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Modelling Relative Water Flow and its Sensitivity of Fish in a Towed Fishing Gear

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예망어구내의 상대유속과 어류의 유수감각 예민도에 대한 모델링

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요 약

예망어구의 유체역학적인 특성과 예망어구내에서의 유속 측정 자료를 기초로 어류의 측선 유수감각에 작용하는 유효한 유수자극량을 추산하고 정량화하기 위하여 예망어구내의 3차원적인 상대유속의 선형적인 분포정도를 모델링하였다. 예망어구내의 상대유속은 망지의 제반규격과 예망어구의 수중 전개형상에서의 각부 거리비에 따라 상대유속비를 선형적으로 수식화하여 본문의 식(3)과 (8)로 표현하였다. 이러한 상대유속비는 어류의 측선 유수감각기관에 의하여 탐지될 수 있는 와동 유수자극량의 지표로써 사용될 수 있다. 어류의 유수감각 예민도는 어류의 전장과 어체주위 상대유속에 의하여 선형적으로 변화되는 것으로 가정하고 본문의 식(9)와 같이 탐지가능한 상대유속차의 최소값으로 나타내었다. 예망어구내의 상대유속 분포에 관한 본 모델의 계산 결과는 실물예망어구에서 실측된 상대유속의 범위내에서 거의 근사하게 나타났으며 본 모델은 어류의 대망행동 모델링에서 예망어구의 유수자극과 어류의 유수감각 예민도를 상대적으로 정량화하여 어류행동의 반응요인으로 적용할 수 있을 것이다.

Introduction

Fish cannot speak although some fish sometimes produce sound. This is therefore a most difficult task which can only be solved by studying the so-called behavioural responses of the fish. The observation of fish behaviour in relation to trawls in dark night conditions, probably below or near the brightness threshold, showed fish to be struck by ground gear (Glass and Wardle, 1989). However this type of behaviour, which appears to indicate the lack of water flow sensitivity by lateral line, sometimes happened during daytime observations when fish were concentrated for some reason such as feeding, or were out of visual focus from the approaching ground gear, as observed in the trawl (Kim, 1996). Therefore the lateral line sensitivity to water flow or sound pressure may become a more effective factor when light conditions are below the light threshold (Chapman, 1969).

The relative water flow in trawl gear was measured in a water tank for a model net by Ziembo (1974) and Imai (1974), in a lake with a model trawl by Ferro (1988) and Ferro and Leaver (1989) and in the sea using a full scale pelagic trawl by Kroeger (1984). These measurements were carried out at limited sampling points and yielded quite a large variety of flow speed results. Even in the empirical model of Ziembo (1989) or the theoretical model of Higo et al. (1974), water flow could be estimated in the inside only along the centre line of the trawl.

Fish are able to detect water motion as flow displacement or sound pressure with both the lateral line and the inner ear. The lateral line has traditionally been considered the main sense organ for detecting water disturbances of low frequency. Water flow produced by animals was investigated for plankton (Kirk, 1985) and for fish (Dubois et al., 1974, Ahlborn et al., 1991, Stamhuis and Videler, 1995). There are also hydrodynamical analyses of water flow in relation to excitation of the lateral line of fish (Hassan, 1985, Rozsypal, 1985, Netten, 1991). These studies on animals are considered to be similar to the water flow of objects as knots or meshes inside a towed net. The structure and function of the lateral line organ of fish were reviewed by Coombs et al. (1987) and the behavioural response in relation to the sensitivity of the lateral line was observed for blind cave fish (Teyke, 1985, Hassan, 1986), for piper fish (Saunders and Montgomery, 1985) and for roach (Karlsen and Sand, 1987).

However, there has been no research to define a threshold for relative water flow sensitivity in the application of fish behaviour to fishing gear. The purpose of this study is to establish a simple term for the threshold of flow sensitivity in relation to the lateral line of fish and to develop a model of relative water flow sensitivity considering the water flow pattern in the trawl gear. This model of relative water flow sensitivity of fish will be applied in the grand model of fish behaviour as a manoeuvring factor for fish swimming near the gear where much more turbulence may occur.

