

Modeling the Selectivity of the Cod-end of a Trawl Using Chaotic Fish Behavior and Neural Networks

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Using empirical data of fish performance and physiological limits as well as physical stimuli and environmental data, a cod-end selectivity model based on a chaotic behavior model using the psycho-hydraulic wheel and neural-network approach was established to predict fish escape or herding responses in trawl and cod-end designs. Fish responses in the cod-end were categorized as escape or herding reactions based on their relative positions and reactions to the net wall. Fish movements were regulated by three factors: escape time, a visual looming effect, and an index of body girth-mesh size. The model was applied to haddock in a North Sea bottom trawl including frequencies of movement components, swimming speed, angular velocity, distance to net wall, and the caught-fish ratio; simulation results were similar to field observations. The ratio of retained fish in the cod-end was limited to 37-95% by optomotor coefficient values of 0.3-1.0 and to 13-67% by looming coefficient values of 0.1-1.0. The selectivity curves generated by this model were sensitive to changes in mesh size, towing speed, mesh type, and mesh shape.

Key words: Chaotic fish behavior, Cod-end of trawl, Selectivity model

Introduction

The total catch of fishing gear is the result of the individual movements of each responding fish. Many variables affect these responses and can include a combination of internal traits of the fish and external characteristics of the environment and fishing gear (Wardle, 1993). The responses of haddock in square-mesh windows of the cod-end of a bottom trawl (O'Neill et al., 2006) were previously analyzed as quantitative movement components (Kim et al., 2008). A basic model of fish behavior in relation to towed fishing gear (Kim and Wardle, 2005) was developed from fish responses in the mouth of a trawl (Kim and Wardle, 2003).

Analyses of the fishing selectivity of towed gear primarily consider fish as biological factors and gear as physical factors (MacLennan, 1993). Several changes in gear construction and specifications have been introduced to improve selectivity and decrease by-catch. However, studies of variation in fishing selectivity have focused on the dimensions of the cod-end (Robertson and Ferro, 1988; Reeves et al.,

1992; Lök et al., 1997), the use of single or double cod-ends (Matsushita et al., 1996; Ozbilgin and Tosunoglu, 2003), the thickness of the twine (Sala et al., 2007), and the state of the sea (O'Neill et al., 2003). Various combinations of gear and fish species and their relationships to variation in the underwater environment (e.g., fishing grounds, season, and fish stock) have produced particularly complex selectivity results when applied to the management of by-catch or fish resources (Millar et al., 2004). Wardle (1993) suggested that this complexity in selectivity was due to changeable fish behavior in relation to stimulus-responses in complicated and diverse underwater conditions.

Various selectivity models have been designed to statistically analyze catch data (Fryer, 1991; Tokai, 1997; Millar and Fryer, 1999), and random encounter models (Herman, 2005) have considered the effects of mesh openings and fish size (Herman et al., 2006; 2007a; b; Herman and O'Neill, 2006). These models are useful for generating selectivity graphs in relation to time period variables; however, these models only considered the cod-end and did not account for behavioral variables such as fish swimming ability

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and stamina, visual sensitivity or flow senses, and optomotor or erratic responses. All of these factors are important fish responses that affect the swimming movements involved in mesh penetration.

In this study, we considered an experimental model of fishing selectivity in the cod-end as part of the entire fish-capture process. Our model included predictions of fish responses based on a previously-developed chaotic fish behavior model (Kim and Wardle, 2005), used previous models to determine the stimuli of fishing gear (Kim, 1997; Kim and Wardle, 1998) and fish swimming ability (Kim and Wardle, 1997), and considered observations of fish behavior in the cod-end (Gabr et al., 2007; Kim and Wardle, 2008). Our goal was to compare field observations of mesh penetration by fish to simulation results based on chaotic behavior theory.

Materials and Methods

Principle of chaotic fish behavior model

The behavioral responses of fish to the cod-end netting are illustrated in Fig. 1. These data originate from previous reports (Wardle, 1993; Kim and Wardle, 2003) and subsequent video observations (Kim and Jang, 2005; Kim and Wardle, 2008). The most important factors include the position of the fish head, level of exhaustion of the fish, distance to the net, limits in swimming performance, and mesh specifications. However, the responses of fish were very complex in that these parameters were very irregular and nonlinear.

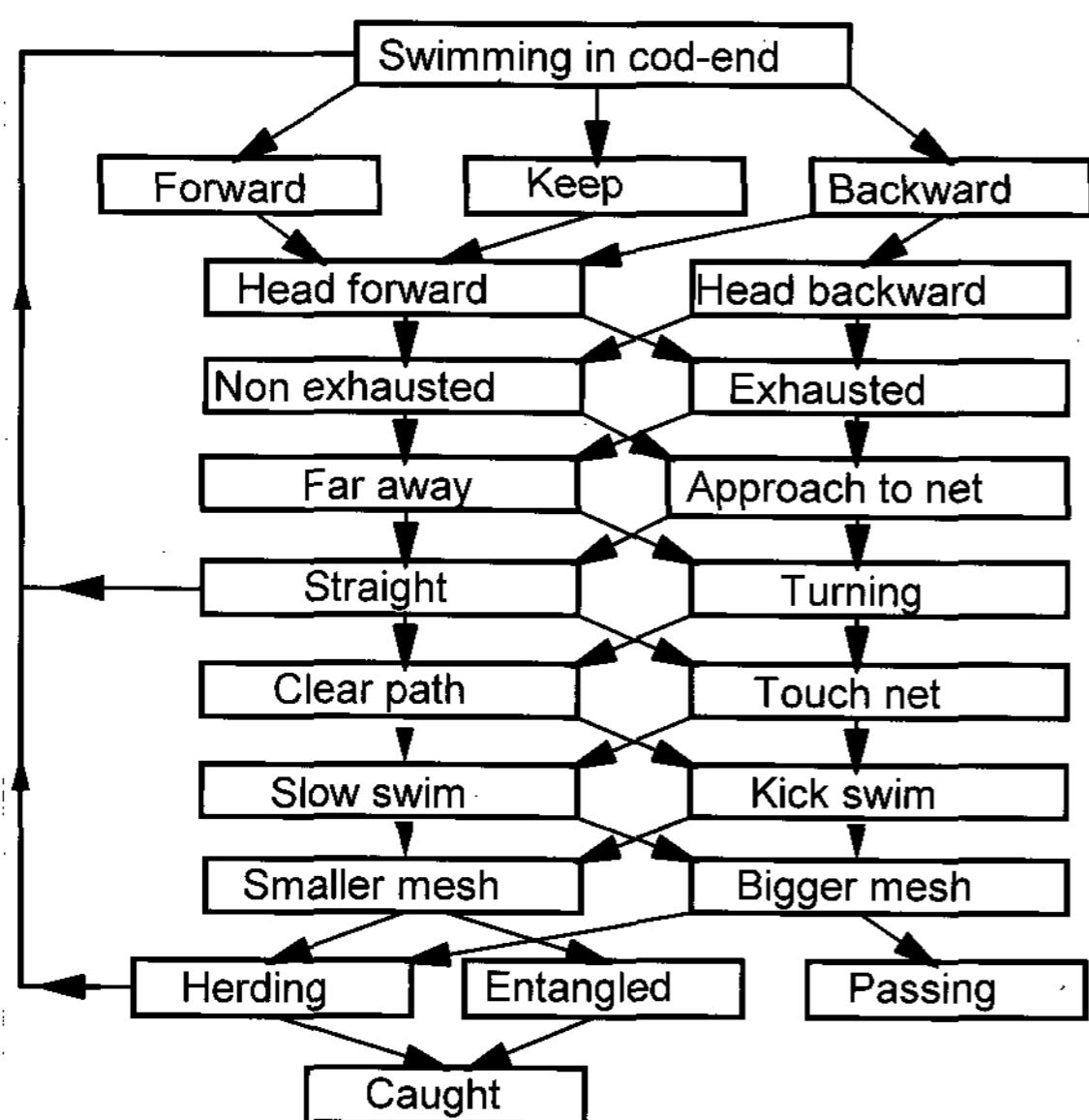


Fig. 1. Block diagram of fish responses in a cod-end for the selectivity model.

