Pelagic longline fishing operation parameters optimization ——A case study on targeting bigeye tuna (*Thunnus obesus*) in the Indian Ocean

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Abstract: In longline fisheries, the habitat and the preferred water layer of the target species should be understood to improve the efficiency of fishing, and the hook depth need to be accurately controlled to set the hooks at the preferred depths of the target species as far as possible. In this paper, the theoretical depths of hooks (D_δ) were calculated by catenary formula. The environmental data, *e.g.* wind speed (V_w), gear drift velocity (V_g), angle of attack (Q_w) (the angle between the prevailing course in deploying the gear and direction that the fishing gear was drifting), and the wind angle (γ) (the angle between the direction of the wind and the prevailing course in deploying the gear), and operation parameters, *e.g.* line shooting speed (V_1), vessel speed (V_2), the number of hooks between two floats (N_b), and time interval (t) between two hooks, were collected and the actual hook depth (D_f) were measured on the longliners Huayuanyu No.18 and Huayuanyu No.19 in 2005 and the longliner Yueyuanyu No.168 in 2006. The length of float line was 22 m, and the length of branch line was 16 m. The relationship model between the independent variables (D_δ, V_w, V_g, $sinQ_w$, $sin\gamma$, the hook position code (denoted as δ)) and the actual hook depths (D_f) as dependent variable was built by multiple stepwise regression and the predicted hook depth ($D_\delta{}'$) was calculated by this model. In this paper, applying the built hook depth prediction model, Matlab software was used to programme the operation parameter optimization when V_1, V_2,γ , Q_w, N_b and t were 6-7m/s, 4-5m/s,0-90°,0-90°,23-27,6-8s into the prediction hook depth model, the range of operating parameters (V_1, V_2,γ , Q_w and t) were filtrated to maintain the distribution frequency of the hooks reaching to bigeye tuna preferred water layer (140-240m) to the largest percentage. The results show that: 1) the predicted hook depth model was: $D_\delta{}' = D_\delta \times (0.974 + 0.097\,sin\,Q_w - 0.203\,sin\,\gamma - 0.018\delta)$; 2) the percentage of the hooks at water layer of 140m-240m was ranged from 73.9% to 77.8% (N_b=23-27), with the smallest percentage (73.9%) at N_b=23 and the largest percentage (77.8%) at N_b=27; 3) when the percentage was the largest (77.8%) (N_b=27), the corresponding range of V_1, V_2,γ , Q_w and t were 6-7m/s, 4.4-5m/s,0-90°,0-90°and 6-8s respectively. This paper suggested that 1) the hook depth could be predicted more accurately by multiple stepwise regression; 2) this study method could be used for optimizing pelagic longline operation parameters and improving the fishing efficiency; 3) when targeting the bigeye tuna, it was suggested that N_b should be 27, and other operation parameters should be adjusted according to actual sea conditions; 4) Optimizing the depth of hooks according to this study will help to reduce bycatch of sharks and turtles, etc.

1 Introduction

The depth of the longline hooks affects the species composition and length composition of the catch. Accurate capture depth can improve the accuracy of analysis of vertical distribution, habitat preference and resource assessment of marine species and improve fishing efficiency (Boggs, 1992; Bigelow, 2006). Many experiments have been carried out to establish more accurate models for calculating the depth of the hook or to predict the shape of the longline under water. Mizuno et al. (1998) studied the fluctuation of shortening ratio of longline fishing and its influence on underwater shape of longline fishing. Mizuno et al. (1999) used the micro-temperature depth recorder to measure the underwater shape of the longline fishing gear. But the above two studies could not directly predict the shape of the main line by taking the influence of actual wind and flow as the input of calculation. Wan et al. (2002; 2005) analyzed the static shape and force of the longline fishing gear by the model test and numerical simulation, but the theoretical calculation was limited to the steady sea current and the fixed shortening ratio. Wan et al. (2004) measured the shape of the longline fishing gear model under stable sea current and fixed shortening ratio to study its performance, but failed to obtain the calculation model of the depth of the hook. Lee et al. (2005) used tank model test and numerical simulation to analyze the shape and stress distribution of the longline fishing gears taking into account the current as constant and failed to take into account the longline fishing gears in different layer might be affected by different currents. Miyamoto et al. (2006) used ultrasonic positioning system and communication satellite buoys to measure the 3D shape of tuna longline fishing gear underwater, and it was concluded that this technique could effectively record 3D shape of the underwater fishing gear, especially to real-time measurement for the depths of the rope. However, there was still a technical problem in this experiment that was impossible to measure the change of the shape of the longline over time, and it was impossible to obtain the calculation model of the depth of the hooks. Bigelow et al. (2002) applied Logistic regression to obtain the calculation formula of actual hook depth under different surface currents based on the data of Japanese fishing vessels operating in the Pacific Ocean. Bigelow et al. (2006) used GLM and GAM model to analyze the relationship between the actual depth, the theoretical depth, the force of wind, the current shear and current velocity (data from OCGM model), but the spatial resolution of these factors was 1°, temporal resolution for a week or a month. Song and Gao (2006) studied the relationship between measured hook depths and theoretical hook depths by taking into account gear drift speed, angle of attack (the angle between the prevailing course in deploying the gear and direction that the fishing gear was drifting), the wind angle (the angle between the direction of the wind and the prevailing course in deploying the gear), wind speed and wind direction, and obtained relatively ideal results (R = 0.748). Song et al. (2011, 2019) predicted the depth of the hook, the shape of the main line and the force using the numerical simulation method.

