

Simulation and Three-dimensional Animation of Skipjack Behavior as Capture Process during Purse Seining

Yong-Hae Kim*, Myeong-Chul Park¹ and Suk-Wun Ha²

Institute of Marine Industry, College of Marine Science, Gyeongsang National University, Kyeognam 650-160, Korea

¹*Department of Computer Information, Songho College, Gangwon 225-704, Korea*

²*Department of Computer Science, College of Natural Science, Gyeongsang National University, Kyeognam 660-701, Korea*

We modeled fish school movements as a capture process in relation to the purse seine method using the three steps of the stimulus-response process (i.e., input stimuli, central decision-making and output reaction). Input stimuli of the model were categorized as either physical stimuli such as visual stimulus, sound stimulus, water flow, and weather or as biological stimuli such as species and size, swimming performance, sensual sensitivity, and presence of prey or predators. The output process determining the spatial orientation of the fish school for 3-D movements was based on swimming speed and angular change in the fish response, and these movements were animated as the relative geometry between the fish school and the purse seine. Simulations were carried out for skipjack tuna (*Katsuwonus pelamis*) schools reacting to a pelagic purse seine in the southwest Pacific Ocean. Simulation results showed that escape ratios varied from 20 to 70% by the relevant ranges in the stimulus-response thresholds, swimming speeds, and angular changes of fish schools were similar to those observed in the field. Therefore, with knowledge of relevant parameters, this model can be used to predict capture and escape probabilities of purse seine operations for different fish species or conditions.

Key words: Fish capture process, Simulation, Purse seine

Introduction

The capture process in purse seine operations is decided by a combination of the dynamic movements in net operation and the reactions of fish schools, which are mostly species that show strong schooling, high swimming performance, and high sensitivity to visual and sound stimuli. The main factors determining a successful catch in such operations are physical parameters such as size and sinking speed of the net and shooting or pursing speed of the vessel, as well as biological parameters such as sensitivity to stimuli, swimming performance, and escape response behavior of the species, and physiological factors (Ben-Yami, 1994). Reasons for the escape of fish include sound, which is mainly noise made by the fishing vessel (Misund, 1993; Freon and Misund, 1999), visibility and visual recognition (Kim, 1998; Kim and Wardle, 1998), decrease

in the surrounding net space by pursing (Kim, 1999; Kim, 2000), and the remaining gate space during pursing (Park et al., 1997; Chang et al., 2002). In skipjack tuna (*Katsuwonus pelamis*) purse seining, the daytime success rate in shooting trials was about 50% (Shimozaki et al., 1975; Kim and Huh, 1987). The most important point for a successful catch with the purse seine is to predict complex fish schooling behavior and to prevent the generation of an escape response by control of the dynamic changes in underwater net geometry. Misund (1992) conducted a study on the prediction of mackerel school tracks in purse seine operations by recording the relative swimming speed and relative heading of fish schools in relation to the vessel heading. A basic model of fish behavior in relation to the purse seine shape by the mess-spring model has been introduced (Lee et al., 2006; Kim et al., 2007). However, this particular model does not include behavioral factors such as stimulus sensitivity or swimming performance in pre-

*Corresponding author: yonghae@gnu.kr

prediction of the catch-escape ratio.

We therefore constructed a more realistic model to predict the catch process of the skipjack purse seine with three stimulus-response steps (input stimuli, central decision-making, and output reaction) and using a modification of a previous complex chaotic behavior model of towed fishing gear (Kim and Wardle, 2005). Simulation with this model was carried out by adopting new definitions of behavioral parameters such as the stimulus-response threshold, and this was related to model dynamic changes of the net geometry in time-elapsing steps of purse seine operations.

Materials and Methods

Modeling methods

The capture process in a purse seine operation is outlined in Fig. 1. Fishing grounds, fishing gear geometry, and the response of fish schools are related according to basic observations and analyses (Kim, 2007). Fish behavior in relation to the capture process of the purse seine was defined by three steps of the stimulus-response process (input stimuli, central decision-making and output reaction; Giske et al., 1998; Kim and Wardle, 2005) as follows.