Therefore, our selectivity model for the cod-end was an extension of a basic model of fish behavior in a towed trawl based on chaos equations (Kim and Wardle, 2005). This chaotic fish behavior model (Kim and Wardle, 2005) is constructed with three processing steps: input of stimuli as generalized parameters, central decision-making, and output movement responses generated by three signals. Here, output processing for producing a locomotion response was modified and extended specifically for the cod-end to include penetration conditions and the angular coefficient ω as an optomotor index by adding detailed factors for net penetration conditions as described below.

The possible range of horizontal A_H or vertical movement angles A_V with a time step (Kim and Wardle, 2005) were represented as functions of the intensity of the stimulus B_V , the random panic ratio S_E for the individual fish, and the exhaustion index S_N , with a horizontal angular coefficient ω_H or vertical angular coefficient ω_V . The coefficient ω was also assumed to be an optomotor coefficient for species or season, such that a higher ω indicated stable optomotor swimming and a lower ω indicated erratic swimming behavior (Kim and Wardle, 2003; Kim and Jang, 2005). Therefore, the optomotor index ω can be closely related to two terms in the selectivity model of the cod-end by the chaotic fish behavior model. Because fish can make more effective upward and downward movements in the cod-end than in the much higher mouth of the bottom trawl, the possible range of horizontal A_H or vertical movement angles A_V (Kim and Wardle, 2005) can be expressed as a common form ω for either horizontal or vertical movements as follows,

$$A_H \text{ or } A_V = \pi \exp \{ - \omega / (B_V + S_E + S_N) \} \quad (1)$$

We assumed that the above optomotor coefficients were closely related to two physical and biological parameters. The first parameter involves the flickering effects E_F , shape index I_S , and space effects E_S , and the second involves the cumulative visual looming index E_L , swimming energy ratio R_Q , water flow index S_W , and the ratio V_R of fish swimming speed V_F to net towing speed V_N as follows:

$$\omega = \alpha (E_F + I_S + E_S) + \beta (E_L + R_Q + S_W + V_R) \quad (2)$$

where α and β are coefficients of stimuli. The parameters E_F , I_S , and E_S are defined and formulated as follows, whereas the second set of parameters are described in the basic fish behavior model (Kim and Wardle, 2005).

The flickering effects E_F of fish vision to moving

meshes are defined as the ratio of critical flickering frequency E_C (Hz) to object flickering frequency E_O (Hz), which defines towing speed V_N divided by mesh size L_M in the viewing range as follows:

$$E_F = E_C / E_O \quad E_O = V_N / L_M \quad (3)$$

The critical flickering frequency of fish vision (Douglas and Hawryshyn, 1990) in relation to background luminance L_B (cd/m^2) can be generally formulated as follows:

$$E_C = c_0 + c_1(L_B) \quad (4)$$

where $c_0 = 11$ or 23 and $c_1 = 1$ or 13 when $L_B < 0.1$ or $L_B \geq 0.1$, respectively.

The shape index I_S defines a visual stimulus affecting fish escape by object shape and material, which is assumed as: netting mesh=1, grid=2, and black canvas=3.

The space effect E_S defines the ratio of cod-end volume to visibility volume as follows:

$$E_S = C_L \times C_B \times C_D / D_V^3 \quad (5)$$

where C_L , C_B , and C_D are the length, breadth, and depth of the cod-end, respectively, and D_V is the visibility of the cod-end as seen by the fish, which can be estimated by the visual stimulus model of the net (Kim and Wardle, 1998).

Mesh penetration conditions in the cod-end

The critical conditions for fish escape through the net wall of the cod-end are quantified by the following boundary behaviors, which are an extension of the fish behavior model by Kim and Wardle (2005). Fish escape from the fishing gear must satisfy all three of the following conditions:

1) A fish is assumed to have to overcome a visual looming stimulus expressed as the integration of visual stimuli over elapsed time. If the expected new looming value, E_N , divided by the escape time is less than the threshold of the looming stimulus for the fish, E_T , fish can escape through the mesh.

$$E_T = \lambda B_V S_E |\cos(t)| \quad (6)$$

where λ is a looming threshold coefficient, B_V is the cumulative intensity of visual stimuli over time t , and S_E is the random panic index of fish.

2) The straight distance, D_N , of a mesh knot, I , in a towing axis is given as follows:

$$D_N = N_I L_M R_H \cos(\theta) \quad (7)$$

where N_I is the number of consecutive knots that affect a fish, L_M is the mesh size, R_H is the hanging

ratio, and θ is the lead angle of the net. The time T_F for a fish to move through distance D_F to the nearest mesh knot and the mesh knot sweep time T_N are as follows:

$$T_F = D_F / V_F \quad T_N = D_N / V_N \quad (8)$$

where V_F is swimming speed of fish and V_N is the towing speed. If T_F is lower than T_N , then fish have a higher probability of penetrating the mesh.

3) In terms of the selectivity of the mesh, the relationship between the girth of passing fish G_F and the mesh circumference G_M as proportional to mesh size L_M can be represented as $G_F \leq G_M \cong 2 L_M$. The gap between G_F and G_M can be varied by fish body shape and mesh opening (O'Neill et al., 2003). The relationship between the gap and fish penetration was defined and categorized for several steps of the passing process as follows:

Set maximum fish height as H_F and maximum fish breadth as B_F . The maximum height H_F (cm), the girth of haddock G_F (cm), and the weight of haddock W_F (g) were represented by body length B_L (cm) as follows;

$$H_F = H_0 + B_L^n \quad W_F = W_0 + B_L^m \quad G_F = G_0 + a B_L \quad (9)$$

In this study, the relevant values for haddock were $H_0 = 0.051$, $n = 1.414$, $W_0 = 0.0157$, $m = 2.827$, $G_0 = 0.399$, and $a = 0.527$ (Coull et al., 1989; Main and Sangster, 1991). The maximum breadth of haddock B_F can be estimated from H_F and G_F as the circumference of an ellipse, if we assume that the cross-sectional shape of a round fish can be represented as an ellipse as follows;

$$(H_F/2)^2 / y_F^2 + (B_F/2)^2 / x_F^2 = 1 \quad (10)$$

where the coordinates are x_F as the vertical axis and y_F as the horizontal axis in the cross-sectional shape of the fish body.

The mesh opening as height $H_M = L_M \cos(\varphi)$ and breadth $B_M = L_M \sin(\varphi)$ is modified by the hanging ratio, tension of nets, stiffness of the twine, and presence of square or diamond mesh, where φ is the opening angle between mesh bars. When relatively bigger fish are penetrating, the mesh opening can be distorted outwardly in the middle of the bars due to the difference of cross-sectional shape between the mesh opening and the fish body (Main and Sangster, 1991). This distortion of the bar ΔR can also be estimated as the difference between the radius of the mesh bar R_M and the radius of fish body R_F as an ellipse.

Let the difference between H_F and H_M be Δh , B_F -

$B_M = \Delta b$, $G_F - G_M = \Delta g$, and the distortion of the bar $R_F - R_M = \Delta R$ be the difference in distance from the center of an ellipse. The strain on the mesh causing distortion ΔR can then be related to the propulsion force F_P of fish when penetrating the mesh and the tension T_B of the bar under relevant towing conditions.