Methods and modelling

1. Relative water flow in a towed fishing gear

1) Assumptions

① The relative water flow velocity in this study is dealt with as parallel components of the relative water flow to the towing direction in relation to fixed points of the towed gear.

② The relative water flow velocity ratio is defined as the relative ratio of relative water flow velocity to towing speed.

③ The water flow velocity ratio is symmetrical on port and starboard sides of the gear.

④ The water flow velocity ratio varies linearly with factors such as net dimension and fish position within the towed gear.

⑤ The relative water flow velocity in the trawl is not influenced by the turbulence of the otter board or any other natural current.

2) Modelling Relative water flow

There is a space where the relative water flow velocity in reference to towing gear is assumed to be the same as the towing speed of the gear, between the wings near the mouth of the gear. In a horizontal 2-dimensional X-Z plane when Y is constant at half the net height, the relative water flow velocity ratio varies from the wing end backwards, as shown in the plan view of the gear (Fig. 1). Net drag is increased with thicker twine, smaller mesh size, higher hanging ratio. Accordingly, relative water flow velocity which was measured inside the trawl by flowmeter fixed to the trawl net increases from the wing to the codend (Kroeger, 1984). Then the area where flow velocity is different from towing speed is represented as a longitudinal distance range Bx in X-coordinate through Z-coordinate. Then the distance range Bx (*m*) can be varied with the difference of the Z-axis distance from the wing tip Z_d (*m*), the diameter of the twine D_t (*m*), mesh bar length L_m (*m*), hanging ratio of net H_n, half of the wing spread W_x (*m*), net length T_z (*m*) from wing tip to end of extension and towing speed V_n (*m/sec*) as follows :

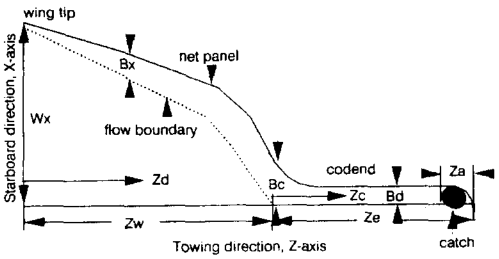

Fig. 1. Schematic plan view of the starboard side of a trawl with X-Z coordinates for representing relative water flow change.

B_x : longitudinal distance range in X-axis
B_c : maximum value of Bx at the extension net
B_d : half of the codend spread
Z_d : difference of the Z-axis distance from the wing tip
W_x : half of the wing tip spread
Z_w : distance from wing tip to point of Bc in Z-axis
Z_e : distance from the point of Bc to end of codend in Z-axis
Z_c : distance from the point of Bc in Z-axis
Z_a : distance of catch in Z-axis

$$B_x = \alpha_1 \cdot {}_{\exp}\{(\beta_1 D_t Z_d H_n W_x)/(L_m T_Z^2)\}/V_n \qquad (1)$$

where α_1 and β_1 are coefficients. If Bx is equal to half of the spread of the extension net, then let $B_x = B_c$ and $Z_d = Z_w$. That means there is no water flow velocity higher than the towing speed from the point Z_w to the end of the codend. So equation (1) is valid when $Z_d < Z_w$ and $B_x < B_c$. It is assumed that relative water flow ratio is decreased from 1, the same as towing speed at the inner edge of B_x, to V_m at the net panel. If relative water flow velocity ratio V_m is the same function as B_x with slope α_2 from equation (1), as a constant, then as follows:

$$V_m = \alpha_2 B_c/(W_x V_n) \qquad (2)$$

Now a change in the relative water flow velocity ratio with X-Y plane at a constant Zd is dependent on the distance from the net panel to a point (X,Y,Z) by Bx. Then the relative water flow velocity ratio $V_B(x,y)$ at a point (X,Y,Z_d) can be approximated with the nearest distance D_n (*m*) from net to a point $(X,Y,Z_d =$ constant) and constant power β_2 as follows:

$$V_B(x,y) = 1 - V_m + V_m(D_n/B_x)^{\beta 2} \qquad (3)$$

and the above equation is valid when $D_n \leq Bx$ and $Z_d < Z_w$. When $Z_d > Z_w$ there is a narrowing channel formed by the extension and the codend. The relative water flow velocity ratio in the central line is decreased from a value of 1 where it is the same as towing speed, to V_e, as the relative flow ratio at the end of the codend. If there are no fish caught in the codend, V_e can be expressed as follows :