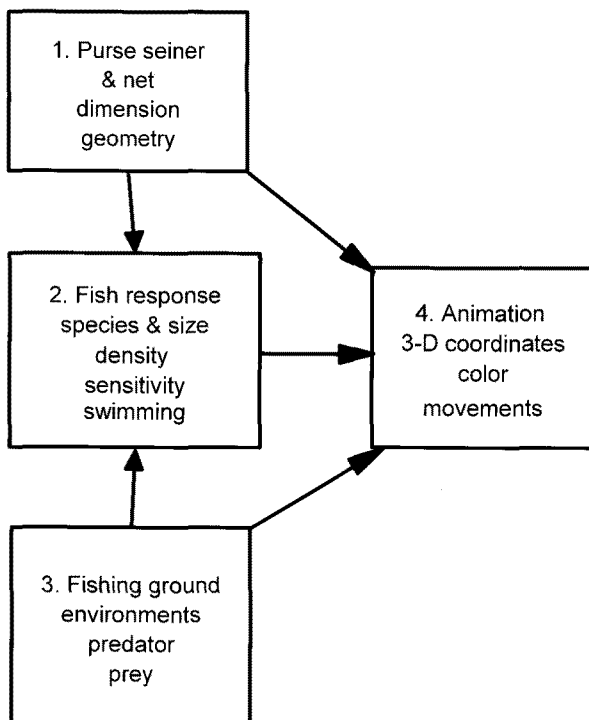


Fig. 1. Block diagram of the main elements in the fish capture process in the purse seine operation.

Input stimuli

Input stimuli in purse seine operations (Ben-Yami, 1994; Wardle, 1993) were categorized mainly as physical stimuli and biological stimuli. The physical stimuli included visual stimulus of the net, sound stimulus of the fishing vessel, water flow due to currents, water temperature, weather, and waves. The biological stimuli included fish species and size, prey, predators, swimming performance, vision and sound sensitivity, and panic index of the school (Wild and Hampton, 1994; Hara and Zielinski, 2006). The visual stimulus S_V representing the strength of visual contrast of the purse seine can be estimated by the model of the visual stimulus of the net (Kim and Wardle 1998) under given underwater environmental variables such as surface light intensity, light attenuation coefficient, relative geometry between fish and net, visual contrast threshold, and angular acuity of the fish eye (Nakamura, 1968; Kim, 1998). Geometry of the purse seine during shooting and pursing was simulated in accordance with net size and net specifications under the specific current conditions and pulling or pursing power of the vessel (Shimozaki et al, 1988; Kim, 1999; Park et al., 1999). The visual stimulus S_V was generalized between 0 and 1 as the visual apparent contrast C_R divided by the contrast threshold of a fish and visual looming of the nearest net strips under purse seine geometry by the visual stimulus model (Kim and Wardle, 1998). The sound level S_L (dB re 1 μ Pa) at distance D_S and frequency f (Hz) was estimated from source level S_0 (dB re 1 μ Pa at 1 m) produced by the purse seiner or skipper (Misund, 1993) by the deduction of noise S_N modified from Urlick (1996) as follows:

$$S_L = S_0 - 20 \log D_S - 0.5 f^2 D_S - S_N \quad (1)$$

Sound stimulus S_S , modified from Bleckmann (1993), was expressed as follows:

$$S_S = \log (S_L^2 / D_S^3) \quad (0 \leq S_S \leq 1) \quad (2)$$

where S_L is the sound level and D_S is the distance.

A fish school may have learned by experience, having previously encountered purse seines. The fish may recognize the seines as a threat and therefore increase their awareness of the netting-generated visual stimulus or the sound of the vessel and react quickly. In such cases, their behavior becomes more sensitive and could be changed in the model by multiplication of the strength of stimuli such as the visual C_V and sound S_S cues and time t as defined by the experience index E_S as follows:

$$E_S = (C_V S_{S(t)})/t \quad (0 \leq E_S \leq 1) \quad (3)$$

The water flow stimulus S_F was defined as the mean flow speed between the depth profiles as a vector. The stimulus of weather S_W was defined as the product of cloud ratio R_C and wave height W_H (m) (Kim and Wardle 1998), affecting fish behavior from information offered by fishermen. The presence of prey during purse seine operations (Magnuson, 1969; Ménard et al., 2000; Ménard and Marchal, 2003) was very common. When the object fish school had gathered and was feeding on prey it was assumed that there was more active movement of individual fish in the school but less change in movement of the school as a whole. With increased distance from prey or with lower density of prey, the target fish school showed more searching behavior and greater movement. The prey stimulus S_P was formulated as the distance to the prey D_P and the density of the prey P_D as a random value between 0 and 1 as follows:

