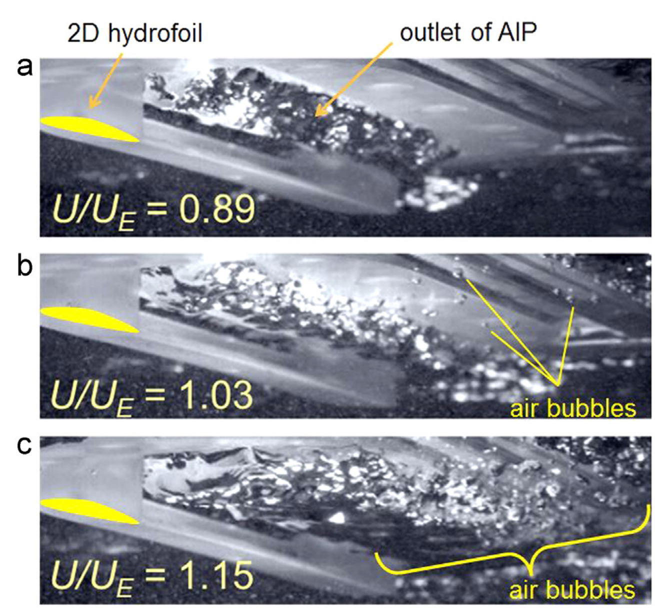

Fig. 2. Oblique upward views showing the thresholds for air entrainment by the WAIPs in towing tank experiments. The WAIP moves from right to left. (a) No air entrainment ($U < U_E$); (b) around the critical velocity U_E; (c) air entrainment and subsequent bubble formation ($U > U_E$).