$$V_e = \alpha_3 D_t H_n B_c/(L_m W_c V_n) \qquad (4)$$

where Wc is the half spread of the codend, Vn is the towing speed and α_3 is the constant slope. If there are fish caught, with a codend filled to a length Z_a, the relative water flow ratio V_c inside codend as follows:

$$V_c = \{(Z_e - Z_a - Z_c) * B_c\}\beta_3 \tag{5}$$

where Z_e is distance from the point of B_c to end of codend in Z-axis, Z_c is distance from the point of Bc in Z-axis and Z_a is distance of catch in Z-axis. Then, the change in relative water flow velocity ratio in the central line of the codend $V_R(z)$ can be expressed as follows:

$$V_R(z) = V_c\{1 - V_e + 0.5\pi V_e \cos\{Z_c/(Z_e - Z_a)\}\} \tag{6}$$

The relative water flow velocity ratio V_p through the X-Z plane at constant Y near a net panel when $Z_c > Z_w$ can be represented with V_e and V_m which are decreased from V_m at Z_w to V_e at the end of codend, as follows:

$$V_p = V_m + V_e Z_c/(Z_c - Z_a) \tag{7}$$

Then the variation of the relative water flow velocity ratio $V_R(x,y)$ at the X-Y plane with constant Z_c can be estimated as follows:

$$V_R(x,y) = V_R(z)\{1 - V_p + V_p(D_n/B_d)\beta_4\} \tag{8}$$

where B_d is the half of the codend spread. The coefficient α_1 is the range of relative flow change at the end of the trawl wing with constant Z_d and α_1 varied by the dimension of the codend. The values of β_2, β_3 and β_4 represent the slopes of the change with the distance ratio of D_n to the reference distance such as B_x or B_d inside the trawl.

2. Relative water flow sensitivity of fish

1) Assumptions

① The lateral line is the only sense organ to detect non-uniform water flow or flow disturbance.

② The threshold or sensitivity of a fish to relative water flow is represented as the relative water flow velocity which in turn is proportional to a water pressure gradient.

③ The sensitivity of fish to relative water flow depends on factors such as the density of cupula and hair cells in the lateral line canal, and is also proportional to body length.

④ Maximum sensitivity to relative water flow is represented as a water flow difference between the snout tip and the start of the tail peduncle.

2) Modelling sensitivity of fish to relative water flow

A larger fish has a water flow sensitivity advantage of roughly 4 times the body length ratio when the lateral line sensor is distributed proportional to the volume of the fish body and has a longer detection distance from snout to tail root (Denton and Gray, 1989). Therefore sensitivity to relative water flow could be defined as the minimum difference of relative water flow velocity between snout and root of tail. The threshold of relative water flow Ut (m/sec) of fish can be a function of the body length of the fish and the relative water flow velocity near the fish body as well as the sensitivity of the lateral line, and can be expressed as the following equation:

$$U_t = fV_0^u/B_L \tag{9}$$

where B_L *(m)* is total body length, V_0 *(m/sec)* is mean relative water flow such as swimming velocity proportional to water pressure, f is coefficient and u is power. The coefficient f and power u in equation (9) could vary with species, or with other factors, and could to be approximated by basic experimental results on lateral line of fish even thought there is no relevant study to adapt above equation directly. The experiments on water flow pressure discrimination by lateral line (Hassan, 1986) were carried out on blind cave fish (*Anoptichthys jordani*) with body lengths of 5 - 7 *cm*, using a 1 *mm* diameter twine array. The minimum difference of two intervals of twine array detected by training fish was observed to be 1.5 *mm* with a surface wave velocity 25 *cm/sec*, and with 70 % certainty of discrimination. This result may reflect a higher sensitivity of lateral line in blind fish than in visual fishes.

