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Parameter optimization of a double-deflector rectangular cambered otter board: Numerical simulation study

Qing Chang Xu[a], Chun Lei Feng[b], Liu Yi Huang[a,*], Ji Qiang Xu[a], Lei Wang[b], Xun Zhang[b], Zhen Lin Liang[a,c], Yan Li Tang[a], Fen Fang Zhao[a], Xin Xin Wang[a], Hui Cheng[a]

[a] College of Fisheries, Ocean University of China, Qingdao 266003, China
[b] East China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Shanghai, 200090, China
[c] Marine College, Shandong University (Weihai), Weihai, 264209, China

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ABSTRACT

An otter board is an important device that provides a desired horizontal opening of a trawl net. A high lift-to-drag ratio is required for an otter board to maintain fishing efficiency. This study optimized the parameters of a double-deflector rectangular cambered otter board based on the maximum lift coefficient and lift-to-drag ratio and studied the hydrodynamic performance of the optimal otter board. Computational fluid dynamics (CFD) analysis was used (verified by a flume tank experiment) in the optimization process. Simulation results showed that the aspect ratios and deflectors had a significant influence on the hydrodynamic performance of an otter board. The optimal otter board had a better performance when the aspect ratio was 1.4 and the cambered ratios of the deflectors were 10%. Its maximum lift-to-drag ratio was 4.835, which was 1.10 times that of the initial otter board. The streamlines around the otter board showed that the structure of the deflectors can delay flow separation. The range of the wing-tip vortex increased with the angle of attack until stall occurred at which time the vortex began to break down.

1. Introduction

An otter board is a hydrodynamic wing traditionally comprising a flat plate rigged at an angle of attack (AOA) to produce lift or shear and the desired horizontal force to a trawl system. The board creates hydrodynamic forces that horizontally open penaeid trawls to spread ratios typically 0.6–0.8 of their total headline length (McHugh et al., 2015). The drag force was hypothesized to account for up to 30% of the entire trawl otter board system (Sterling, 2000). Drag directly relates to the energy consumption, lift characterizes the otter board effectiveness, and the lift-to-drag ratio characterizes the efficiency (Balash and Sterling, 2014). Therefore, improving the lift and reducing the drag are important issues in improving fishing efficiency and saving energy.

To improve the hydrodynamic efficiency of otter boards, extensive research has been carried out during the past decades. Wang et al. (2004) studied the hydrodynamic performance of a vertical V type otter board and optimized the main structure parameters (i.e. the curvature, dihedral angle and aspect ratio) of the otter board; results showed that the otter board had a better hydrodynamic performance when the curvature was 14%, the dihedral angle was 12°, the aspect ratio was 1.6 and the sweepback angle was 10°. Yamasaki et al. (2007) designed a high-lift V type otter board used in a semi-pelagic trawl net in Ise-wan Bay, model tests and sea trial results showed a higher lift-to-drag ratio which was 1.41 times that of a conventional rectangular otter board. A fundamentally different design of otter board, named 'batwing', was proposed by Sterling (2008, 2010); this design used a flexible sail operated at a low AOA and a seabed-contact shoe aligned with the tow direction. Flume tank experiment results showed that the flexible sails had at least three times greater efficiency at a 20° AOA compared with that of flat rectangular otter boards (Balash and Sterling, 2014; Balash et al., 2015 a; b). The concurrent sea trials showed about a 20% drag reduction for the entire trawl system when using the batwing otter board (McHugh et al., 2015). An airfoil-shaped otter board named 'hyper-lift trawl door' was designed by Hu et al. (2011) that utilized two wing-end plates, and the back of the leading edge was modified into an airfoil to improve lift and reduce drag forces. Flume tank experiments showed a lift improvement of 15.2% compared with a simple cambered plate with the same camber ratio (Shen et al., 2015).

Many researchers have designed new otter boards or optimized the conventional otter boards to improve their hydrodynamic efficiency. Model experiments and sea trials were the main methods to study the hydrodynamic performance of the otter board. Alternatively, CFD, a

* Corresponding author.
E-mail address: huangly@ouc.edu.cn (L.Y. Huang).

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numerical method for solving the equation of fluid mechanics, has been widely used in ocean engineering (Yelland et al., 1996; Percival et al., 2001). Within otter board research, Takahashi et al. (2015) validated the suitability of CFD analysis for otter board design with the similar results between numerical simulation and flume experiments. Xu et al. (2017, a) studied the hydrodynamic performance of a full-scale rectangular otter board using CFD, results showed that the otter board exhibited better performance when the aspect ratio was 0.5, and a higher aspect ratio had a smaller critical AOA.

In this study, we conducted CFD analysis to optimize the parameters of a rectangular cambered otter board, investigated the effect on hydrodynamic performance caused by different structure factors of deflectors and aspect ratios, and proposed the optimum structures of the otter board.

2. Materials and methods

2.1. Prototype otter board

The prototype otter board (initial model) is a double-deflector rectangular cambered structure and working at a speed of 3–4 kn. It was made of steel, and its main dimensions were a wing span of $l = 2.2$ m, a chord of $c = 2.2$ m, an aspect ratio of AR = 1 and a plane area of $S = 4.84\ \text{m}^2$.

