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Effects of aspect ratio on the hydrodynamic performance of full-scale rectangular otter board: Numerical simulation study

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ABSTRACT

In the present work, the hydrodynamic characteristics of full-scale rectangular otter board were studied by numerical simulation, including the effects of aspect ratios (AR), flow distribution around the otter board, induced velocity, induced angle of attack (AOA), effective AOA and induced drag coefficient. It was demonstrated that the otter board had a critical AOA of 40° (when the stall appeared) and induced AOA of 3~10°. The maximum induced drag coefficient was 0.185, which is a great contribution to the total drag coefficient. The otter board exhibited better performance when the AR was set to 0.5, and higher AR had a smaller critical AOA (the stall happened earlier). The maximum lift coefficient decreased with an increasing AR, while the maximum lift-to-drag ratio increased. The induced drag coefficients showed similar trends across ARs, initially rising with an increase of the AOA, and then dropping. The flow distribution around the otter board showed that the wing-tip vortex was fully developed at the AOA of 40°, and the AR can affect the development of the wing-tip vortex.

1. Introduction

The otter board, which is designed to maintain the horizontal opening of the trawl net and consequently affects the fishing efficiency, is a vital component for a trawl system. It has many types, among which the rectangular otter board is widely used in shrimp trawls in China. The resistance of the otter board accounts for up to 30% of the total-system drag, which is ranked second (Sterling, 2000). Therefore, research on the hydrodynamic performance of the otter boards has great significance for energy saving and has increasingly attracted attention of the researchers in China and internationally.

To better understand the hydrodynamic characteristics of otter board, extensive investigations were carried out during the past decades. Matuda et al. (1990) measured the maximum lift coefficient (1.27) and lift-to-drag ratio (4.03) of vertical V-type otter boards by conducting flume tank experiment. Yamasaki et al. (2007) designed a high-lift V type otter board to improve the otter board used in a semi-pelagic trawl net in Ise-wan Bay, model tests and sea trials were carried out for the otter board and showed a higher lift-to-drag ratio (1.41 times) than the conventional rectangular otter board. Sala et al. (2009) designed a new otter board, the Clarck-Y door, based on improving the water flow on the upper part of the otter board to avoid vortices, flume test was carried out for the otter board and showed a higher efficiency than the cambered V type otter board. A fundamentally different design of otter boards, namely 'batwing', was proposed by Sterling (2008, 2010); this design utilized a flexible sail operated at a low AOA, and a seabed-contact shoe aligned with tow direction. Compared to flat rectangular otter boards, the flexible sails were demonstrated to have at least 3 times greater efficiency (lift-to-drag ratio) while maintaining sufficient stability (defined by the center-of-pressure) at a 20° AOA (Balash and Sterling, 2014; Balash et al., 2015a, 2015b). The concurrent field trials showed ~20% drag reduction for the entire trawl system when using the batwing compared to three conventional otter boards (McHugh et al., 2015). In addition, Park et al. (1994) studied the flow distribution around a cambered otter board using hydrogen bubbles and found that the separation point moved from the trailing edge to the leading edge at the central section on the suction side of the plates. By the same method, Shen et al. (2015) studied the flow

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distribution around the down-tip section of a cambered plate and found that the formation and development of the wing-tip vortex were coincidental with the maximum lift coefficient.

Generally, model tests and sea-trials were two main means to study the hydrodynamic characteristics of the otter board for many years. Alternatively, computational fluid dynamics (CFD), a numerical method for solving the equation of fluid mechanics, has been developed rapidly with the progress of computer technologies. Having the advantages of low cost and being able to simulate more complex situations, it is widely used in the development and design of ships and artificial reefs (Percival et al., 2001; Jiang et al., 2010; Ghadiri et al., 2011; Zheng et al., 2015). And now, researchers begin to study the hydrodynamic characteristics of otter boards using numerical simulation. Takahashi et al. (2015) studied the biplane-type otter board by means of CFD analysis and the results showed a maximum lift coefficient value of 1.65 for AOA of 17.5°, which was in agreement of the flume tank experiment ($C_{L\ MAX}$ = 1.64 when AOA = 20°) under the same conditions. Xu et al. (2017) studied the rectangular V-type otter board using two kinds of numerical simulation methods and found that CFX analysis was better at simulating forces while FLUENT analysis was better at simulating the velocities, and the otter board exhibited better performance when the AR was set to 0.49 with a dihedral angle of 17°.

Even though rectangular otter boards are intrinsically inefficient, they are still widely used, particularly in developing countries, because of their simple and cheap construction. Further, these boards of reduced size can be efficiently matched with trawls designed to have a low spreading requirement (i.e. W-trawl; Balash et al., 2015c, 2015d). Hence in this study, we evaluated the hydrodynamic performance of full-scale rectangular otter boards via the numerical simulation, which was verified by flume tank experiments conducted in the preceding study (Xu et al., 2016).

