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Mathematical Modeling Of The Hydrodynamic Forces On A Vertical Cambered Slotted Otter Board

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Abstract. As an important accessory of single trawl, otter board directly affects net horizontal expansion, further the catching and fishing efficiency^[1-2]. For improving the fishing efficiency and technology level and solving the world energy crisis in some way, the hydraulic performance is chosen and the effects of different structural parameters are studied. Such as aspect ratio, curvature, bending and receding angle, deflector angle and slot width, number of slots and so on^[3-10]. This paper selects a vertical cambered slotted otter board as research object, presents a principle of hydrodynamic efficient based on the experiment data, then a mathematical model of the hydrodynamic efficient is obtained. This model has been found as a function of angles of attack and deflector, and is suitable for similar otter board design and optimization.

1. Introduction

Otter board is the important accessory of single trawl, and its hydraulic performance is important factor affecting catches and fishing efficiency, promoting the sustainable development of trawl fishing, solving the world energy crisis^[1-2]. The hydrodynamic force on otter board can be decomposed into two parts: drag and lift force. The lift force plays a role in expanding the trawl and increasing the sweeping. The lift and drag ratio is used to do the hydraulic evaluation. Developed fishery countries attach importance to the improvement of hydrodynamic performance in recent years.

There are two kinds of otter board hydrodynamics research: flume experiments were carried out on different types to discuss the influence of structural types differences; on the other hand, in order to optimize and improve the performance, the effects of different structural parameters are studied. Such as aspect ratio, curvature, bending and receding angle, deflector angle and slot width, number of slots and so on^[3-10].

A biplane-type otter board composed of a pair of ordinary cambered otter boards with the same size and shape was proposed by Fukuda, a series of flume experiments was carried out using 1:10 scale models. Lift force, drag force, lift-drag ratio and moment coefficients were measured with a three component balance at attack angles ranging from 0-70°. Investigated and compared with ordinary types, the maximum lift coefficient of a biplane type was nearly the same and the range of the attack angle was wider with higher lift force than ordinary type. This suggested that the former is hydrodynamically more efficient^[5-6]. Subsequently they carried out flume experiments on biplane type with different



aspect ratios and curvatures, measured the relationship between lift and drag force versus attack angle under different combinations of parameters, and discussed the influence of structural differences on the hydrodynamic performance. The results show that the aspect ratio has no effect on the maximum lift-drag ratio coefficient, but curvature has an effect on it^[11-12].

Park et al. studied the hydrodynamic performance experiment with different aspect ratios. The hydrodynamic coefficients of free flow and bottoming flow were measured, and the conclusion was that the larger aspect ratio, the smaller influence by bottoming on lift force. In 1995, they continued to study the hydrodynamic performance of different curvatures. It was concluded that, the lift coefficient was the largest when curvatures was 15% with less affected by bottoming. Subsequently, a flume experiment was carried out with different bending and receding angle. The results show that the influence of bending angle is not significant, but the lift coefficient is the largest when the free flow with 20° receding angle and bottoming flow with 10° receding angle^[7-9].

Zhang Xun et al. based on the survey data, combined with research, development and application experience, introduced the present situation of the use, research and development of otter board, and compares the hydrodynamic performances of six typical otter boards. Subsequently they carried out wind tunnel experiments on rectangular V-shaped curved otter board, obtained relationship between the curvature and the lift-drag ratio, the results showed the influence of curvature on moment coefficient and pressure center is very small. In addition, the influence of aspect ratio, slot location and slot width on hydrodynamic performance was also discussed, and the aspect ratio, slot position and width at the highest lift-drag ratio are obtained, and the optimum results are proved^[4-6].

In order to optimize the hydrodynamic performance of otter board by adjusting the deflector angle, Liu Jian et al. measured the lift, drag force and lift-drag ratio with three deflector angles of two vertical cambered slotted otter boards by flume model test. The results show that: for single-slot, the lift and drag force decrease with the increase of deflector angle when the attack angle is 20° ~35°. In the range of attack angle, the deflector angle of 35° has better hydrodynamic performance; for the double slots, with deflector angle 20° of the front deflector and 25° of the middle has better hydrodynamic performance when attack angle is 25°-35°^[13].