The above researchers built various models to adjust the theoretical depths of hooks, and few studies optimize the actual operating parameters of fishing vessels to improve the fishing efficiency. In this paper, a total of 609 sets of the operation parameters and the marine environment data were collected by the tuna longline fishing vessels with a super spool machine in the Indian Ocean in 2005 and 2006. The hook depth calculation model of long line in the Indian Ocean was established taking into account the gear drift speed (V_g), wind speed (V_w), wind direction (C_w), the wind angle (γ), angle of attack (Q_w) and the hook number (δ) as the impacts of the hook depth. The operating parameters including the wind angle (γ), angle of attack (Q_w), the number of hooks between two floats (N_b), line shooter speed(V_1), speed of the vessel (V_2), and the time interval between deploying the fore and after branch lines (t) were optimized to maximize the distribution of depths of hooks in bigeye tuna preferred water layer (140-240m) (Song et al., 2009) in order to increase the catch rate of bigeye tuna and reduce the bycatch of other species.

2 Materials and methods

2.1 Survey content and methods

Fishing vessels were targeting bigeye tuna, and the bycatch included yellowfin tuna (*Thunnus albacares*), swordfish (*Xiphias gladius*), albacore (*Thunnus alalunga*), and billfishes (*Istiophoridae*).

Data were collected from operations on three longliners *e.g.* Huayuanyu No.18 and Huayuanyu No.19 in 2005 and the longliner Yueyuanyu No.168 in 2006. The longliners Huayuanyu No.18 and Huayuanyu No.19 had the identical specifications, with overall length of 26.12 m, registered beam of 6.05 m, registered depth of 2.70 m, gross tonnage of 150 t, net tonnage of 45 t, and main engine power of 407 kW. The longliner Yueyuanyu No.168 had the specifications with overall length of 25.68 m, registered beam of 6.00 m, registered depth of 2.98 m, gross tonnage of 125 t, net tonnage of 44 t, and main engine power of 318.88 kW.

Survey gear were pelagic longline fishing gears. The longline gears consisted of a 3.6 mm diameter monofilament main line, 360 mm diameter hard plastic floats, 5 mm diameter nylon float line. The lengths of the main line, float line, branch line were 110 km, 22 m, and 16 m, respectively.

In general, the starting time of deploying gear was between 03:00 and 06:00 local time, and lasted for about 5 h. The time of retrieving gear was between 12:00 and 15:00. Total operation would last for 10–12 h. During the deployment, the vessel’s speed was about 4.3 m/s, line shooter speed was 6.2–7.0 m/s, and the time interval between deploying fore and after branch lines was about 7.8 s. The length of main line between two branch lines was 43.5 m and there were 25 hooks between two floats (HBF).

The observed hook depths were measured by temperature depth recorder (Temperature depth recorder，TDR-2050) (RBR, Canada). The gear drift velocity relative to the ground under the action of the combined force of wind and current, was estimated by GPS data. The wind speed was measured by an anemometer. The wind was measured by a compass. The angle of attack (Q_w) was the angle between the prevailing course in deploying the gear and direction that the fishing gear was drifting and the wind angle (γ) was the angle between the direction of the wind and the prevailing course in deploying the gear.