Other experiments by Denton and Grey (1989) showed that ruffle (Gymnocephalus cernua) can detect a 1.5 *mm* diameter sphere with a peak acceleration 8 mm/*sec*^{2} at frequency of 13 *Hz* (estimated surface relative water flow about 10 *cm/sec*). From the above results, by adapting values for body length of 7 *cm* and $U_t = 0.8$ *cm/sec* when $V_0 = 10$ *cm/sec* and $U_t = 1.7$ *cm/sec* at $V_0 = 100$ *cm/sec*, coefficients of the equation (9) are approximated as f=0.00112 and power u=0.305. The coefficient f can represent an index of the threshold of relative water flow and can be approximated by the table of incidence of canals in lateral lines within each family of fishes (Coombs et al., 1987).

The intensity of water flow stimulus FI as turbulence of the towed gear can be defined with relative water flow relative ratio inside the gear $V_B(x,y)$ in equation (3) or $V_R(x,y)$ in equation (8) and the relative water flow threshold of fish U_t in equation (9) as follows:

$$F_I = CV_n\{1 - V_{B,R}(x,y)\}/U_t \qquad (10)$$

where C is coefficient and V_n is towing speed. F_I values will be used as input stimulus parameter for the behaviour model in relation to a towed fishing gear.

Results

1. Relative water flow in a towed fishing gear

The variation of the relative water flow velocity ratio as an example was estimated for the bottom trawl BT130C (Galbraith, 1983) and its geometry from simulation results of Netsim (Ferro, 1989) used in the North Sea. The parameters for previous equations are $D_t/L_m = 0.05$ in the main bag net as from wing net to the end of extension net and $D_t/L_m = 0.1$ in the codend from the design of the trawl BT130C. Other coefficients are estimated following the measurement of the relative water flow in trawl which means 10 % less than towing speed near the net in the bag net when $Z_d \leq Z_w$ and about 20 % of the towing speed at the end of the codend (Kroeger, 1984, Ferro, 1988, Ferro and Leaver, 1989). Those relevant coefficients are $\alpha_1 = 0.023$, $\alpha_2 = 0.692$, $\alpha_3 = 4.286$, $\beta_1 = 380$, $\beta_2 = \beta_4 = 0.27$, $\beta_3 = 0.5$ and these coefficients represented $V_m = 0.1$. The calculated results of relative water flow velocity ratio with distance ratio of D_n to B_x in the trawl BT130C when the towing speed was 1.5 m/sec is shown in Fig. 2.

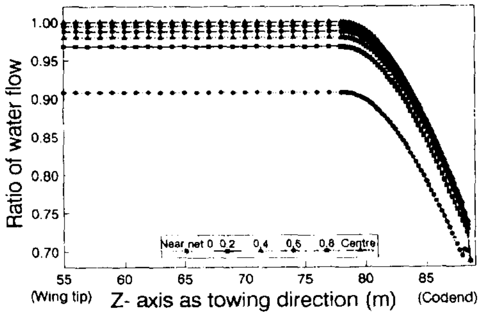

Fig. 2. The calculated results of ratio of relative water flow velocity with ratio of distance Dn from the net to Bx, represented as the towing direction from the wing tip to the codend of the North Sea bottom trawl BT130C when towed at 1.5 m/sec.

2. Relative water flow sensitivity of fish

From the table of the lateral line of fishes by Coombs et al.(1987), relative indices of coefficient f in equation (9) can be adapted for some marine fishes using the previous assumptions and an approximation of cupula and haircell density in the lateral line canal. For example, a haddock (*Melanogrammus aeglefinus*) is assumed to detect relative water flow velocity difference, as a water flow turbulence between snout and tail, at a nominal water velocity of 1.5 *m/sec*, when taking f=0.003, which is 3 times higher than those of blind cave fishes. The calculated result of flow sensitivity for five body lengths of haddock with change of relative water flow velocity is shown in Fig. 3.

In relation to the water flow model of a trawl, a relative water flow sensitivity from equation (9) for a difference of relative water flow between 2 ends of the body length can be detected by a fish depending on its assuming the best orientation of its body, i.e when either parallel or longitudinal to the towing direction.