Rao xin et al. selected a low aspect-ratio curved otter board as research object, presented a method based on the flume experiment results and for mathematical modeling of the hydrodynamic forces on the otter board. These forces have been found as a function of angles of attack and slip. The coefficients are parameterized for smoothing and computational performance. A method is summarized for extending to the evaluation of arbitrary shape otter board and outside the normal operating. A verified by experiment results computational efficient model of the steady state hydrodynamic forces is finally proposed, suitable for trawl control system design and analysis^[14].

In this paper, a vertical cambered slotted otter board is selected as the research object. Based on the flume experiment data, the coefficients relationship with attack and deflector angle is obtained, mathematical model is established, and the accuracy is proved.

2. Material and Method

2.1. Flume experiment setup

The experiment was conducted in the recirculating water tank of the East China Sea Fisheries Research Institute. The scale of the experimental section is 180cm * 50cm * 50cm and the maximum flow velocity is 2.5m/s. The otter board model was located in the middle section of the flume, and connected with the three component force sensor. The sensor was fixed on the rotary table of the experiment tool, the angle of three direction component could be changed. The experiment setup is shown in Figure 1. The measuring instrument is LSM-B-500NSA1-P three component force sensor manufactured by the Japan electric power company. The measuring range is 500N, and the measuring data are recorded by computer.

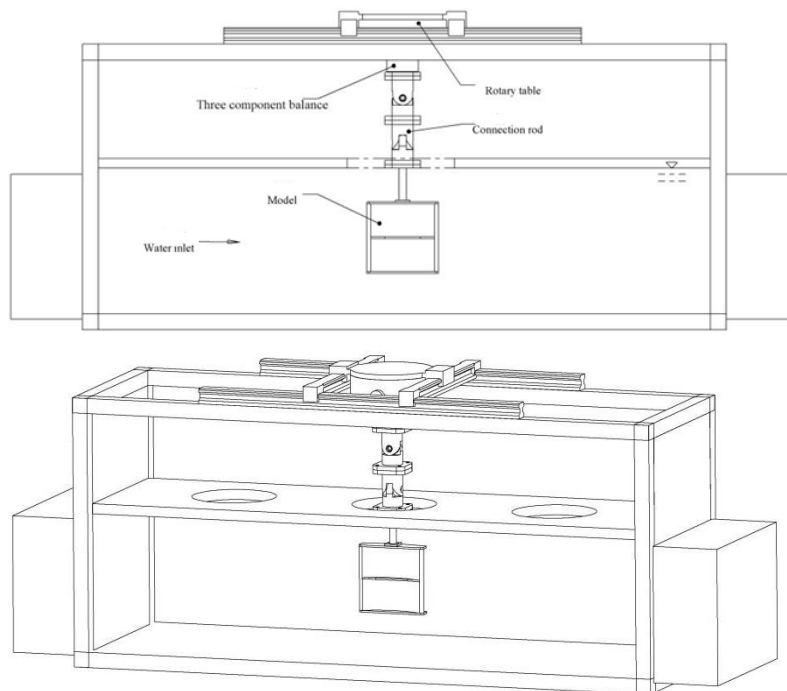


Figure 1. Flume experiment setup

2.2. otter board model

According to the similarity principle of fluid mechanics, the Reynolds similarity rule is adopted. The Reynolds number of the otter board model equals to the object. The model is made of stainless steel with a thickness of 2mm.

The sketch map of otter board model is outlined in Figure 2, and the deflector angle is shown as Figure 3. The structural parameters of otter board and experiment factors are defined as Table 1.

Table 1. Otter board model structural parameters and experiment factors

Factor	Level
Deflector angle	35°; 40°; 50°
Angle of attack	0°; 5°; 10°; 15°; 20°; 25°; 30°; 35°; 40°; 50°; 60°; 70°
Flow velocity	20cm/s, 40cm/s, 60cm/s, 80cm/s, 100cm/s, 120cm/s
Model	vertical cambered slotted
Scale	1: 20
Chord length(cm)	9.2
Aspect ratio	2.8
Area(m ²)	0.024

2.3. Experimental conditions

The experimental velocity range is 20cm/s-120cm/s. In the experiment, when the Reynolds number is less than a certain value, with the increasing of the Reynolds number, the hydrodynamic coefficients present a disorder situation. After this stage, hydrodynamic coefficients basically keep almost stable called automatic model region. The hydrodynamic coefficients measured in the area is averaged, the results are discussed in this paper.



