Studies on mechanical matching calculation of low aspect ratio vertical cambered otter board in trawl system under heeling

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Abstract. In this paper, for obtaining the influence of otter board heeling condition, a trawl system mechanical matching calculation model was established based on the equilibrium equation of otter board and tension equation of wrap, a widely used low aspect ratio vertical cambered otter board was selected, based on the hydrodynamic performance experiment data, combining with the data of Longteng vessel and four patch and big mesh size mid water trawl experiment results, mechanical calculation and analysis under heeling condition was conducted, the attack angle, warp tension and length, net depth, horizontal drag force and other trawl system parameters were obtained. The influences of otter board parameters under heeling condition were analyzed, the rules of mechanical matching calculation under heeling were summarized, it was proved that: warp tension and net depth increases with the increase of outward heeling angle, the range was separately 18145N-18225N and 51.2m-52.4m; decreases with the increase of inward heeling angle; the range was separately 49.6m-51.2m and 18069N-18145N.

1. Introduction
Chinese pelagic fishery started from trawl in the West African coast in 1985, and has been developing for more than 30 years. During this period, the operating sea area and fishing varieties have been continuously expanded, the total fishing output and scale have maintained stable growth. China has become an important pelagic fishery country in the world, however, we still face many challenges and bottlenecks. The backward of equipment and technology level is the restrictive factors for the development of Chinese pelagic fishery[1]. Taking the important accessory of trawl, otter board as an example, the hydrodynamic performance of the otter board directly affects the catch, fishing efficiency and energy consumption[2-3]. Since the 1970s, the advanced fishing countries have begun to pay attention to and carry out the research on the hydrodynamic performance of the otter board, and developed a variety of otter board with good hydrodynamic performance and better stability[4-5]. At present, most of the otter board used by large trawl are imported from Iceland, Denmark, Japan and other developed countries, such as vertical V-shaped curved otter board and rectangular V-shaped curved slotted otter board[2-3]. However, due to the differences in the structure of the introduced otter board, the fishing operation will be carried out on the basis of the lack of the performance data. No
matter in the selection of the matching or the optimization of the otter board in the future, there will be a lack of theoretical basis\cite{2-3}. Therefore, domestic scholars have carried out wind tunnel and flume experiments on the hydrodynamic performance. X Zhang et al.\cite{6} selected rectangular V-shaped curved otter board for wind tunnel experiment, and established the relationship between the curvature of the guide plate, slit parameters and lift drag ratio. J Liu et al.\cite{7} have carried out experiments and summarized the relationship between the steady-state hydrodynamic performance parameters and the attack angle, and discussed the hydrodynamic performance under the condition of heeling.

At present, most of the research of the otter board performance is independent. However, in the actual fishing operation, the otter board, trawl and vessel work together, and the single mechanical analysis can not reflect the overall matching operation. Therefore, it can not be ignored to calculate the mechanical coordination of the three in advance. X W She\cite{8} for the first time constructed the overall mechanical matching model of the three. Assuming that the trawl conditions are known, the cable tension parameters are summarized according to the experiment, the cable tension equation is established to solve the stress condition, the balance equation of the otter board is established to solve the working state, and the warp tension at the joint point meets the requirement of the vessel data. In the actual operation of trawling system, it is sometimes necessary to adjust the heeling angle and tilt angle of the otter board to change the operation depth and wrap force. X W She\cite{9} also constructed the mechanical coordination model of the trawl, vessel and otter board under the heeling condition, analyzed and calculated the force of the otter board in various heeling states, and discussed the influence of the heeling angle on the operation state. In this study, a widely used vertical curved otter board with small aspect ratio is selected, the Longteng vessel and a four patch and big mesh size mid-water trawl is taken. Combined with the data of the three, in this paper it is simulated of several working states of no heeling and heeling, the relationship between various working parameters is discussed, and the influence of heeling on the working state and the range of heeling are discussed, so as to provide the basis for the matching and practical application.