Sampling time for longliners Huayuanyu No.18 and Huayuanyu No.19 was from September 15 to December 12, 2005 and each boat surveyed for 54 sites. Sampling time for the longliner Yueyuanyu No.168 was from October 1 to November 30, 2006 and the boat surveyed for 36 sites. The survey sites were shown in Fig.1. The fishing activity was mainly limited within the area defined by 0°47'N–10°16'Nand 61°40'E–70°40'E in 2005 and 3°07′S~4°07′N，62°12′E~71°15′E in 2006.

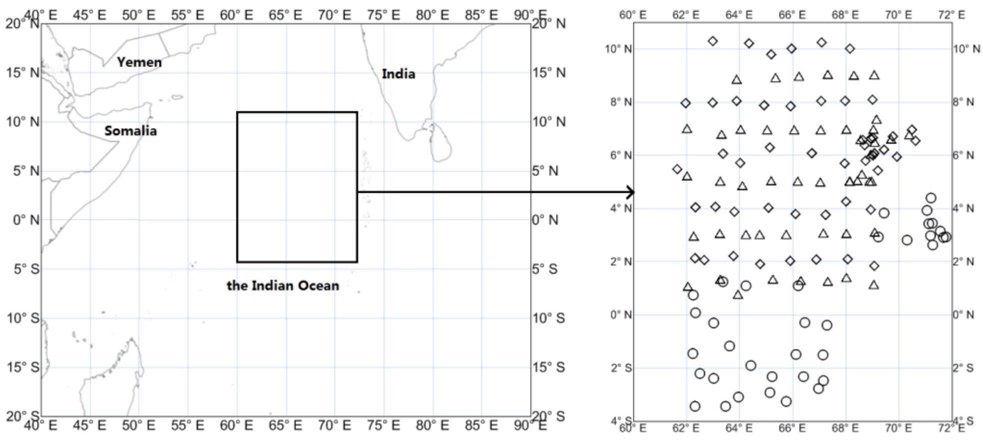

Fig. 1 The survey sites (◇: Huayuanyu No.18; △: Huayuanyu No.19; ○: Yueyuanyu No.168)

2.2 Analysis methods

The theoretical hook depth was calculated according to the catenary calculation formula (Saito, 1992), and the theoretical depth of each hook could be described as follows:

$$D_\delta = h_a + h_b + l\left[\sqrt{1+cot^2\varphi_0} - \sqrt{\left(1-\frac{2\delta}{m}\right)^2 + cot^2\varphi_0}\right](1)$$

$$L = V_2 \times m \times t(2)$$

$$l = V_1 \times m \times \frac{t}{2}(3)$$

$$k = L/2l = V_2/V_1 = cot^2\varphi_0\, sh^{-1}\, tan\varphi_0(4)$$

where D_δ is the theoretical hook depth ; h_a is the length of branch line; h_b is the length of float line; l is the half length of the main line; φ_0 is the intersection angle of tangent line and horizontal plane on the supporting point of main line, which is related to *k*. It is difficult to measure φ_0 in fishing operation, so we adopt shortening ratio *k* to calculate φ_0; δ is the ordinal number of hook from one side of the gear between the two floats; *m* is the number of mainline segments between two floats ($m=N_b+1$); *L* is the distance on the sea surface between two floats; V_2 is the vessel speed; V_1 is the line shooter speed.

The actual average hook depth D_f is the average value measured in a certain range of fluctuation after TDR reaches a certain depth. The ratio of actual average hook depth to theoretical depth of hook (P_D) is expressed as:

$$P_D = \frac{D_f}{D_\delta} \qquad (5)$$

The relationship model for predicting hook depth and theoretical depth was established by multiple linear stepwise regression using SPSS software (Song and Gao, 2006). We assumed that the actual hook depth was mainly influenced by gear drift velocity (V_g), wind speed (V_w), wind direction (C_w), angle of attack (Q_w) between prevailing course in deploying gear and drifting direction of fishing gear, wind angel (γ) between wind direction and prevailing course in deploying gear and hook number (δ) and assumed that:

$$P_D = b_0 + b_1V_g + b_2V_w + b_3 \sin Q_w + b_4 \sin\gamma + b_5\delta \qquad (6)$$