Figure 2. Sketch map of otter board model

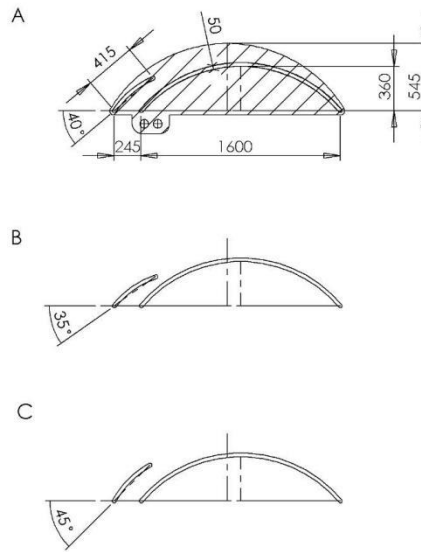


Figure 3. The setup of deflector angles for the experiments

3. Otter board hydrodynamic properties results

3.1. Flume experiment results

The hydrodynamic coefficients of three components are calculated as^[15]:

$$C_i(\alpha, \beta) = \frac{f_i(\alpha, \beta)}{0.5 \rho_w A_m U_m^2}, i=1,2,3 \quad (1)$$

Where α is attack angle, β is deflector angle, ρ_w is the water density, A_m is the otter board area, U_m is the flow velocity, f is measured hydrodynamic force, subscript m means model.

$$C_L(\alpha, \beta) = \frac{(f_1(\alpha, \beta) \cos \beta + f_3(\alpha, \beta) \sin \beta) \cdot \cos \alpha + \sin \alpha f_2(\alpha, \beta)}{0.5 \rho_w A_m U_m^2} \quad (2)$$

$$C_D(\alpha, \beta) = \frac{(f_1(\alpha, \beta) \cos \beta + f_3(\alpha, \beta) \sin \beta) \cdot \sin \alpha + \cos \alpha f_2(\alpha, \beta)}{0.5 \rho_w A_m U_m^2} \quad (3)$$

$$K(\alpha, \beta) = \frac{C_L(\alpha, \beta)}{C_D(\alpha, \beta)} \quad (4)$$

The measured hydrodynamic coefficients (lift, drag and lift-drag ratio) are shown in Figs 4–6, according to equations (2)–(4)^[15].

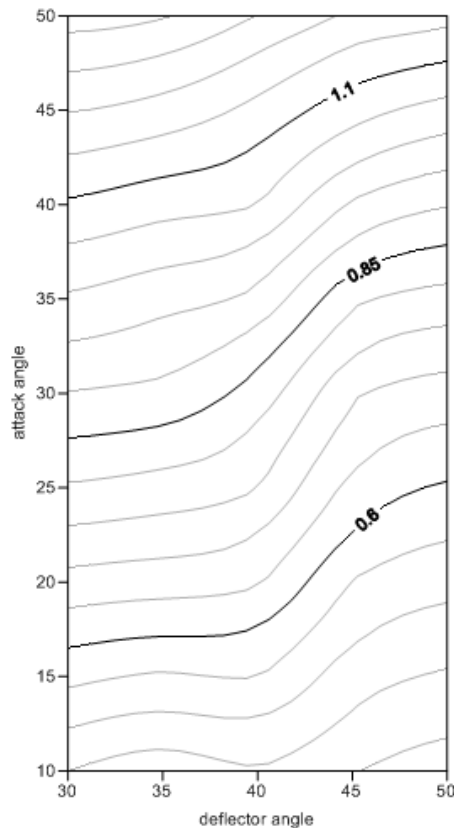


Figure 4. Measured drag force coefficient C_D for varying angles of deflector and attack