The tension T_B of the mesh bar can be related to water resistance, pre-tension by cod-end construction, and catch in the cod-end. From published tension data (Main and Sangster, 1991) using 90-mm diamond mesh and square mesh cod-ends, the relationship between ΔR (cm) and tension T_B (g) to opening mesh is formulated as follows:

$$T_B = T_0 + j\Delta R \quad (11)$$

where T_0 is the intercept as pre-tension and j is the slope. The reported values of T_0 and j for 90-mm diamond mesh and 90-mm square mesh were 269.8 g and 219.7 and 124.4 g and 404.8, respectively (Main and Sangster, 1991).

The propulsion force F_P of fish can be related to body weight W_F in eq (9), and swimming speed V_F is affected by the state of exhaustion (Kim and Wardle, 1997) as follows:

$$F_P = p W_F V_F \quad (12)$$

where p is a coefficient.

The process of penetrating cod-end mesh can be categorized into the following three cases: first, if fish height is smaller than mesh height ($\Delta h < 0$), fish

breadth is smaller than mesh breadth ($\Delta b < 0$), fish radius is smaller than mesh radius ($\Delta R < 0$), and mesh circumference is greater than fish girth ($\Delta g < 0$), then fish can pass without touching the bars of the mesh. Second, if the mesh circumference is equal to fish girth ($\Delta g = 0$) and the fish propulsion force is greater than bar tension ($F_P > T_B$) when $\Delta R > 0$, regardless of the values of Δh or Δb , then fish may be caught in the mesh, turn back before the mesh tightens around them, or sometimes pass with possible damage. Third, if the mesh circumference is equal to or smaller than fish girth ($\Delta g \leq 0$) or the fish propulsion force is smaller than bar tension ($F_P \leq T_B$), then fish cannot pass and turn back, but may try to pass through again. Additional methods for determining fish movement were the same as those used in a previous model of fish behavior (Kim and Wardle, 2005).

Simulation methods

Computer simulations were conducted for the North Sea bottom trawl BT130C (Galbraith, 1983) using 16 Alpha cluster workstations (833 MHz) for parallel computing (Kim et al., 2004). The simulated fish were 1,000 - 5,000 haddock per 30 min, with randomly generated body lengths and a normal distribution of peak length (28 cm; deviation=8 cm) as well as a movement time step of 0.2 s. In eq (2), the initial angular coefficient α was constant at 1.4, and the coefficient of angular change β varied from 0.3 to 1.0. The looming threshold index λ in eq (6)

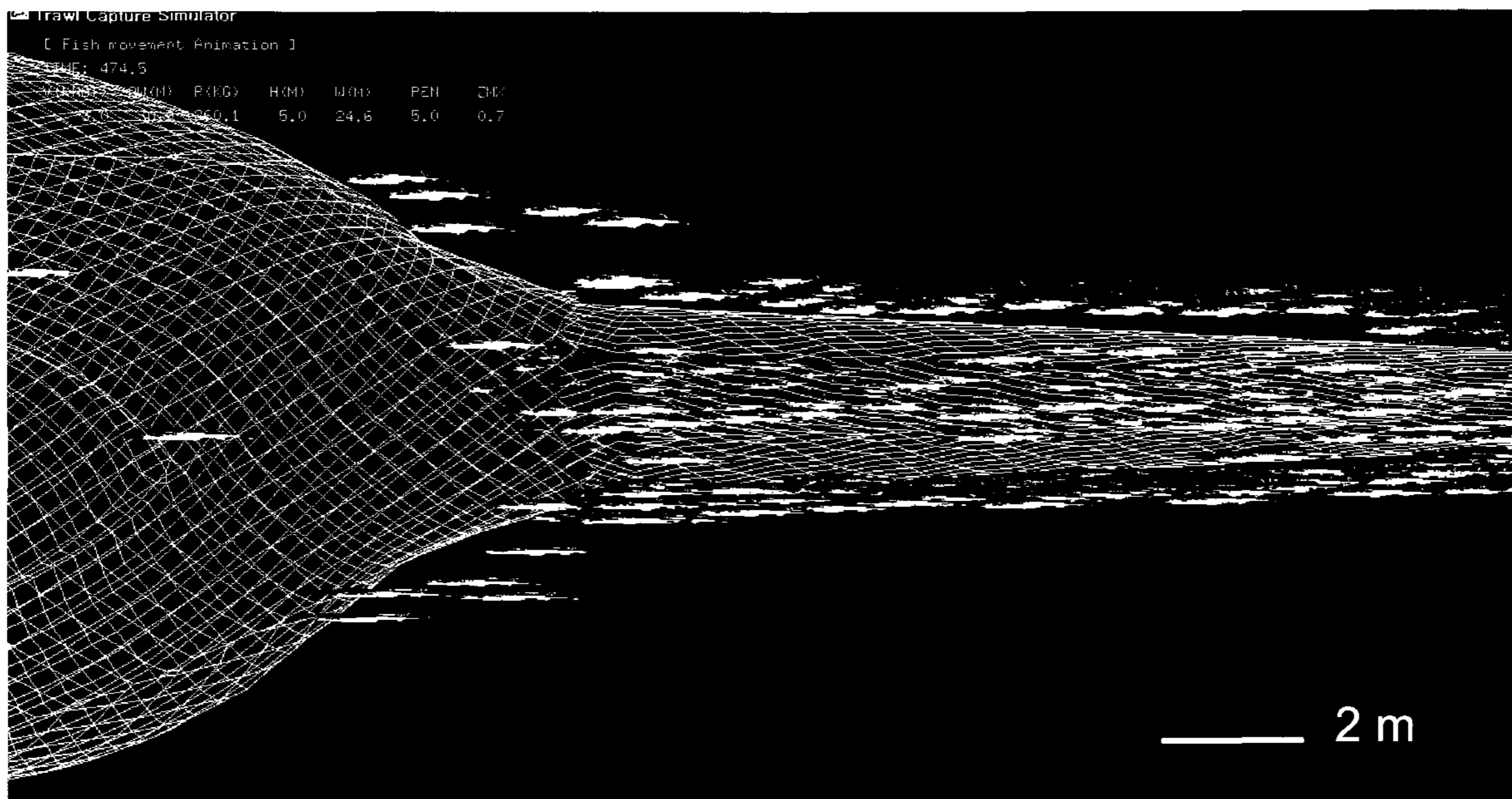


Fig. 2. An example of still image from the simulation results for haddock in the cod-end of BT130C North Sea bottom trawl.

varied from 0.2 to 1.0. The towing speed V_N varied from 1.0 to 2.0 m/s, and the diamond mesh sizes were 80, 100, or 120 mm, with a cod-end length of 10 m and a circumference of 100 meshes. The fixed constants were the hanging ratio in the cod-end ($V_N=0.8$), the number of herding knots ($N_I=3$) in eq (7), and the coefficient for fish propulsion force ($p=0.8$). Other parameters in this simulation were the same as those used in a previous fish behavior model for haddock (Kim and Wardle, 2005).

Results

A still-image example of the simulation results for haddock in the cod-end of a BT130C North Sea bottom trawl is presented in Fig. 2. Simulated escape and herding fish responses in the cod-end of the trawl were categorized as either penetration or herding, and related movement components (e.g., swimming speed, angular velocity, speed acceleration, and distance to net) were represented by the simulation results of the developed model.