Fig. 1 shows the sketch of the otter board. Two deflectors (D_1 and D_2) and a main panel (P) composed it. The deflectors were installed on the front with the installation angles $DA_1 = 25°$, $DA_2 = 20°$ and $MA = 6°$. The camber ratios of D_1, D_2 and P were 12%. The intervals of the deflectors and the main panel were $d_1 = 40$ cm and $d_2 = 40$ cm.

2.2. Experimental methods

There are many installation types of deflectors and main panel with different ARs, camber ratios and installation angles. In this study, the orthogonal experiment (Dey, 1985) was used to optimize the otter board and nine parameters were selected as the influencing factors. The optimization experiment had three phases.

The first phase determined the range of values of the selected factors via a preliminary experiment. Each factor had three levels and an L_{27} (3^{13}) orthogonal array (Taguchi Designs, 2004) was chosen for the experiment. According to the preliminary experiment results, the parameters of the otter board were selected as shown in Table 1.

The second phase analyzed the effect of the selected parameters on the lift coefficient and lift-to-drag ratio of the otter board, and discussed the optimal cooperation form. Based on the results of the first phase (Table 1), each factor had five levels, an L_{50} (5^{11}) orthogonal array (Taguchi Designs, 2004) was chosen for the experiment, and the prototype otter board was established and defined as the control group. The details of the orthogonal design of fifty otter board models are shown in Table 2.

The third phase compared and investigated the optimal cooperation form based on the results of the second phase. Meanwhile, the hydrodynamic performance and the flow distribution of the optimized otter board were analyzed further.

Table 1
Parameters of otter board according to preliminary experiment results.

Level	*AR*	DC_1	DC_2	*MC*	DA_1	DA_2	*MA*	d_1	d_2
1	0.6	10%	10%	4%	20°	20°	2°	25 cm	35 cm
2	0.8	12%	12%	6%	25°	25°	4°	30 cm	40 cm
3	1.0	14%	14%	8%	30°	30°	6°	35 cm	45 cm
4	1.2	16%	16%	10%	35°	35°	8°	40 cm	50 cm
5	1.4	18%	18%	12%	40°	40°	10°	45 cm	55 cm

2.3. Numerical simulation

Numerical simulation was carried out by CFX analysis of ANSYS 15.0 software. In the calculations, the finite-volume method was used to solve the Reynolds-averaged Navier-Stokes equations. The *k-ε* EARSM turbulence model (Wallin and Johansson, 2002) was adapted for the simulation and scalable wall treatment was employed for the wall function.

Before numerical calculation, the effect of the computational domain on the computational accuracy was studied to determine the optimal computational domain in this work. Finally, the length, width and height of the calculation domain for simulating a full-scale otter board were set at $7\,l$ (wing span, $l_{max} = 2.6$ m), $4.5\,l$ and $3\,l$, respectively, and the calculation converged with a relative error less than 1% (Xu et al., 2017; b). The otter board was fixed at the bottom of water and at a distance of $2.0\,l$ from the flow entrance as shown in Fig. 2. Computational grids were generated to unstructured grids for each case, and the number of elements and node elements totaled approximately 2.67×10^6 and 4.88×10^5 respectively. The grids around the otter board were refined and the value of y^+ was 11.06–68.09.

Boundary conditions are shown in Fig. 3. Water was assumed to be incompressible with a temperature T of 20 °C, density ρ of 998.2 kg m^{-3} and kinematic viscosity ν of $1.003 \times 10^{-6}\ \text{m}^2\,\text{s}^{-1}$. The inlet boundary

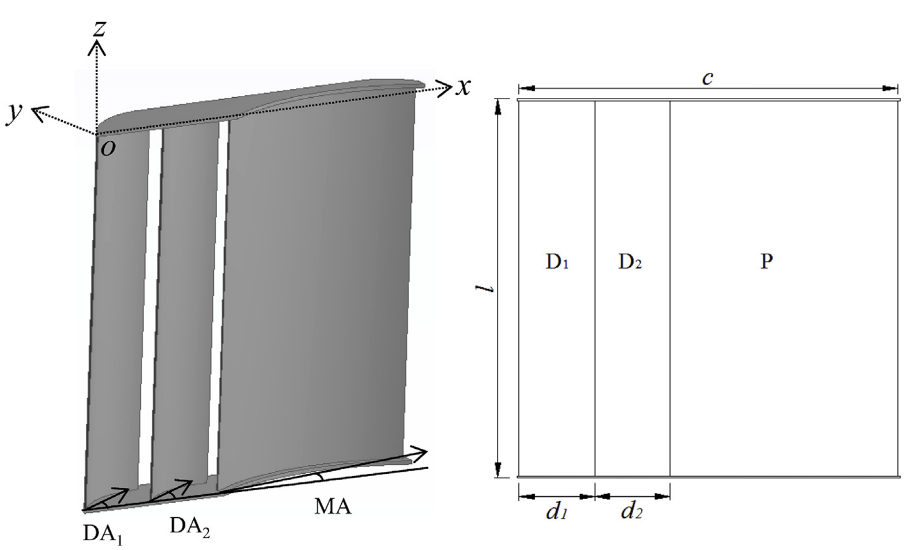

Fig. 1. Diagram of double-defector rectangular cambered otter board (coordinate frame was used to calculate center-of-pressure coefficients).