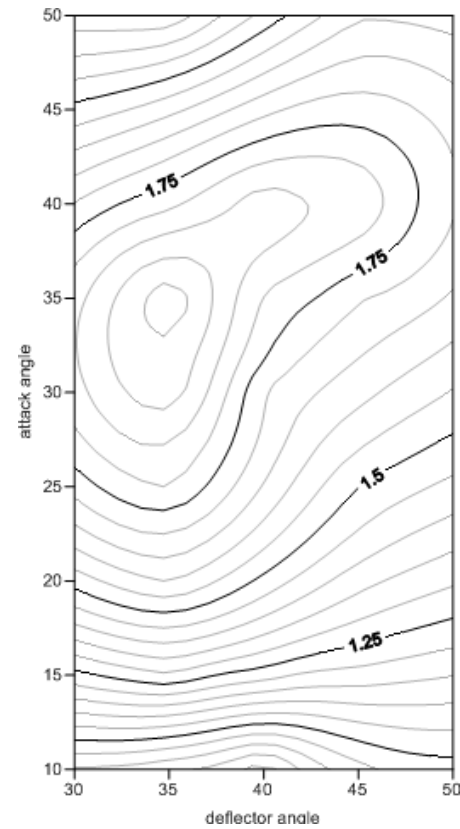


Figure 5. Measured lift force coefficient C_L for varying angles of deflector and attack

Figure 5. shows the lift force coefficient of the model for varying angles of deflector and attack. When attack angle is less than 15° , deflector angle has fairly no impact on lift force coefficient; when attack angle is between 15° - 35° , lift force coefficient decreases slightly at first then sharply increases; when attack angle is greater than 35° , lift force coefficient increases firstly then decrease. The fluctuation in is comparatively stable. The maximum value is approximately 1.983 when attack angle is 35° and deflector angle is 35° .

Figure 4. shows drag force coefficient of the model for varying angles of deflector and attack. The drag coefficient is linearly increases with attack angle. For a given attack angle, drag coefficient increases slowly with deflector angle increasing and approaching to 40° , then rise rapidly. For the combination angles with maximum lift force 1.983 (attack angle= 35° , deflector angle= 35°), the drag coefficient is approximately 0.965, the calculated lift-drag ratio $k = 1.983/0.965 = 2.055$.

Figure 6. shows lift-drag ratio of the model for varying angles of deflector and attack. Lift-drag ratio increases firstly then decreases with attack angle increasing. Deflector angle has small influence on lift-drag ratio. For combination angles with drag force 0.315 and lift force 0.797 (attack angle= 5° , deflector angle= 45°), the maximum lift-drag ratio 2.530 is obtained.

It could be seen that both the deflector and attack angle are very important to operation control, means these two parameters are significant to optimization and design for the otter board.

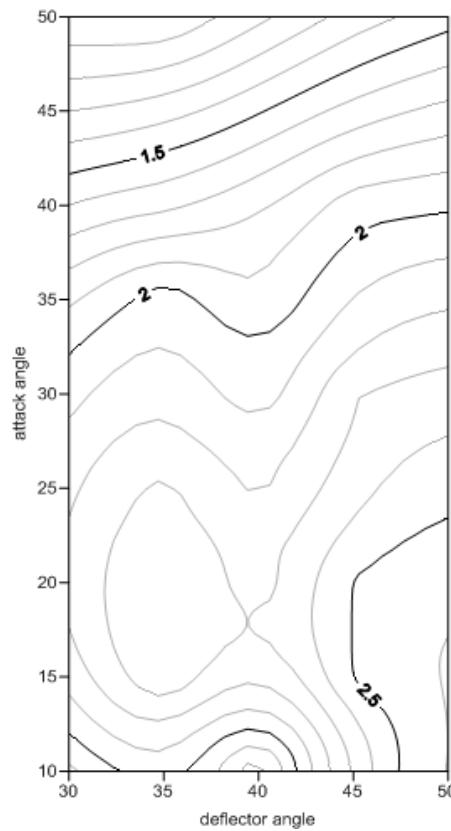


Figure 6. Measured lift and drag ratio K for varying angles of deflector and attack

Figure 7. shows the maximum profile of lift force coefficient C_L . The maximum lift coefficient appears with the attack angle in the range of 30° - 40° . The maximum lift coefficient shows an uptrend before the deflector angle approach to 35° , then stay stable. The maximum value is 1.983. Figure 8. shows the maximum profile of lift-drag ratio K. The maximum drag-lift ratio shows an uptrend with increasing of deflector angle, although there are some fluctuations. The ratio shows a downtrend with increasing of attack angle. The maximum value is 2.610 when deflector angle is 60° .