The ratio of escaped fish to total encountered fish during trawl operation in this chaotic behavior model was affected primarily by variation in the coefficient of angular change β in eq (2), the looming threshold index λ in eq (6), towing speed V_N , and the mesh size of the cod-end. When the initial value of the angular coefficient β was varied from 0.3 to 1.0 and the looming threshold index λ was kept constant at 0.5, the ratio of escaped fish in the BT130C trawl was lowest (37%) when β was 0.5 and highest (95%) when β was 0.3 as shown in Fig. 3. When the looming threshold index λ in eq (6) was varied from

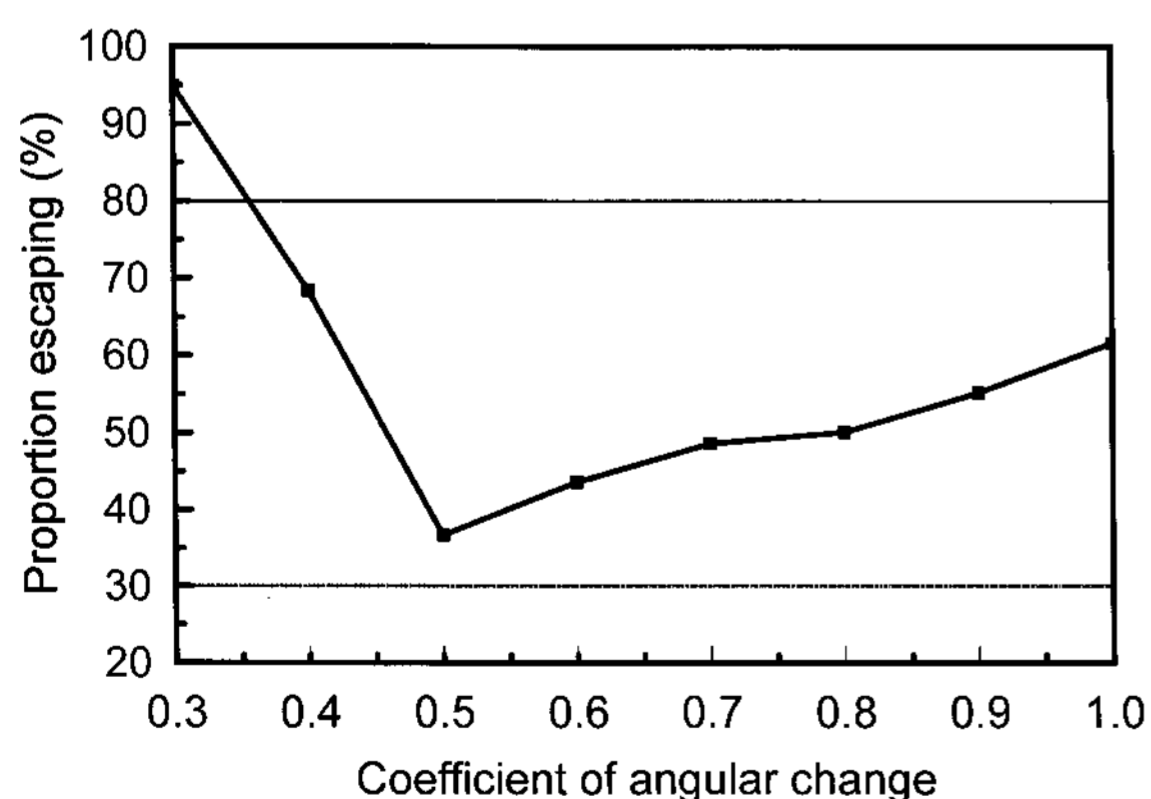


Fig. 3. The proportion of escaping haddock in relation to the angular coefficient β in eq (2) when the looming threshold index λ in eq (6) is constant at 0.5 by the developed selectivity model of the cod-end of the North Sea bottom trawl.

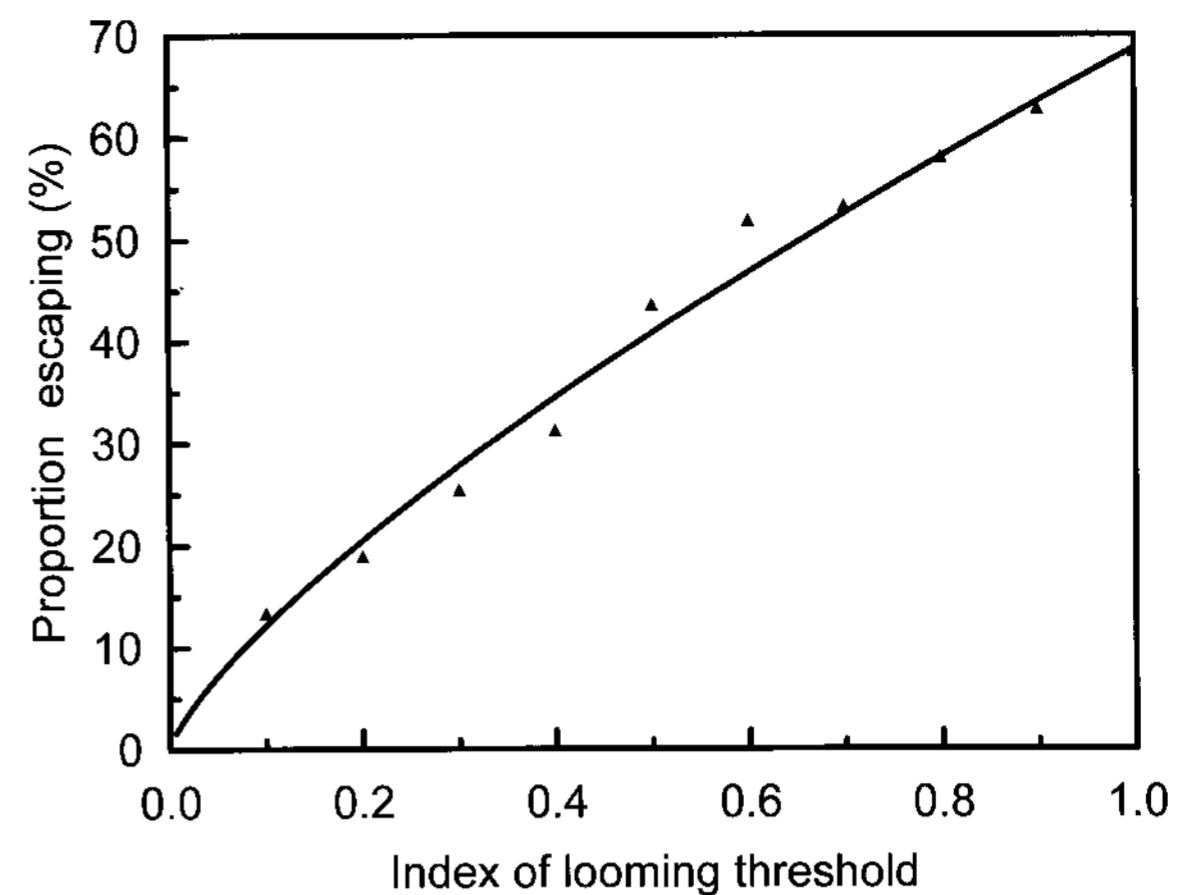


Fig. 4. The ratio of escaped haddock in relation to the looming threshold index λ in eq (6) when the angular coefficient is constant at $\beta=0.6$ by developed selectivity model of the cod-end of the North Sea bottom trawl.

0.1 to 1.0 with a fixed coefficient of angular change ($\beta=0.6$), the ratio of escaped fish (Er , %) increased as shown in Fig. 4 and followed eq (13):

$$Er = 68.7 \lambda^{0.751} \quad (n=10, \text{determined coefficient } r^2 = 0.983) \quad (13)$$

As examples, time series of the relative swimming speed and vertical angular velocity of herding and escaping fish are presented in Fig. 5 (the looming threshold index and coefficient of angular change were constant, $\beta=\lambda=0.6$).

The relative swimming speeds of herding and escaping haddock were -0.16 ± 0.36 [mean \pm S.D.] and -0.22 ± 1.07 m/s, respectively, and the vertical angular velocities were -0.22 ± 1.07 and -0.20 ± 1.09 rad/s, respectively. Neither the relative swimming speed nor the angular velocity was significantly different between herding and escaping haddock, and none of the movement components was normally distributed. In addition, there were no significant relationships between distance to net and swimming speed or vertical angular velocity as shown in Fig. 6.