$$S_P = \delta P_D D_P / D_N \quad (0 \leq S_P \leq 1) \quad (4)$$

where D_N is the horizontal radius of the purse seine shooting, and δ is a coefficient. Predators such as whales, porpoises, and sharks are especially common in the skipjack purse seine fishery even after shooting and could affect fish behavior (Hall et al., 1986; Fuiman, 1993; Furuichi, 2002). We assumed that with increased proximity of the predator, the panic behavior of the fish school would be greater, and with increased aggressive behavior of the predator, the escape behavior of the fish school would be more sudden. Therefore, the predator stimulus S_D was formulated with the random aggressiveness of predator N_Q between 0 and 1 and the distance from fish to predator D_D with slope α as follows:

$$S_D = \alpha N_Q (D_N / D_D)^{1/2} \quad (0 \leq S_D \leq 1) \quad (5)$$

The other factor of fish behavior was the random panic index N_P (Kim and Wardle, 2005) for either an individual or a school (Viscido et al., 2005). This was modeled by adopting a random ratio between 0 and 1 using a normal distribution.

Central decision-making

Chaos equations for the complex behavior of fish movements were adopted from previous modeling of fish behavior in relation to trawl gear (Kim and Wardle, 2005) and redefined from the 3-D dynamics of chaos theory (Lorenz, 1979) as follows:

$$\begin{aligned} dU/dt &= K(W-U), & dW/dt &= MU-UV-W, \\ dV/dt &= UW-V \end{aligned} \quad (6)$$

Three of the variables in the above equations are movement components that are used to define fish

responses. U is proportional to the vertical movement response to the stimulus, W is proportional to the horizontal angular velocity of the fish, and V is proportional to the swimming speed of the fish. The parameter K is the coefficient of response filtering, and M is the coefficient of stimulus variation. Parameters K and M were adopted as cosine oscillation functions by Fourier expansion (Dorning et al., 1992). K and M in Eq (6) were fixed with limited ranges for K (1 6) and M (5 20) in order to limit the intensity of the stimuli in their multiple interactions (Kim and Wardle, 2005) as follows:

$$\begin{aligned} K &= (1+5 K_0) \cos\{(2+6 K_1) t\} \\ M &= (5+15 M_0) \cos\{(6+12 M_1) t\} \end{aligned} \quad (7)$$

Parameters K_0 , K_1 , M_0 , and M_1 were normalized between 0, giving steady variation of movement components such as those characterizing a straight linear response, and 1, providing an upper limit for the most irregular variation of a klinokinesis response. These four parameters were generalized between 0 and 1 by a combination of previous input factors as follows. K_0 was defined by the visual index on the nets S_V and stimulus of the weather S_W as follows:

$$K_0 = S_V + (1-S_V) S_W \quad (8)$$

K_1 was defined by the prey index S_P in Eq (4) and the stimulus of water flow S_F as follows:

$$K_1 = S_P + (1-S_P) S_F \quad (9)$$

M_0 was defined by the sound stimulus S_S in Eq (2) and the experience index E_S in Eq (3) as follows:

$$M_0 = S_S + (1-S_S) E_S \quad (10)$$

M_1 was defined by the predator index S_D in Eq (5) and random panic index N_P as follows:

$$M_1 = S_D + (1-S_D) N_P \quad (11)$$

When these four parameters were inserted into Eq (7) and then Eq (6), the values of variables U , V , and W with time were solved to produce 100 of each of the values within one time step normally representing 1 second. These changeable values of variables U , V , and W representing the movement parameters were used as selected and optimized in the output processing of fish movements.