3.2. Parameterization of hydrodynamic Coefficients

The main purpose of the paper was to propose a mathematical model based on the flume experiment results for evaluating the otter board hydrodynamic performance.

In this paper, Matlab software is used to propose a mathematical model based on the flume experiment results. The fitting curve function is used and the formulation is obtained, the coefficients are parameterized, then the model could be used for evaluating the otter board hydrodynamic performance. The accuracy of experiment data is important to accuracy of evaluation model.

The parameter functions $\hat{C}_{r,in}$ return the three coefficients as a function of attack angle, deflector angle, and a constant matrix M, which needs to be optimized to reflect the experimental data as well as possible.

For each vector, a candidate object function is proposed to be:

$$O_i = \hat{C}_{in}(\alpha_n, \beta_n, \hat{M}_i) - C_{in} \quad (5)$$

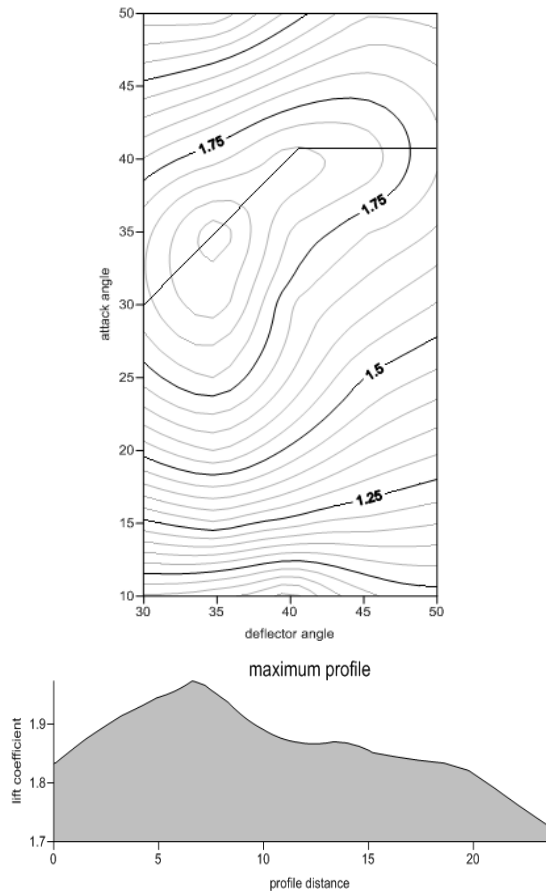


Figure 7. The maximum profile of measured lift force coefficient C_L

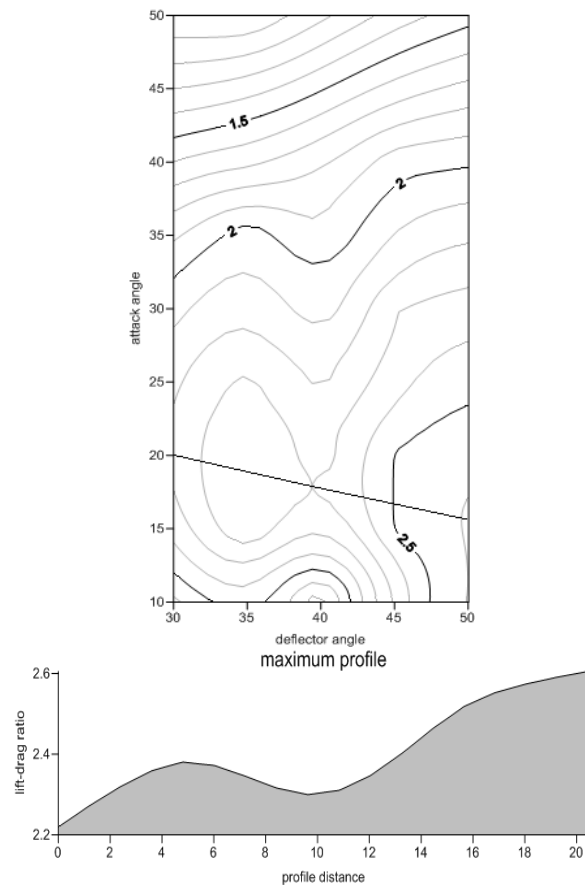


Figure 8. The maximum profile of measured lift-drag ratio K

Where C_{in} is the measurement n of the coefficient i , \hat{C}_{in} is the calculated coefficient i for this measurement, and M is the row of constant matrix that gives the lowest value of the object function of each vector.