2. Material and method

2.1. Coordinate setting

In this study, it is necessary to set the coordinate system for the trawl system according to different condition\cite{9}. The coordinate system setting under the condition of no heeling is shown in Figure 1(a), the coordinate system setting under the condition of heeling is shown in Figure 1(b). As can be seen in Figure 1(a), in the state of no heeling, the joint point between the trawl and the bridle is the origin of the coordinate system, the advance direction is the direction of X axis, the direction of vertical upward is the direction of Y axis, and that perpendicular to X and Y axis is the direction of Z axis. The midpoint of the chord $O_1$ is the origin of the $O_1X^1Y^1Z^1$ coordinate system, the $O_1X^1$ axis is perpendicular to the chord, the $O_1Z^1$ axis is in the same direction with the chord, and the $O_1Y^1$ axis is perpendicular to $O_1X^1$ and $O_1Z^1$. In addition, the coordinate system $O_1X^1Y^1Z^1$ is set for the origin $O_1$, which is in the same plane as the coordinate system $O_1X^1Y^1Z^1$, and each coordinate axis is parallel to each corresponding coordinate axis of the coordinate system $OXYZ$. As can be seen in Figure 1 (b), when the heeling occurred, it can be regarded as the rotation angle $\theta$ of the otter board around the axis. Therefore, a coordinate system $O_1X^1Y^1Z^1$ is added on the basis of $O_1X^1Y^1Z^1$, and $O_1X^1Y^1Z^1$ coordinate systems. The geometric symmetry axis of the otter board is axis $O_1Y^1$, the axis $O_1Z^1$ and $O_1Z^1$ have the same direction, and the axis $O_1X^1$ is perpendicular to $O_1Y^1$ and $O_1Z^1$.
2.2. Basic equations

According to the tension of the trawl, the tension of the joint point between otter board and bridle is calculated by the cable tension equation, and the tension of the joint point between the otter board and wrap is calculated by the otter board balance equation. Finally, the tension of the joint point between the vessel and the wrap is calculated. If the horizontal drag force of the vessel and the position of the joint point between the wrap and vessel are consistent with the vessel data, the mechanic matching is successful.

The calculation equation of cable tension shows as follows[10]:

\[
\text{equation}
\]
\[
\begin{align*}
\frac{dx}{ds} &= \sqrt{1 - \cos^2 \beta - \cos^2 \gamma} \\
\frac{dy}{ds} &= \cos \beta \\
\frac{dz}{ds} &= \cos \gamma \\
\frac{dT}{ds} &= \pm \{0.6778k_D(1 - \cos^2 \gamma - \cos^2 \beta)^{0.5166}\left[\frac{\cos^{2.3415} \beta + \cos^{2.3415} \gamma}{\sin^{1.0238} \gamma + \sin^{1.0238} \beta}\right] \\
&- k_D \sqrt{1 - \cos^2 \gamma - \cos^2 \beta}[0.9383 - 0.5452(1 - \cos^2 \gamma - \cos^2 \beta)] - p \cos \beta\}
\end{align*}
\]

When solving the above equation, if the wrap tension and other data are known, the tension and coordinate of the wrap can be calculated from the joint point of the vessel and wrap; if the drag force and other data at joint point to the water surface can be calculated. In this study, the tension and angle of the trawl obtained through the model experiment are taken as the initial value of the bridle. From this point to the joint point between the bridle and the otter board, the tension and angle of the bridle are obtained according to the cable tension equation, and then the tension and angle of the joint point between the wrap and otter board can be calculated by the otter board balance equation, finally the state of wrap is obtained.

It should be noted that due to the slightly different on the otter board of no heeling and heeling, different balance equations should be used in different states. The balance equation under no heeling state shows as equations (2)[8].

If inward heeling occurs[9], in the equations(3), the second equation takes plus sign and the fourth, sixth takes minus sign, if else, the sign is opposite. Where, \( \rho \) is the fluid density, \( V \) is the velocity of motion, \( d \) is the cable diameter, \( T \) is the cable tension, \( \beta \) and \( \gamma \) is the angle of T between Y and Z axes.