The body length distribution of retained fish to total encountered fish in the cod-end revealed a higher peak body length (30 cm) than the peak value (28 cm) for all encountered haddock as shown in Fig. 7. The frequency distribution of retained fish for each rank of body length in the cod-end in relation to the looming threshold index λ is presented in Fig. 8. The ratio of retained fish generally decreased with nonlinear increases in λ .

Fig. 9 presents the ratio of escaped fish in relation to the towing net length of the BT130C trawl when

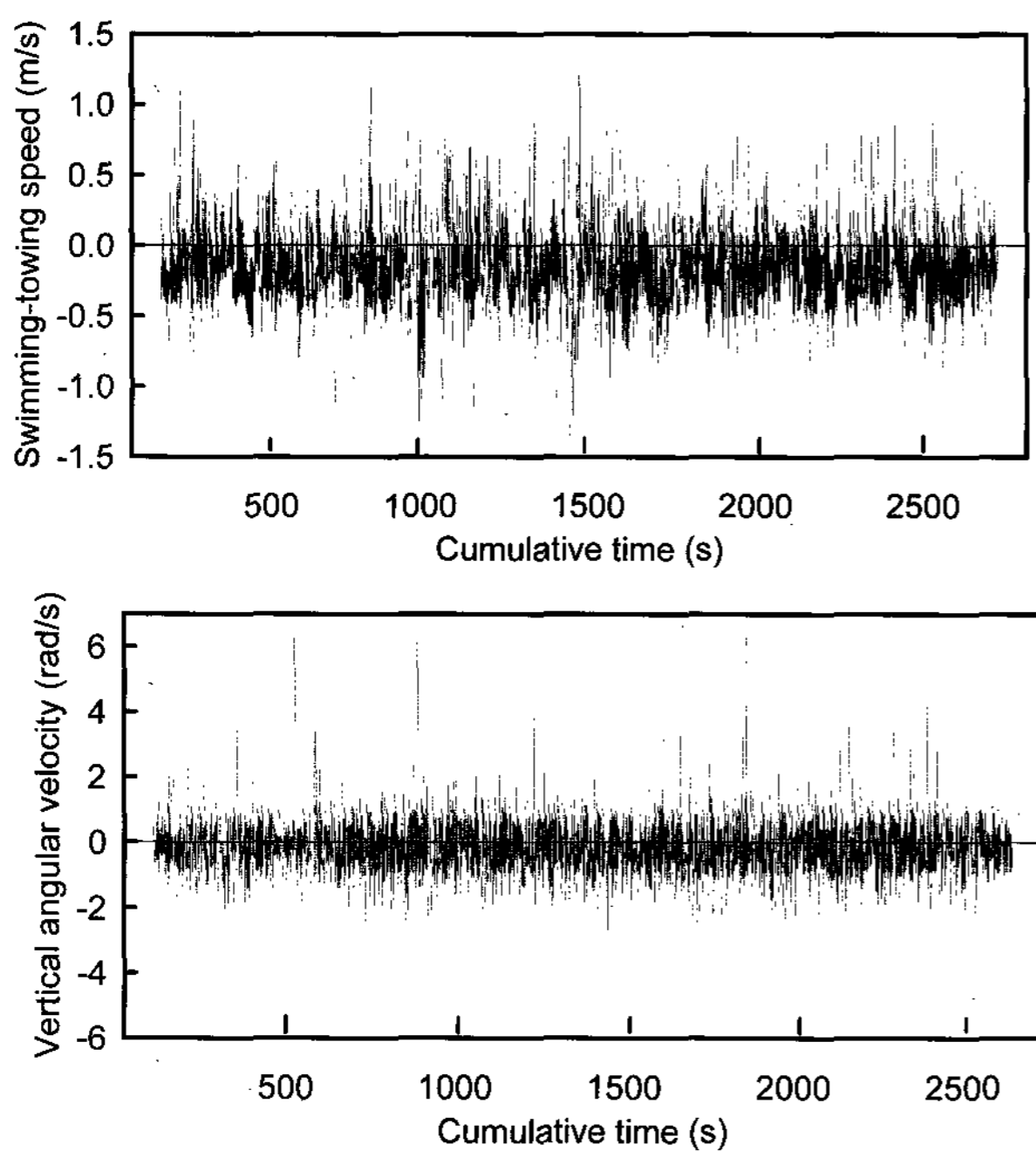


Fig. 5. Examples of time series of relative swimming speed (top) and vertical angular velocity (bottom) for escaping haddock when the looming threshold index and coefficient of angular change were constant $\beta=\lambda=0.6$.

towing speeds V_N were varied from 1.0 to 2.0 (m/s), the mesh size was 100 mm, and $\beta=\lambda=0.6$. The escape ratio of haddock with towing speeds of 1.0, 1.2, 1.5, 1.8, and 2.0 m/s were 74, 66, 63, 64, and 71%, respectively. The proportion of fish escaping increased as 48, 82, and 90% with increasing mesh sizes as 80, 100, and 120 mm as shown in Fig. 10.

Discussion

The simulation results of this chaotic fish behavior model indicated that relevant coefficients such as the angular coefficient and looming threshold index can affect the mesh penetration ratio and catch size. Furthermore, our findings confirm that fishing selectivity modeled as the catch ratio can be realistically modified by changing appropriate parameters, such as the cod-end mesh size or shape. In terms of the variance analysis or frequency distributions of swimming speed and angular velocity, the simulation results did not significantly differ from field observations of fish movements in the cod-end (Kim and Jang, 2005; Kim and Wardle, 2008). Similar to observational results of round fish in square-mesh windows (Kim and Wardle, 2008), the simulations found no significant relationships between distance to net and swimming speed or vertical angular velocity.