Output reaction

The output response of the fish school in this behavior model of purse seine operations was mainly estimated as spatial movements in relation to the purse seiner and the netting. Therefore, the movements of the fish school were tracked with polar

coordinates (Kim and Wardle, 2005) indicating horizontal and vertical directions. Swimming speeds, which are more suitable indicators of aquatic animal movement behavior, were also measured. The output process for swimming speed and angular change of the fish response in relation to the purse seine were categorized by the kind and intensity of stimuli under relative geometry between the fish school and stimuli as mentioned previously. These main stimuli were the sound stimulus, the visual stimulus, and the predator stimulus. In order to limit a maximum response distance of fish in relation to sensitivity of fish such as vision (Kim, 1998), sound (Hawkins, 1993), and predators (Aksnes and Utne, 1997), the minimum response intensity of each stimulus as a stimulus-response threshold was adopted: R_S in relation to the sound stimulus S_S , R_V in relation to the visual stimulus S_V , and R_D in relation to the predator stimulus S_D . The actual limit of a minimum approaching distance of fish was estimated by the substitution of the stimulus-response threshold, instead of relevant intensities of the stimuli, into each relevant equation. The resultant stimulus vector was calculated by S_1 and S_2 as the highest stimulus (S_{1st}) and the second-highest stimulus (S_{2nd}) among stimuli. If S_{1st} was greater than the relevant intensity of the stimulus-response threshold, the range of angular change A_R became active. The actual angular change of fish heading A_F was then calculated as follows:

$$A_F = A_R N_P W_T / W_M \cos(\omega t) \quad (12)$$

where W_T contains time series values of Eq (6), and W_M is the maximum value of W_T . When the response threshold (R) is greater than the relevant stimulus (S), $\omega=0$, otherwise $\omega=1$. The horizontal swimming speed V_H was estimated by the sum of the highest two stimuli as $S_{1st}+S_{2nd}=S_{12}$ as follows:

$$V_H = V_F N_P S_{12} V_T / V_M \quad (13)$$

where V_T contains the time series values of Eq (6), and V_M is the maximum value of V_T . If the sinking index $S_1=(S_W+S_D+S_V)N_F$ is greater than the sinking response threshold R_K , the vertical sinking speed V_V can be calculated as follows:

$$V_V = \beta V_F N_P S_{12} U_T / U_M \quad (14)$$

where V_F is the prolonged swimming speed of fish with a coefficient β (Yuen, 1966; 1970; Magnuson, 1978; Videler and Wardle, 1991; Kim and Wardle, 1997; Syme and Shadwick, 2002), U_T contains the time series values of Eq (6), and U_M is the maximum value of U_T .

Simulation methods

The purse seine net used for skipjack tuna in the Pacific Ocean for field commercial operations had a rectangular shape (2,264 m in float line length and 160 m in vertical depth for the simulation). Shape changes were estimated in each of the 300 net nodes in the horizontal and 40 nodes in the vertical dimension at 1-s intervals and represented by 3-D coordinates. The fishing operation time (Kim and Huh, 1987; Kim, 2007) in this simulation was 7 min for shooting in a counter-clockwise direction and circling with a 400-m radius, 3 min for pulling each of the end wings, and 15 min for pursuing each of the purse lines. The simulation was performed with time steps of 1 s for calculating the position of the fish school. The sound intensity of the purse seiner or skipper was set so that $S_0=190$ dB (re 1 μ Pa at 1 m) and $f=200$ Hz (Seo et al., 1989; Myrberg, 1990; Misund, 1993; Urlick, 1996) in Eq (1) and a skipper moved between the two wing ends while generating sound noise (Scholik and Yan, 2002) after shooting. The underwater noise in fishing grounds of the southwest Pacific Ocean was set so that $S_N=90$ dB (re 1 μ Pa) considering weather and waves according to the measurements of Yoon (1985) and Park (1985). The fishing ground for field fishing operations was set at Lat. 7.90 S and Long. 160.70 E in the southwest Pacific Ocean; other settings were clouds 0.5 and wave height 1.0 m with the start of fishing operations at a local time of 12:30 on 9 April 2004. Underwater turbidity was set with a vertical attenuation coefficient of 0.02 and a light beam attenuation coefficient of 0.2. The depth profiles at depths of 10, 60, and 110 m (Février et al., 2000; Kim et al., 2007) were assigned water temperatures of 29, 27, and 25 C current speeds of 0.2, 0.3, and 0.3 m/s, and absolute flow directions of 17, 197, and 217 respectively, from field observations. The size of skipjack tuna was generated using a normal random distribution with a peak body length of 50 cm and a deviation of 10 cm (Olson et al., 2006). The density of prey (P_D) and the aggressiveness of the predator (N_Q) were held between 0 and 1. Positions of predators within a 400-m radius were also generated using a normal random distribution. The relevant sensitivity coefficients for skipjack were adopted for vision (Nakamura, 1968; Kim, 1998; Fritsches et al., 2005) and sound (Hawkins, 1993; Hara and Zielinski, 2006). The swimming speed of the skipjack school was estimated by the model of swimming ability by Kim and Wardle (1997) and Syme and Shadwick (2002). The sinking speed coefficient β in Eq (14) was 0.5, assuming half of the prolonged swimming speed