By controlling the above parameters, the depth of the hook could be predicted to reach the required depth. In the range of reasonable operating parameters, Matlab (Cleve, 2013) was used to calculate the predicted hook depth. The possible range of each parameter was selected when the fishing hook depth was distributed in the bigeye tuna preferred water layer (140m-240m) (Song et al, 2009) as the optimal operation parameter for the future longline operation. The method was as follows:

Matlab software was used to calculate the number of hooks in the bigeye tuna preferred water layer (140-240m). In the condition that V_1 ranged from 6 to 7 m/s, calculation step length 0.1 m/s, V_2 ranged from 4 to 5 m/s, calculation step length 0.1 m/s, t ranged from 6 to 8s, calculation step length 0.1s, Q_w and γ ranged from 0 to 90°, $sinQ_w$ and $sin\gamma$ calculation step length 0.1when the number of hooks between two floats was 23~27, respectively, the possible range of each parameter was obtained when the number of hooks in the bigeye tuna preferred water layer (140-240m) was the maximum. Finally the special case of V_1 were given when the number of hooks in the bigeye tuna preference layer (140-240m) was the maximum and t, V_2, Q_w and γ was 7s，4.5m/s，0°，45°, respectively.

3 Results

3.1 prediction model of fishing hook depth

SPSS software (Zhang, 2011) was used to establish the relationship model of predicting hook depth and theoretical depth by multiple linear stepwise regression.

$$P_D = 0.974 + 0.097\,sin\,Q_w - 0.203\,sin\,\gamma - 0.018\delta \text{(R=0.390, F=10.172, P=0.000)} \quad (7)$$

The relationship between the theoretical depth and the measured average depth of the hook measured by TDR was shown in Fig. 2-a, and the relationship between the predicted hook depth and the measured average depth of the hook was shown in Fig. 2-b. Comparing the standard deviation between the theoretical depth and TDR depth (65.6 m) with the standard deviation between the predicted depth and TDR depth (56.4 m), we found that the variance of the difference between the prediction depth and TDR depth was significantly smaller than that between the theoretical depth and TDR depth. It was indicated that this model could significantly improve the accuracy of underwater hook depth.

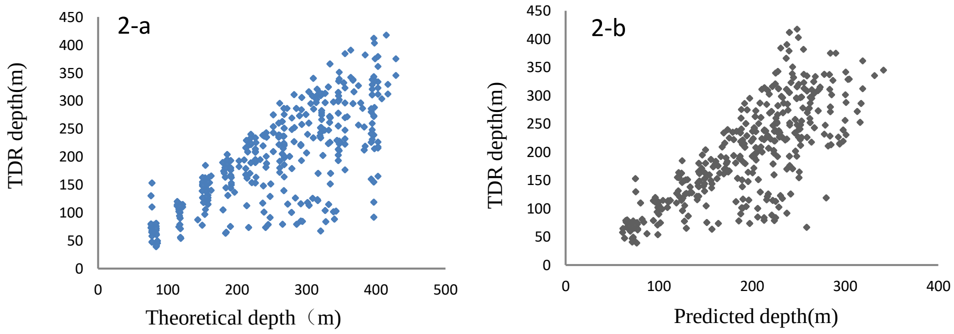

Fig. 2 Relationship between TDR depth and theoretical hook depth and prediction hook depth

3.2 Optimization of operation parameters

The predicted depth of each hook could be calculated by formula (1), (2), (3), (4), (5) and (7). When the number of hooks between two floats (N_b) was 23~27, respectively, the distribution of hooks in the water layer of 140-240 m was shown in Fig. 3. When the number of hooks between two floats was 27, the number of hooks in the water layer of 140-240m was 21 and the distribution frequency was 77.8%. When the number of hooks between two floats (N_b) was 23~27 respectively, the possible ranges of each optimized operation parameter were shown in Table 1. The other parameters could be obtained when four of the parameters were determined. When t, V_2, Q_w and γ was 7s，4.5m/s，0°，45°, respectively, the range of V_1 was shown in Table 2.