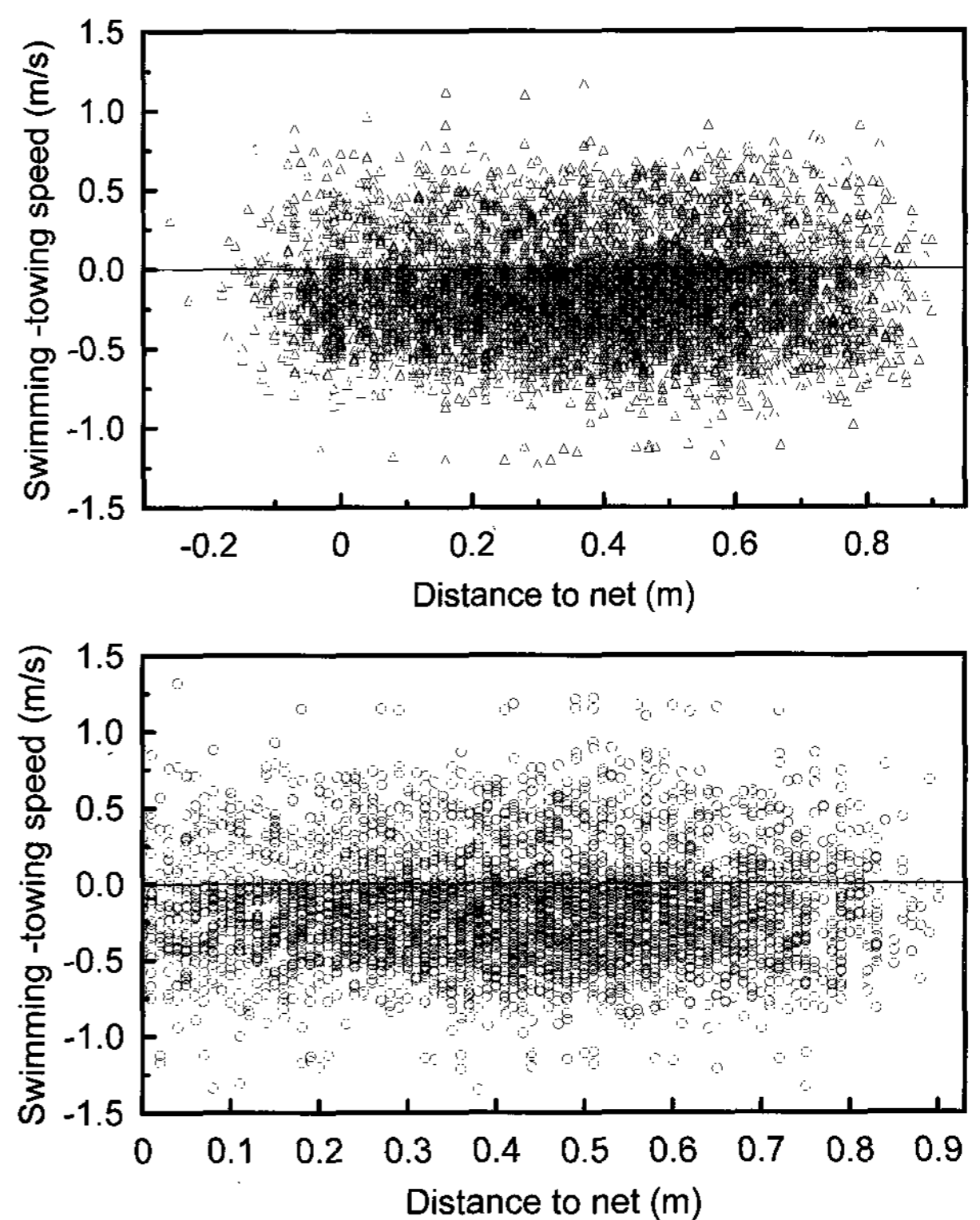


Fig. 6. The relationship between swimming speed and distance to net in escaping haddock (top) and herding haddock (bottom) from the simulation results ($\beta=\lambda=0.6$) when comparing keep scale for distance to net the same i.e. -0.2 to 0.9 m.

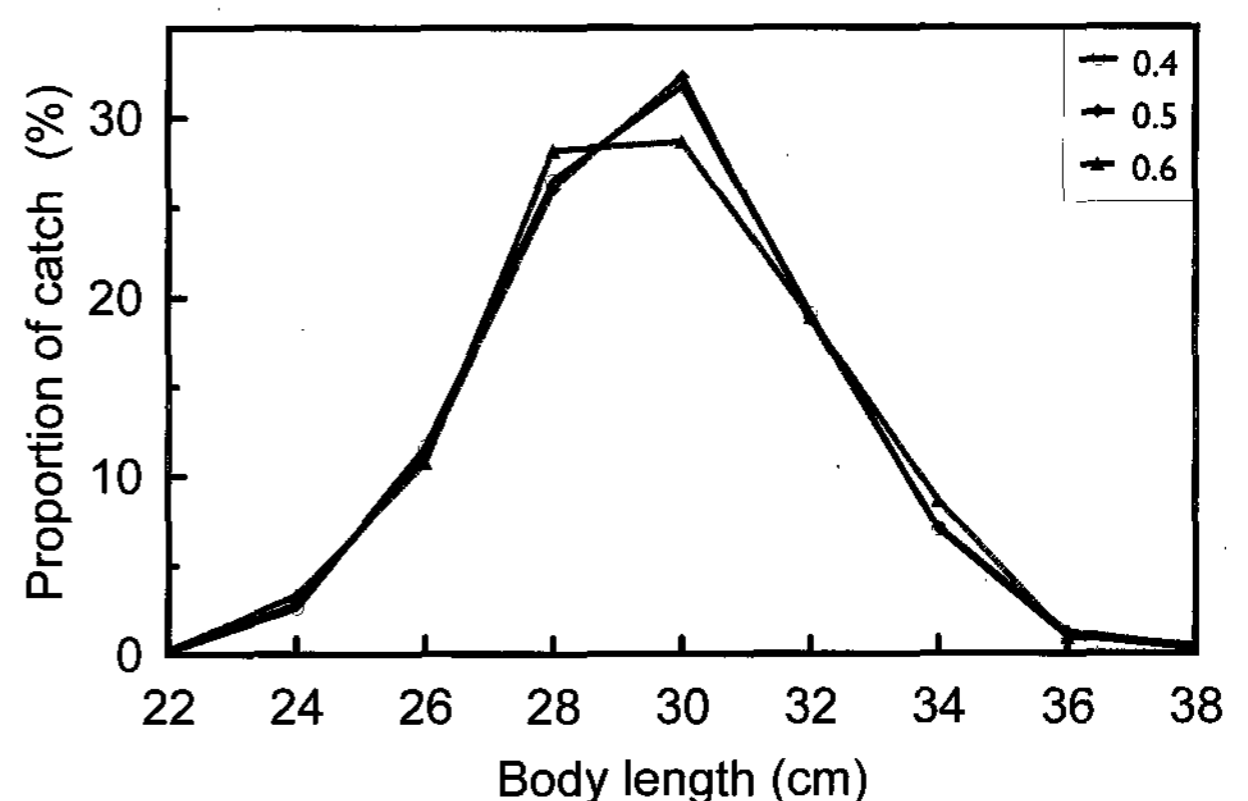


Fig. 7. The body length distribution of fish retained to total encountered fish in the cod-end in relation to the looming threshold index $\lambda=0.4$, 0.5 and 0.6, respectively, from the simulation results.

The increases in the proportion of escaped fish with larger mesh sizes of the cod-end were also similar to field observations for haddock (Glass and Wardle, 1995; O'Neill and Kynoch, 1996; Hallidays et al., 1999; Bethke, 2001). The escape ratios of haddock ranged from 63 to 74% with towing speeds varying