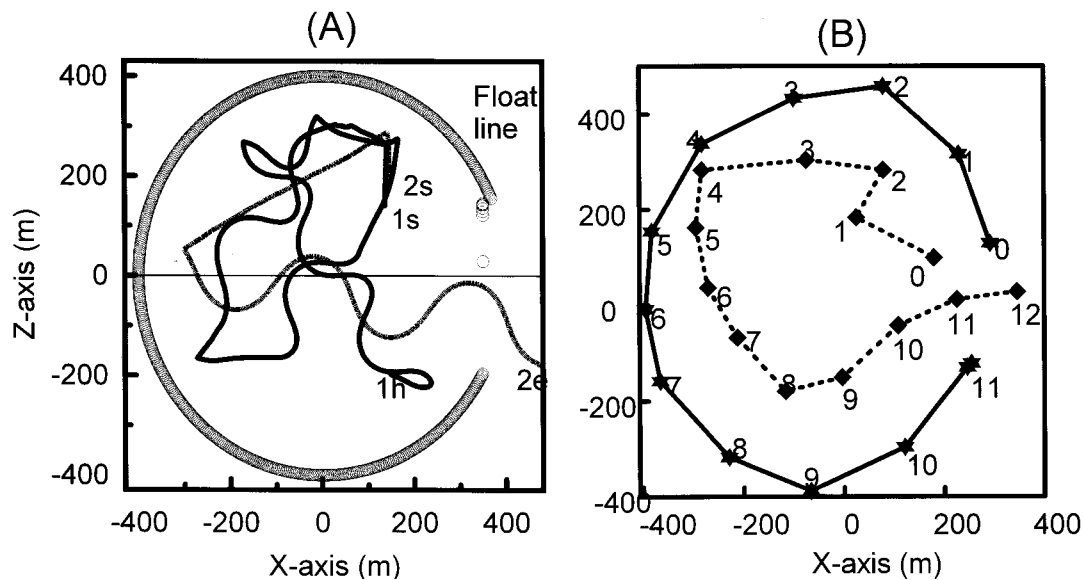


Fig. 2. Examples of the horizontal tracks of two skipjack schools by the simulation (A) as an escape case between wing ends and others herding when the sound response-threshold R_S was 0.7 under the constant $R_V=0.7$ without a predator. The observation results (B) from Kim (2007) are for an escape of skipjack school by every minute where numbers denote each school; s, means start position; h, herding; and e, escape.

(Kim and Wardle, 1997) derived from Schaefer and Fuller (2007). The prey density coefficient δ in Eq (4) was 4. A test simulation was carried out by changing the intensity of the stimulus-response threshold. In particular, R_S was set to 0.6, 0.7, and 0.8 in relation to the sound stimulus in Eq (2), and R_V was set to 0.6, 0.7, and 0.8 in relation to the visual stimulus. Skipjack school size was set at L30, B30, D10 m in accordance with field observations (Kim, 2007). Each skipjack was assumed to have the same biological characteristics, and random parameters such as sensitivity, threshold, and swimming ability were constant for one simulation of a fishing operation (i.e., the same for all fish in a school). For each set of fixed conditions with relevant parameters, 100 skipjack schools, each with unique, randomly generated biological factors such as sensitivity and panic tendency, were tested for their 3-D track of the central fish in the school. The swimming movements of skipjack schools were observed onboard a commercial tuna purse seiner (800 G/T) of an offshore fisheries company in the southwest Pacific Ocean near the Solomon Islands (Kim, 2007). The observations were conducted by scanning sonar (Furuno-FSV24) during April 2004 and February-April 2006. The general dimensions of the purse seine used in the field study were 2,264 m of float line and 2,480 m of lead line. The swimming speeds and changes in heading of the skipjack school in the field observations (Kim, 2007) were compared to the results of

simulations.