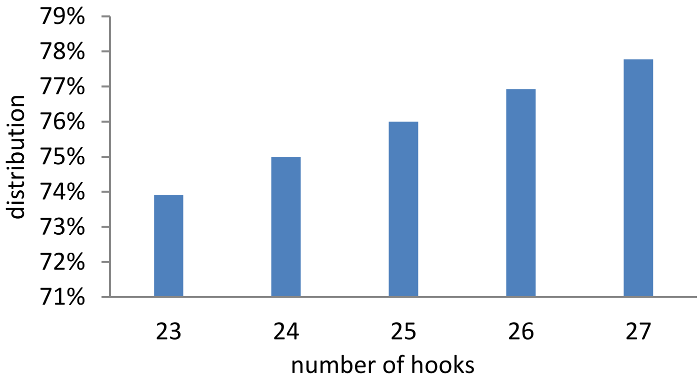

Fig.3 Distribution frequency of hooks which depth was in the range of 140-240 m in different hook numbers between two floats

Table 1 Possible range of optimized operating parameters at the maximum distribution frequency of hooks in water layer of 140-240m

N_b	t(s)	V_2(m/s)	Q_w(°)	γ(°)	V_1(m/s)
23	6-8	4-5	0~90	0~90	6-7
24	6-8	4-5	0~90	0~90	6-7
25	6-8	4-5	0~90	0~90	6-7
26	6-8	4.2-5	0~90	0~90	6-7
27	6-8	4.4-5	0~90	0~90	6-7

Table 2 Example of operation parameters at the maximum distribution frequency of hooks in water layer of 140-240m

N_b	t(s)	V_2(m/s)	Q_w(°)	γ(°)	V_1(m/s)
23	7	4.5	0	45	6.2-6.4
24	7	4.5	0	45	6.2-6.3
25	7	4.5	0	45	6.2
26	7	4.5	0	45	6.1
27	7	4.5	0	45	6

4. Discussion

This paper suggested that the wind angle(γ), angle of attack (Q_w) and the hook number (δ) might be the impact factors of the hook depth. Comparing with Bigelow et al. (2006), using GLM and GAM models to analyze the relationship between actual depth and theoretical depth, wind force, current shear force and velocity (data from OCGM model), the parameters taking into account in this study were more easily obtained, and it was more convenient for the real-time adjustment for fishing vessels during operation to achieve the optimal hook depth distribution. Meanwhile, this study adopted 609 sets of data in 2005 and 2006, which improved the credibility compared with 248 sets of data in Song et al. (2009). The maximum difference between the fishing hook depth calculated in this study and the actual observed value was 191m (only a few), and the difference within 40m accounted for 59.2%. The reasons for the difference between the predicted hook depth and the actual hook depth measured by TDR might be as follows :1) There were large record errors (the fisherman did not throw this TDR according to the design requirements); 2) The depth fluctuation range recorded by TDR itself was large (sometimes up and down fluctuation was more than 200 m); 3) The distance between TDR and the connection point of the main line from the planned connection point was large, which was not well fixed, resulting in the deviation of the hook depth; 4) Line shooter speed and vessel speed were unstable, *etc* (Song, 2014).

Polovina et al. (2003) studied the influence of the deployment of longline fishing gear on the incidental catch rate of sea turtles, and suggested that the shallow water longline fishing with swordfish as the target species had significantly higher incidental catch rate of sea turtles than the deep water longline fishing with tuna as the target species, and the shallow hooks of deep water longline fishing had significantly higher incidental catch rate of sea turtles than the deep hooks. Gilman et al. (2006) also believed that controlling the depth of the hook is conducive to the reduction of non-target species, especially the turtle retention rate of the protected species. Cao et al. (2011) found that the range of water layer for the high catchability was 240-360 m for bigeye thresher shark (*Alopias superciliosus*) and 160-240m for thresher shark (*Alopias vulpinus*). Song et al. (2015) found that the range of water layer for the high catchability was 80–120m for blue shark (*Prionace glauca*) and 40–80 m for silky shark (*Carcharhinus falciformis*), respectively. Song et al. (2017) found that the highest catch rate of wahoo (*Acanthocybium solandri*) was 40-80m water layer in the waters of Cook Islands. In this study, the percentage of the hooks distributed in the water layer of 140-240 m was 73.9%-77.8% after optimization. The optimized hook depth could avoid largely the preferred water layer of blue shark, silky shark, wahoo and bigeye thresher shark so as to reduce the bycatch of these species effectively. Thresher shark mostly distributed in hot water (18-20℃）(Song et al. ,2015), and bigeye tuna mostly distributed in cold water (13-16°C) (Song et al. , 2009), so that we could also avoid the bycatch of thresher shark by choosing the fishing area.

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