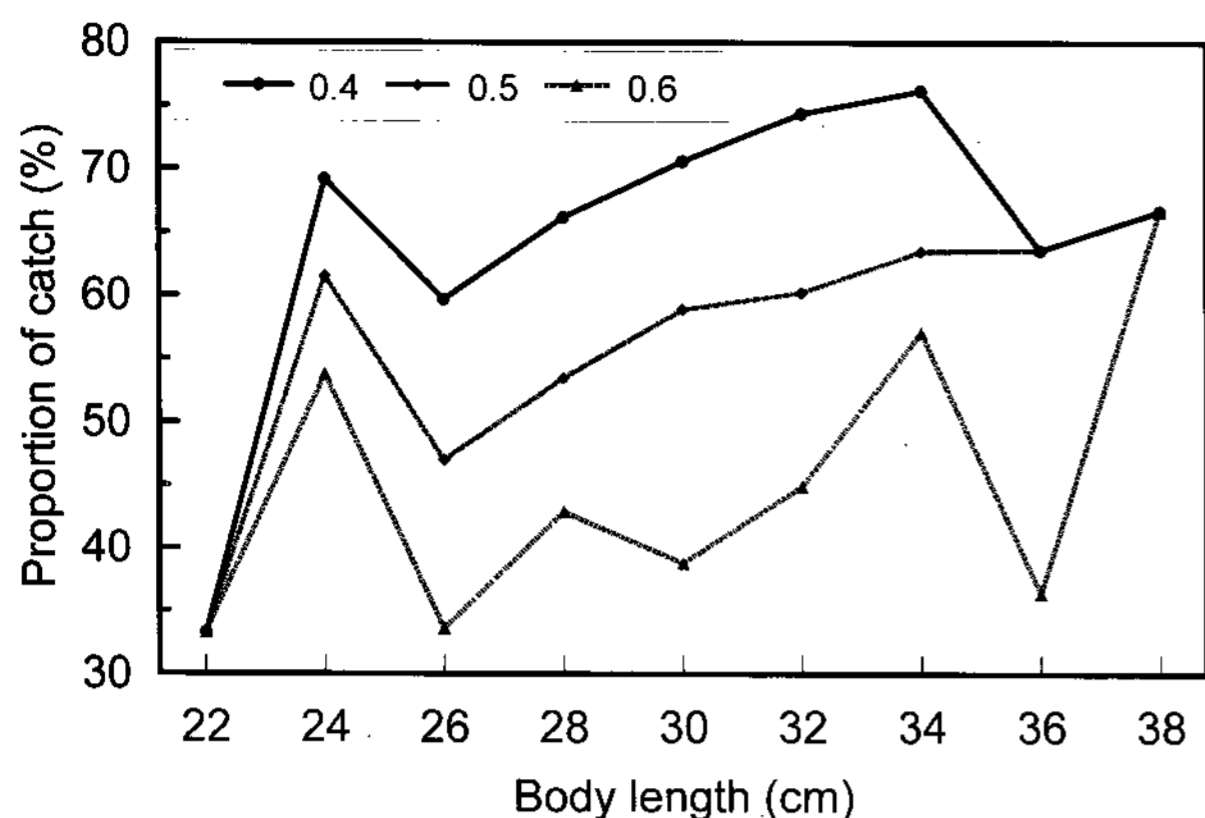


Fig. 8. The frequency distribution of retained fish for each rank of body length in the cod-end in relation to the looming threshold index $\lambda=0.4, 0.5$ and 0.6 , respectively, in eq (6) from the simulation results.

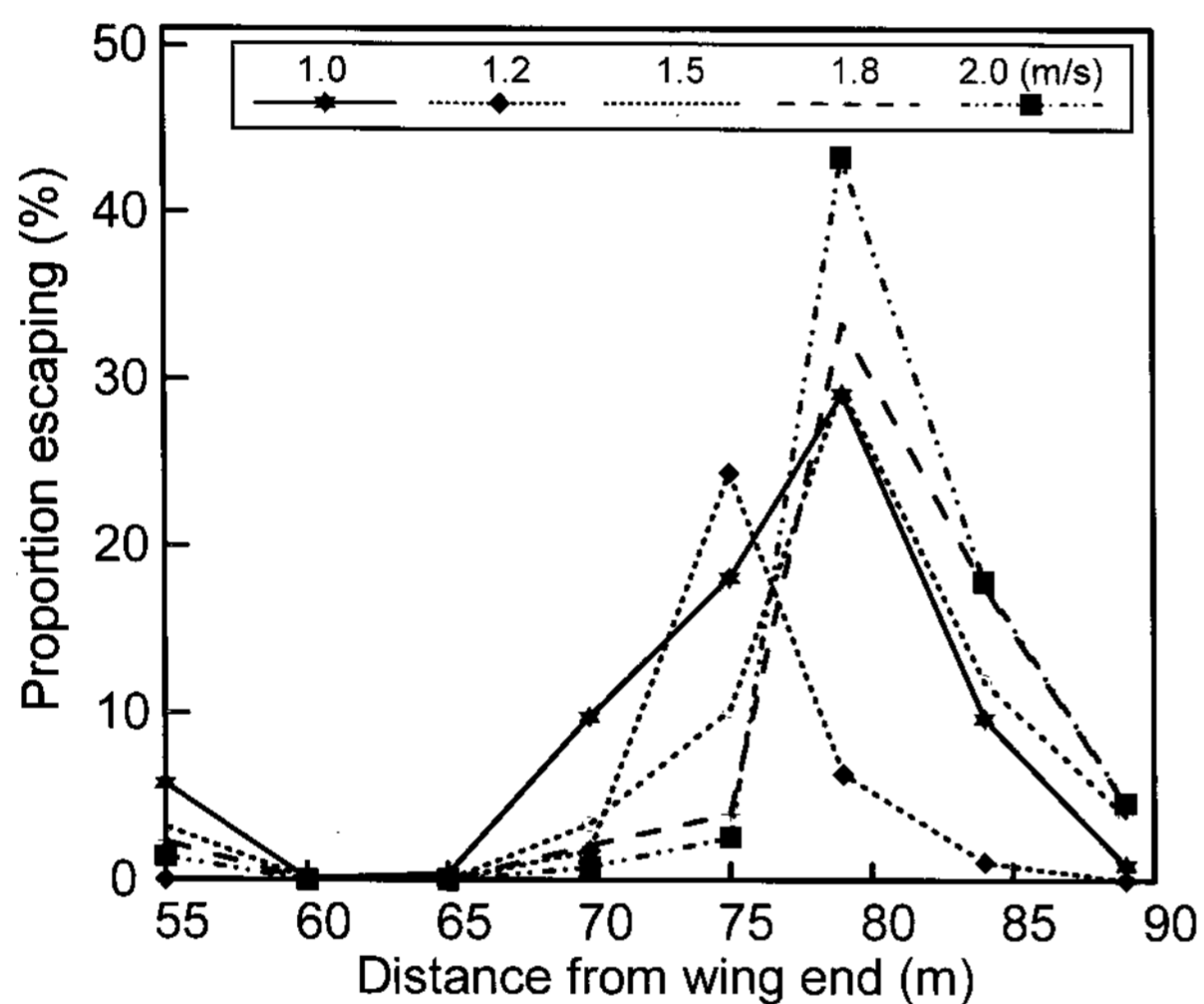


Fig. 9. The proportion of fish escaping in relation to distance along net from wing end of BT130C trawl when towing speed increased from 1.0 to 2.0 (m/s) and $\beta=\lambda=0.6$. Cod-end was between 79 and 89 m from wing end.

from 1.0 to 2.0 m/s, whereas selectivity slightly decreased when towing speed was increased from 1.3 to 1.8 m/s in field observations (Dahm et al., 2002). Chaotic variation in swimming components was effectively reproduced in our numerical model of fishing selectivity in the towing cod-end when compared to previous fish behavior models, such as swimming ability models (Kim and Wardle, 1997), sensitivity models (Kim, 1997; 1998), or reactions in trawl gear (Kim and Wardle, 2005). In our simulations, the escape response, which represents the selectivity of the cod-end, was modeled by variation in the intensity of the stimulus, the exhaustion index, the random panic ratio, the optomotor coefficient, and the