The fitting formulation is inserted into functions, the coefficients can be calculated as shown :

$$\begin{aligned} \hat{C}_{r,in}(\alpha_{in}, \beta_{in}, K_{r,in}^{opt}) = & p_{00} + p_{10}\alpha_{in} + p_{01}\beta_{in} + p_{20}(\alpha_{in})^2 \\ & + p_{11}\alpha_{in}\beta_{in} + p_{02}(\beta_{in})^2 \end{aligned} \quad (6)$$

where the matrix M is shown as:

$$K_r^{opt} = \begin{bmatrix} -1.738 & 0.1068 & 0.0204 & -0.0014 & -0.0001 & 0.0001 \\ 2.277 & -0.1049 & 0.088 & 0.001 & 0 & -0.0012 \\ 10.94 & -0.4904 & 0.0554 & 0.0066 & -0.0005 & -0.001 \end{bmatrix} \quad (7)$$

Figure.9 shows the parameterized coefficients surface and the experiment results. Based on the parameterized model, $R^2 = 0.994; 0.936; 0.872$ in proper order.

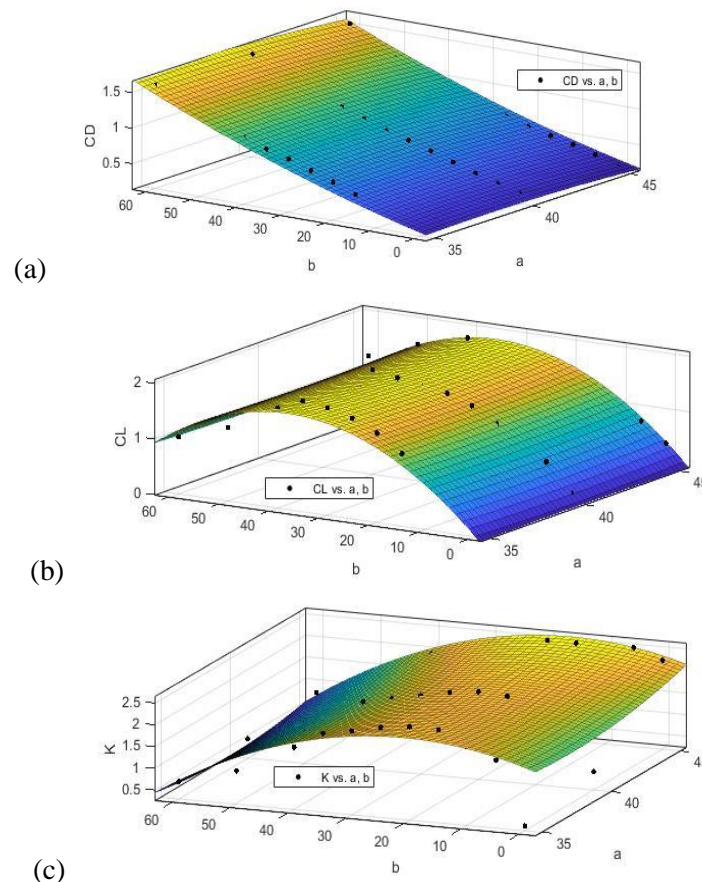


Figure 9. The comparison of parameterized coefficients model and the experiment results

4. Discussion

The proposed parameterized coefficients model in this paper can be used to estimate the hydrodynamic parameters performance of vertical cambered slotted otter board. It is helpful for optimization and design. If the number of slot increases and the deflector angle is different, the number of parameters needs to be added in the estimating model. Therefore, the accuracy of single-slot model will be slightly inadequate. In this paper, the three component force sensor is used in the experiment. If it is necessary to estimate the shear force or moment-related coefficient data, the data is not enough. This is also the direction of our future work.

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