Results

The simulation results for 100 skipjack schools with variation of relevant parameters such as stimulus-response thresholds were represented as 3-D tracks along with catch-escape ratios, and they were related to the changing geometry of the purse seine during the fishing operation. The simulated horizontal

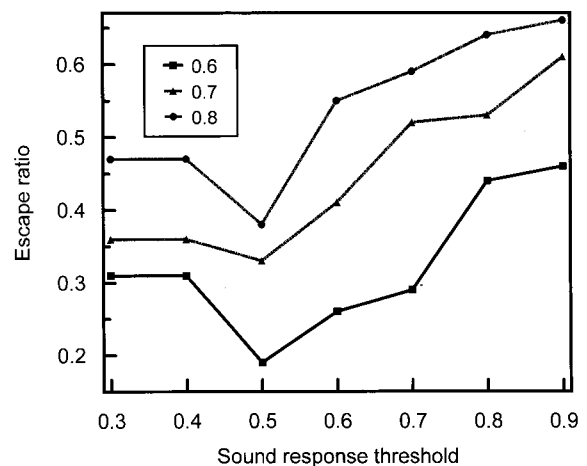


Fig. 3. The escape ratio of skipjack school in relation to the sound response threshold R_S from 0.3 to 0.9 in accordance with the visual response threshold $R_V=0.6-0.8$ under no predator case.

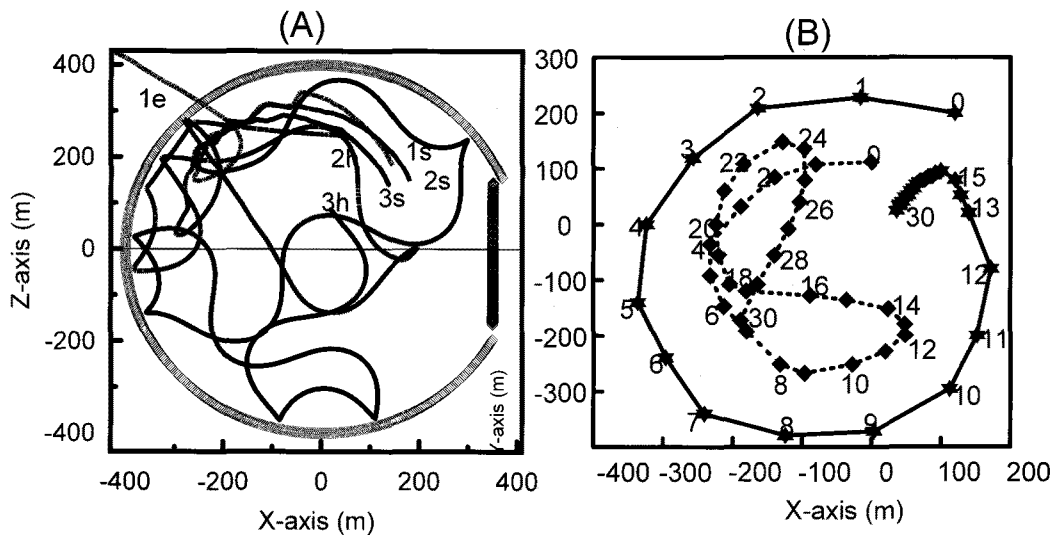


Fig. 4. The horizontal tracks of 3 skipjack schools when the visual response threshold R_V 0.9, and $R_S=0.7$ without predator by the simulation (A). A skipjack school escaped underneath the leadline before the net reached that depth while the other two schools were herded and caught. The observation result (B) represents a herding skipjack school by every minute from shooting to pursuing from Kim (2007).