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If inward heeling occurs[9], in the equations(3), the second equation takes plus sign and the fourth, sixth takes minus sign, if else, the sign is opposite. Where, \( T_\alpha \) is the tension at the joint point between bridle and otter board, and the included angles with the X, Y and Z axes are respectively \( \alpha_k, \beta_k, \gamma_k \); \( T_\beta \) is the tension at the joint point between wrap and the otter board, and the included angles with the X, y and Z axes are respectively \( \alpha, \beta, \gamma \); \( R_{BR} \) and \( R_{BR} \) are X and Y axes component forces of the otter board hydrodynamic force acting on the hydrodynamic center; \( G \) is the self weight of the otter board in the water, \( P \) is the hydrodynamic action point of otter board, and \( g \) is the self weight action point of the otter board.
When the trawl, the otter board and the vessel cooperate successfully, the distance between the two joint points of wrap and vessel must be equal to the distance between the pulleys of the wrap, and the maximum drag force of the vessel must be greater than or equal to the sum of the horizontal drag forces at the joint point [8]

\[ T_A \cos \alpha_A - T_K \cos \alpha_K - R_{Bx} = 0 \]
\[ T_A \cos \beta_A - T_K \cos \beta_K - G = 0 \]
\[ -T_A \cos \gamma_A - T_K \cos \gamma_K + R_Z = 0 \]
\[ G(z_A - z_G) - R_{Bz}(y_A - y_P) - T_K \cos \beta_K(z_A - z_K) + T_K \cos \gamma_K(y_A - y_K) = 0 \]
\[ R_{Bz}(x_A - x_P) - R_{Bz}(z_p - z_A) - T_K \cos \gamma_K(x_A - x_K) + T_K \cos \alpha_K(z_A - z_K) = 0 \]
\[ G(x_A - x_G) - R_{Bz}(y_A - y_P) + T_K \cos \beta_K(x_A - x_K) - T_K \cos \alpha_K(y_A - y_K) = 0 \]

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\[ Z_A - Z_B = \frac{L_0 - L_B}{2} \]
\[ P \geq 2T_B \cos \alpha_B \]

The z-coordinate of the joint point B between the vessel and wrap is \( z_B \), the z-coordinate of the joint point A between the otter board and the wrap is \( z_A \), \( L_0 \) is the distance between two otter boards, \( L_B \) is the distance between pulleys of wrap, \( P \) is the maximum drag force of the vessel, \( T_B \) is the tension of the joint point between the wrap and vessel, and \( \cos \alpha_B \) is the tension included angle with \( x \)-axis at the joint point of the wrap and vessel.

2.3. Initial parameters

According to the known data, the target otter board area is \( 1 \text{ m}^2 \), the weight in water is 1875N, and other parameters are shown in Figure 2 and 3. The drag speed is 2Kn, the length of the bridle is fixed to 100m, the diameter is 25.5mm, and the weight in water is 19.17N/m. Wrap length is variable, its diameter is 32.5mm, and its weight in water is 31 \( N/m \) [11].

The coordinates of the action points of the forces acting on the otter board (when heeling) are as follows, and the unit is m:
Gravity action point g: \( x_g = -0.05 \), \( y_g = 0.5 \), \( z_g = 0 \)

Hydrodynamic action point P: \( x_p = 0 \), \( y_p = 0.5 \), \( z_p = 0 \)

Wrap action point A: \( x_A = -0.075 \), \( y_A = 0.5 \), \( z_A = 0.15 \)

Bridle action point K: \( x_K = -0.16 \), \( y_K = 0.5 \), \( z_K = -0.4 \)

In practical application, the bridle is connected with the otter board through cross rope. In this study, in order to simplify the action point, the midpoint of the cross rope joint is regarded as the bridle joint point, and the tension acts on the joint point directly. The hydrodynamic action points refer to the Reite method[12], which are set at half the height above the origin of otter board coordinate system, and other action points are obtained from the structural data. The difference between \( y_k \) and \( y_k' \) is \( DH = 0.5m \), the trawl wing horizontal expansion \( L_N = 30m \), the distance between pulleys of the vessel \( L_p = 19m \), the resistance at one end of the trawl wing \( T_0 = 15753.6N \) when the drag speed is 2.0kn, and the included angle with Y axis is 89° and that with Z axis is 50° [14]. The resistance coefficient curve of otter board was obtained by flume experiment, which was completed in the Key Laboratory of east China sea and pelagic fishery resources development and utilization, Ministry of Agriculture of China[15].