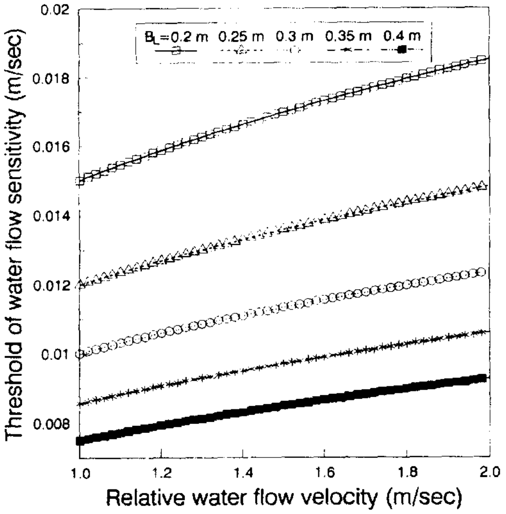

Fig. 3. An example of the calculated threshold of relative water flow sensitivity for five body lengths(B_L) of haddock with change of the surrounding water flow velocity between 1 and 2 m/sec as towing speed.

Discussion

The prediction of relative water flow velocity ratio inside the trawl in this study were carried out in relation to the 3-dimensional position of the net opening, through the mouth, to the codend. With the variation of towing speed and fishing gear specification, the water flow velocity ratios of this model decreased linearly with the distance from the wing tips while it was decreased by the increasing projected net surface area.

Minimum ratio of relative water flow to towing speed at the end of the codend in a model net were reported as about 0.5 without a catch or with a more flexible net at the mouth, or around 0.3 with some catch and a less flexible net (Ziembo, 1974). Furthermore, higher relative water flows than towing speed were observed near the extension when lower the towing speed. These measured values of relative water flow inside gear were adapted to evaluate the coefficients of the equations for estimation of the water flow ratio and turbulence.

On the basis of previous results, there are analytical models, as functions of the flow surface coefficient and the angle of attack of the net panels (Ziembo, 1989) and hydrodynamic models (Higo *et al.*, 1974). However, these models are limited to applications with 3 dimensional variations of water flow. Another study showed water flow measurements for a full scale pelagic trawl by Kroeger (1984) and it showed nonlinear changes of water flow ratio from the wing ends to the codend when measuring from points 20 cm below the upper net panel. It also showed that relative water flow near the ends of the extension was approximately the same as the towing speed, but at the codend about 20 % of towing speed.

The relative water flow distribution of the model trawl in a flume tank showed uneven asymmetrical water flow (Imai, 1974). However, the relative flow model in this study treated as linear the change of water flow ratio with the distance ratio of the trawl. geometry The laminar character of the relative water flow near the wing eventually lost its stability with the change of relative water flow ratio and appeared turbulent near the trawl net panel as walls (Ziembo, 1993). Near the wall of the net, outflows through meshes with large turbulence may affect the opening of meshes and influence the manoeuvring of fish swimming or escaping from the net (Moderhak, 1993). Therefore, relative water flow velocity ratio in the present model indicated not only relative water flow parallel to the towing direction but also indicated greater turbulence at lower water flow velocity ratios. In addition, the predicted relative water flow could be a suitable flow stimulus for the lateral line of fish.

There are no results of threshold of flow sensitivity for commercial species in fisheries at present. So, the threshold of relative water flow Ut in equation (9) is regarded as a relative value to compare the minimum sensitivity to water flow turbulence among species considered in the relative water flow model of trawl gear.

Conclusion

An analytical model for the 3 dimensional relative water flow in the towed gear was formulated in order to present an effective stimulus for the lateral line sensitivity of fish, based on the hydrodynamic characters of the fishing net and the empirical flow data of the trawl. The relative water flow inside the trawl gear was estimated as a linear change of relative water flow velocity ratio and depends on the distance ratio from net panels as well as net specification. This relative water flow ratio was represented in equation (3) and (8) and was regarded as an index of turbulent flow stimulus that could be detected by the lateral line of a fish.

The water flow sensitivity of fish was derived in equation (9) using body length and relative water flow velocity surrounding fish body. The parameters of equation (9) for the water flow sensitivity of fish could be deduced for some commercially important fishes by comparing the lateral line sensitivities between fish species. The simulation results of this relative water flow model showed a good approximation to the measured range of relative water flow and this will be applied in the fish behaviour model as a flow stimulus.

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