tracks of the skipjack school from shooting to pursuing operations when the sound-response threshold R_S was changed from 0.5 to 0.7 under a constant R_V of 0.7 and no predators are shown in Fig. 2(A) as examples along with actual observations of an escaping skipjack school in Fig. 2(B). The escape ratio of the skipjack school in 100 fishing trials increased when the sound response threshold R_S was changed from 0.3 to 0.9 in accordance with the visual response threshold $R_V=0.6-0.8$ without predators as shown in Fig. 3. A minimum escape ratio of 20% was found at $R_S=0.5$ and $R_V=0.6$, and a maximum value of 65% was found at $R_S=0.9$ and $R_V=0.8$. Although the escape ratio did not change linearly, the sound response threshold R_S served to control the escape ratio in relation to the awareness of the fish school to the fishing boat. The simulated horizontal tracks of the skipjack school from shooting to pursuing operations when the visual response-threshold R_V was changed from 0.7 to 0.9 under a constant R_S of 0.7 without predators are shown in Fig. 4(A) as examples along with actual observations of a herding skipjack school in Fig. 4(B). The nearest distance from the fish school to the nets decreased with an increase in the visual response threshold R_V . Their meandering curves were similar to the field observations of herding skipjack schools. When the visual response threshold R_V was changed from 0.3 to 0.9 in accordance with the sound response threshold $R_S=0.6-0.8$ without predators, the escape ratio of skipjack schools in 100 fishing trials increased as shown in Fig.

5. A minimum escape ratio of 12% was revealed for $R_V=0.4$ and $R_S=0.6$, and a maximum value of 65% was found for $R_V=0.9$ and $R_S=0.8$. As the escape ratio changed linearly with the sound response threshold R_S , it served to predict the catch or escape ratio by awareness of the fish school to the sound level of the capture process of the purse seine. Swimming speeds during herding and escape of skipjack schools in the simulations and field observations are shown in Fig. 6.

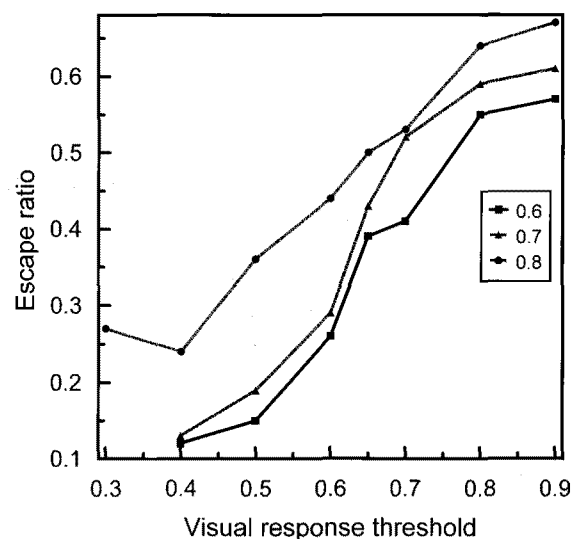


Fig. 5. The escape ratio of skipjack school in relation to the visual response threshold R_V from 0.3 to 0.9 in accordance with the sound response threshold $R_S=0.6-0.8$ without predator.