Figure 2. Sketch map of otter board

Figure 3. Hydrodynamic performance curve of otter board

3. Results and analysis

3.1. Results of no heeling

According to the above initial parameters, the force equation and corresponding coordinate system of the otter board under the condition of no heeling was used, and 0.1m/step was used to calculate the bridle, the tension at joint point between bridle and otter board is 16218N, and the tension included
angles with X, Y, Z axes are 38.9 °, 78.2 ° and 53.5 °. According to the calculated tension, the tension at joint point between wrap and of the otter board is 17035N, and the included angles with X, y and Z axes are 36.3 °, 72.3 ° and 59.5 ° respectively. Then, taking the tension at the joint point of the wrap and otter board as the initial value, the step length of 0.1 M was used. the tension between the wrap and vessel is 18145N, and the included angles with the X, y and Z axes are 38.0 °, 65.3 ° and 117.0 °. Other trawl system parameters calculated are shown in Table 1.

| otter board attack angle(°) | 44.7 |
|----------------------------|------|
| wrap length(m)             | 141.1|
| net depth(m)               | 51.2 |
| wrap tension(N)            | 18145|
| wrap horizontal angle(°)   | 38.0 |
| horizontal drag force(N)   | 14291|

### 3.2. Results of heeling

When the otter board was under the heeling condition, the force equations and corresponding coordinate system under heeling were adopted. Other initial settings were the same as no heeling. The trawl system parameters were obtained and the results were shown in Figure 4. It can be seen from the figure that when the otter board heeled inward, the tension at the joint point between wrap and otter board changes due to the otter board is not in the vertical state, and decreases from 17035n to 16988n with the increase of the included angle. After the tension transmission of wrap, the wrap tension at the vessel side also decreases from 18145n to 18069n with the increase of the included angle, and the required length of the wrap decreases accordingly. At the same time, due to the decrease of the angle between wrap and the trawl, the horizontal drag force decreases rapidly, and the range is 14292n-14277n. On the contrary, when the otter board heeled outward, the tension at the joint point between wrap and otter board increases from 17035n to 17092n with the increase of the included angle. The vessel side tension increases from 18145n to 18225n, and more wrap length are needed to achieve mechanical balance. However, due to the decrease of the included angle between the wrap and trawl, the increasing trend of horizontal tension slows down from 14292n to 14295n.
Figure 4. The wrap tension, horizontal drag force and wrap tension of junction versus different heeling angle

4. Discussion
In the condition of heeling, it is difficult to maintain the optimal expansion of the otter board[12], and the main engine of vessel is also difficult to give full power[12]. Since the importance of the heeling influence on the working state of trawl system, the working state of heeling in this study is analyzed. It is found that the influence of the heeling is mainly reflected in two aspects[12]: the change of the wrap tension and the impact on the vessel energy consumption; the change of the trawl depth and the impact on the working layer.

4.1. Influence of heeling on vessel energy consumption
The increase of heeling outward angle will lead to the increase of wrap tension, which will lead to the increase of vessel power; while the increase of heeling inward angle will reduce the wrap tension, but at the same time, due to the reduction of the wrap length, it will lead to the floating of the working layer of the trawl, so it is necessary to increase the wrap length and indirectly increase the power required. It can be seen that with the increase of heeling angle, the working state of the whole trawl system will be affected, resulting in unnecessary power waste.