2. Materials and methods

2.1. Full-scale otter board

The prototype of otter board for this experiment is a rectangular otter board used in the small single trawler, with a power of 14.7 kW and working at a speed 2 kn. The otter board is made of iron and wood, and its main dimensions are given as follows: the wing span l = 0.4 m, the chord c = 1.590 m and the AR $\lambda = l/c$ = 0.252.

2.2. Numerical simulation of the full-scale otter board

The numerical simulation was carried out by CFX analysis contained in the software ANSYS 15.0. In the calculations, the finite-volume method was used to solve the Reynolds-averaged Navier-Stokes equations. The realizable k~ε turbulence model, an improved model from standard k~ε model (Shih et al., 1995), was adapted to the simulation, and scalable wall treatment was employed for the wall function.

The computational domain is shown in Fig. 1. The domain was determined by adjusting the length, width and height one by one. This was done by enlarging the length, as well as width or height of calculation domain step by step and examining the convergence of calculated results. Consequently, the length, width and height of the calculation domain for simulating full-scale otter board were set at 20l (wing span, l_{max} = 0.6 m), 16l, 5l respectively, and the calculation converges with a relative error less than 1% (Xu et al., 2017). The otter board was fixed at the bottom of water and at a distance of 3.5l from the flow entrance.

The computational grids around the otter board are shown in Fig. 2. The grids are tetrahedrons, which are unstructured grids. The grids density around the otter board were intensified by setting 10 layer inflations, of which the first layer thickness was 5×10^{-5} m ($11.06 < y^+ < 60$), with a growth rate of 1.2 for each of next layers. The number of elements and node elements totaled approximately 2.4×10^6 and 5.6×10^5 respectively.

The boundary conditions are shown in Fig. 3. Water was modeled as fresh water with a temperature T = 15 °C, density ρ = 999.1 kg m^{-3} and kinematic viscosity $\nu = 1.14 \times 10^{-6}$ m^2 s^{-1}. The fluid was assumed to be incompressible. The inlet boundary was velocity inlet with a uniform flow in the x-direction and turbulence intensity was 5%, turbulence viscosity was 3.75×10^{-3} m^2 s^{-1}. The outlet boundary was pressure outlet with a relative pressure of 0 Pa. The side and top boundaries of the domain were set to free slip walls, while the otter board surfaces and the bottom boundary were assumed to be smooth and non-slip walls.

During the numerical simulation, the fluid was set to 1.028 m/s (about 2 knot, and $R_e = 1.43 \times 10^6$), i.e. the typical towing speed of trawls while fishing. The AOA (α) were changed in the range of 10~55° (with a step of 5°).

2.3. Induced drag and effective AOA

According to the aero-foil theory (Prandtl, 1952; Oertel, 2010), when the fluid flows to the finite span of wing, with no physical barrier, it induces a lateral flow around the wing tip from pressure side (lower surface) to suction side (upper surface) (Fig. 4-a). These result in streamlines curving toward and from wing tip on lower and upper surface, respectively (Fig. 4-b). The lateral flow around the wing tip results in a wake vortex (Fig. 4-c) that induces down-pointing velocities (induced velocity, v_y) that reduces the effective AOA of the wing and, with it, the effective lift. On top of this effect, the airfoil section lift, which is orthogonal to inflow velocity (v), becomes inclined backwards with respect to actual flight velocity (v_k), its projection on the direction perpendicular to the inflow velocity is the measured effective lift force (F_L) and its projection on the inflow velocity axis can be interpreted as the so-called induced drag. The $\Delta\alpha$ (Fig. 4-d) between v and v_k is called the induced AOA. And the induced drag and the induced drag coefficient were calculated as the follow equations according to the theoretical analysis:

$$F_I = \frac{1}{2} C_I \rho S v_k^2 \tag{1}$$

$$C_I = \frac{C_L^2}{\pi\lambda} \tag{2}$$

However, the above theory corresponds to an elliptical wing and it assumes two wing-tips. While in the present work, the otter board was fixed at the bottom, one of the wing tip vortexes was blocked by the ground. Therefore, the theoretical results for half an elliptic wing, i.e. $F_I/2$ (account for the single wake vortex), were compared with actual simulation results. And the simulation results were calculated as follows:

$$\tan(\Delta\alpha) = \frac{F_I}{F_L} = \frac{v_y}{v} \tag{3}$$

$$F_I = \frac{F_L \times v_y}{v} \tag{4}$$

Here, the induced velocity (v_y) was obtained by subtracting the vertical velocities at the trailing edge of a 2D simulation from the 3D simulation. For the 3D simulation, the vertical velocity was measured by setting 5 stations in the trailing edge of the otter board, and the velocities in the z-axis (Fig. 1, calculation domain) for each station were calculated, with it, the averaged value was regarded as the 3D vertical velocity. And the 2D simulation was calculated for the same otter board at the same AOA.