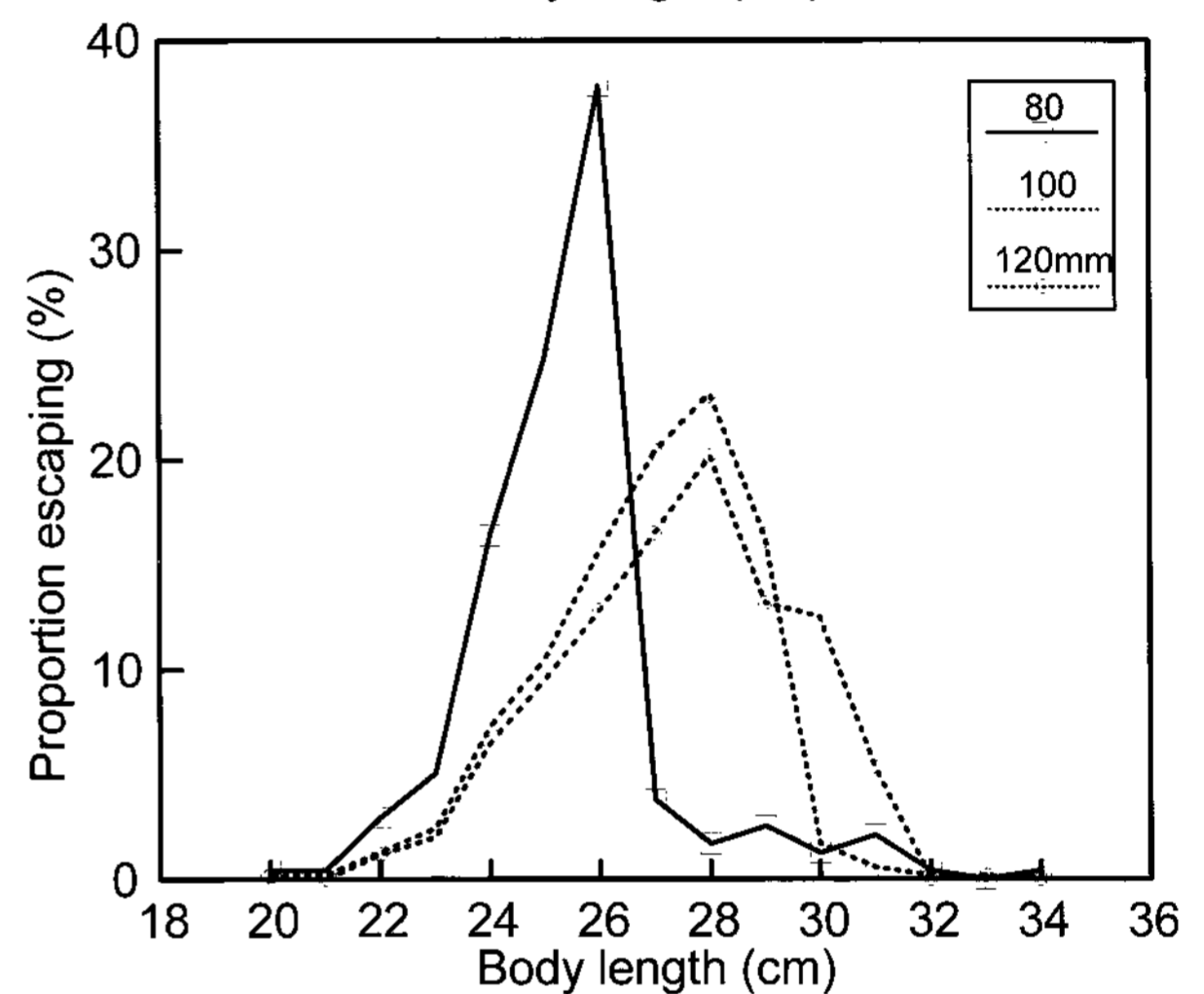
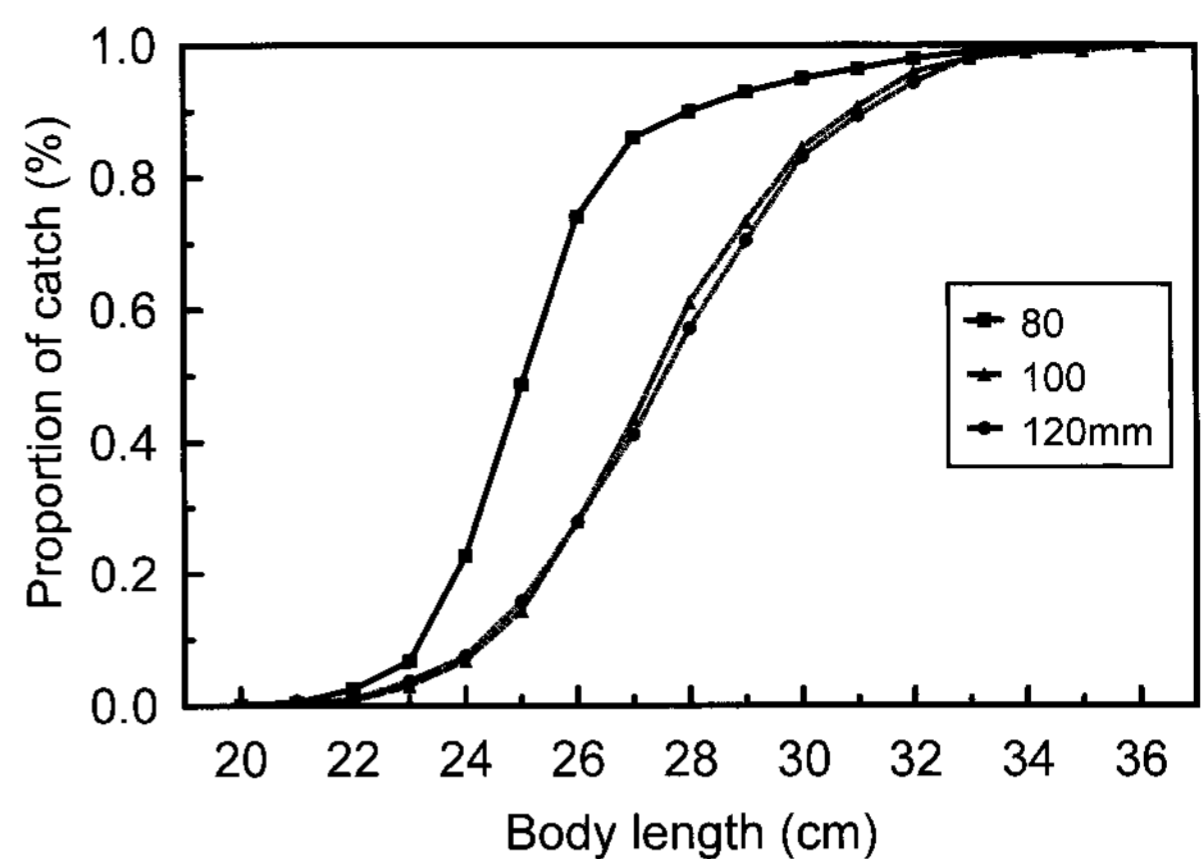


Fig. 10. Selectivity curve of haddock in the 80, 100 mm and 120 mm mesh cod-end (top) and proportion escaping with mesh sizes of 80, 100 and 120 mm (bottom) when the looming threshold index and coefficient of angular change were constant $\beta=\lambda=0.6$.

looming coefficient. The complex behaviors revealed by our model were similar to movements defined as erratic responses in the front part of a trawl (Kim and Wardle, 2003). The realistic behavior (i.e., swimming movements) of fish in the cod-end was summarized from observations and analyses of fish movements in square-mesh windows of a trawl cod-end (Fig. 1; Kim and Wardle, 2008). The main parameters in this selectivity model based on fish behavior in a cod-end were head direction, exhaustion, distance to net, angular change, swimming speed, mesh size, and voluntary penetration, all of which are integral aspects of the fish capture process in a cod-end. The basic algorithm of this selectivity model (as chaotic fish responses) differed from other selectivity models, such as the PRESMO model of the selection process in cod-ends (Herrmann, 2005; Herrmann and O'Neill, 2006). The PRESMO model assigned behavior para-

meters, such as time to entry of the cod-end, the period of time spent in the cod-end, the period of time during which fish swam without exhaustion, and the period of time between escape attempts. These times were given fixed values that were either random or related to body length. However, in our behavioral selectivity model, these parameter values encompassed fish responses during the entire capture process by assigning biological and physical values from experimental data and related basic models of fish swimming (Kim and Wardle, 1997). Therefore, our model can automatically generate and simulate fish movements from the otter board to the cod-end in three-dimensional space-time. In contrast to statistical models based on selectivity data (Fryer, 1991), our approach models the entire capture process of the trawl with realistic variation in the fish escaping behavior involved in the selectivity process. We offer our model as an experimental and basic approach to test the effects of behavioral factors in fishing gear selectivity models. When optimal parameter coefficients for each fish species and their behavioral characteristics are known, this type of model can be used to test the selectivity controls of new fishing gear designs. However, simulations using this selectivity model for gear with grid-windows (Larsen and Isaksen, 1993; Madsen et al., 2002; Kvamme and Isaksen, 2004) or black tunnel windows (Glass and Wardle, 1995) must be conducted with optimal parameter values for these particular gear types. Further study on various mesh sizes, mesh shapes, and gear sizes of towed fishing gear are necessary to compare field data of fishing selectivity.

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