4.2. Influence of heeling on working layer
In order to ensure the trawl works in the appropriate layer and target the fishing objects more effectively, it is necessary to adjust and control the trawl to reach the predetermined water layer, while the heeling will cause the change of working layer, which will affect the fishing efficiency.

In this study, the variation of the trawl depth is as follows: in the vertical state, the depth is 51.2m; when the heeling occurs and the heeling inward angle is in the range of 0-15 °, the depth decreases with the increase of the heeling angle, and the variation range is 51.2m-49.6m; when the heeling outward angle is within 0-15 °, the depth of increases with the increase of the heeling angle and the range is 51.2m-52.4m. In the actual operation, if the trawl depth changes, the heeling outward angle should be reduced if the trawl needs to float up; if the trawl depth needs to be reduced, the inward heeling angle should be reduced.

Acknowledgments
The authors would like to thank the support of National Key R&D Program of China (2018YFC1406803), Clean coasts by harvesting and reusing bloomed jellyfish at right time point(2017YFE0111100) and Natural Science Foundation of China project Youth fund (31402351)

References
[1] Cui, L.F., Xu, L.X., Zhu, G.P., et al. (2011) A survey of the world's Oceanic Fisheries.Ocean Press, Beijing, 1-189.
[2] Xu, B. S., Zhang, X., Wang, M.Y. (2010) A review on the trawl otter board evolution. Journal of Fujian Fisheries, 3(1): 86-90.
[3] Zhang, X., Wang, M.Y., Xu, B.S. (2004) A primary study on type, structure and performance of trawl otter board. Journal of Fishery Sciences of China, 11( suppl.1) : 107 -113.
[4] Yamasaki, S., Matsushita, Y., Kawashima, T., et al. (2007) Evaluation of a conventional otter board used in trawl fishery in Ise-wan Bay and proposal of a new design. Nippon Suisan Gakkaishi, 73(2): 220.
[5] Fukuda, K., Fuxiang, H., Tokai, T., et al. (1999) Effects of aspect and camber ratios on hydrodynamic characteristics of biplane-type otter board. Nippon Suisan Gakkaishi, 65(5): 860-865.
[6] Xu, B.S., Zhang, X., Yu, Y.F., et al. (2006) A comparative test of the rectangular V-type curved otter Board and V-type curved otter at sea. Ocean fishery, 28(1): 66-70.
[7] Liu, J., Huang, H.L., Chen, S., et al. (2014) Model test of the hydrodynamic characteristics of two vertical cambered V type otter boards. Chinese Journal of Hydrodynamics, 29(2): 183 -188.
[8] She, X.W. (1986) The mechanical calculation of the match of trawl board, trawl and trawler. Journal of Zhejiang Fishery Academy, 5(1): 21-35.
[9] She, X.W. (1988) Mechanical calculation relating to the inclination of the otter board. Journal of Zhejiang Fishery Academy, 7(2): 83 -98.
[10] She, X.W., Yu, C.D., Hu, F. X. (1984) A calculation of the configuration and tension of the warp. Journal of Zhejiang Fishery Academy, 3(2): 167 -177.
[11] Huang, X.C. (1990) Marine fishing manual. Chinese Agricultural Press, Beijing, 180 -202.
[12] Reite, K.J., Sorensen, A.J. (2006) Mathematical modeling of the hydrodynamic forces on a trawl door. Oceanic Engineering, 31(2): 432-453.
[13] Feng, C.L., Huang, H.L., Zhou, A.Z., et al. (2012) Performance optimization of a trawl for Antarctic krill. Journal of Fishery Sciences of China, 19(4): 662 -670.
[14] Rao, X., Huang, H.L., Liu, J., et al. (2015) Studies on mechanical matching calculation of vertical cambered V type otter board in trawl system. Journal of Fisheries of China, 39(2): 284 -293.
[15] Liu, J., Huang, H.L., Chen, S., et al. (2013) Hydrodynamic characteristics of low aspect ratio vertical cambered otter board. Journal of Fisheries of China, 37(11): 1742 -1749.