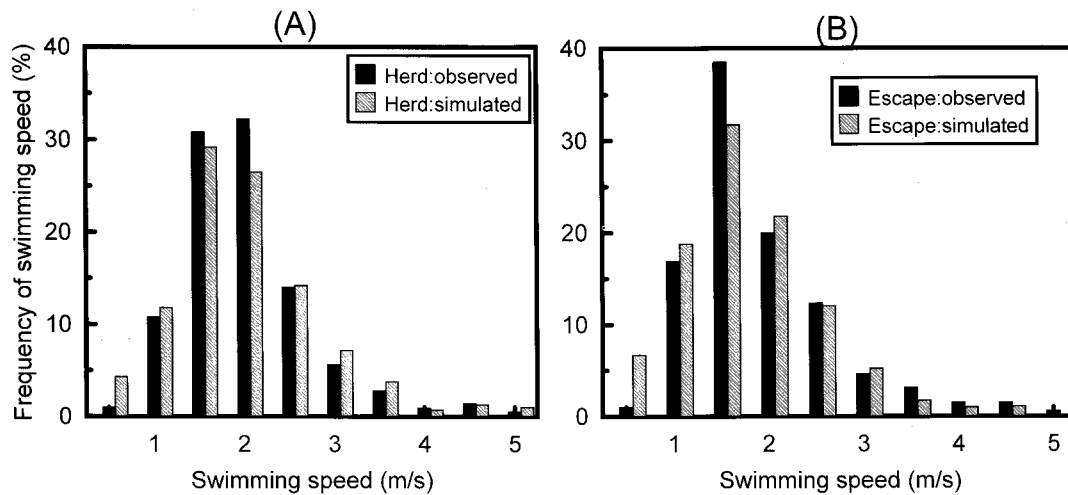


Fig. 6. Frequency of the swimming speed when herding (A) and escape (B) skipjack schools in comparison between the results of the observations and the results of the simulations.

The frequencies of swimming speeds in Fig. 6 represent gamma distributions. There was no significant difference ($p>0.1$) in swimming speed either between the observations and the simulations or between the herding and the escaping skipjack schools; the range of mean swimming speed was 1.9-2.3 m/s, similar to 1.7-2.2 m/s in the field observations. There was no significant difference ($p>0.1$) in changes of swimming direction either between the observations and the results of the simulations or between herding and escaping skipjack schools; the variation in swimming direction was 100 m in the field observations. The tracks of the skipjack school indicated more avoidance reactions near predators. The escape ratio increased from 23 to 70% and predator index α increased from 0.1 to 0.5, respectively, as in Eq (5). The escape ratio with predators was about 10-30% higher than without predators. Frequencies of herding or escape skipjack when the predator index $\alpha=0$ or 0.3 were combined with the panic index N_p , which was increased from 0.2 to 1.0 in increments of 0.1, with and without predators as shown in Fig. 7. The escape ratio and the herding ratio were significantly different with and without predators ($p<0.001$), but the escape ratio was not significantly different with and without predators for each escape ratio and panic index frequency ($p>0.1$). Therefore, these results show complex characteristics in this behavior model by the main parameters as well as the panic index of fish. Examples of horizontal skipjack tracks were calculated for the sinking mode by Eq (14) with the sinking response threshold $R_K=0.9$ and $S_S=S_V=0.7$. The tracks are shown for escape underneath the lead-

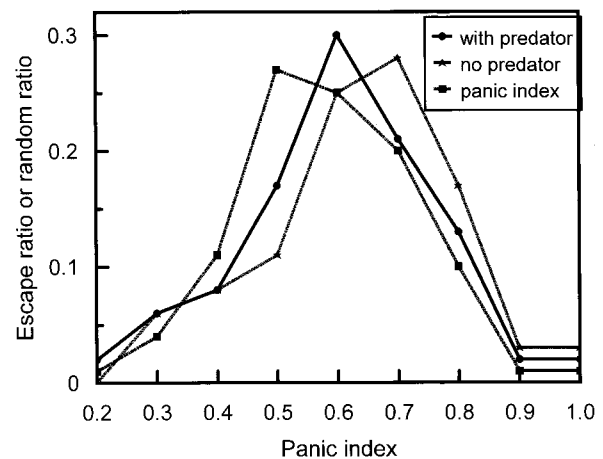


Fig. 7. The escape ratio of skipjack schools in relation to the panic index N_F in comparison with predator index $\alpha=0.3$ or without predator, i.e. $\alpha=0$ under constant $R_0=0.7$.

line or another horizontal escaping skipjack school between the wing ends with the sinking response in Fig. 8. The sinking speeds from the simulation ranged from 0.8 to 1.7 m/s. The escape ratio of skipjack schools when the sinking mode was calculated by Eq (12) with the sinking response threshold R_K increasing from 0.85 to 1.0, with $S_S=S_V=0.6, 0.7$, or 0.8, is shown as the sinking escape ratio along with the total escape ratio in Fig. 9. A higher sinking response threshold R_K means more reluctance to sink, and the escape ratio by the sinking response decreased linearly with the sinking response threshold R_K . The range of escape ratio by the sinking response was about 10-37%, and it increased with higher S_S or S_V . Examples of the still images from 3-D animation of

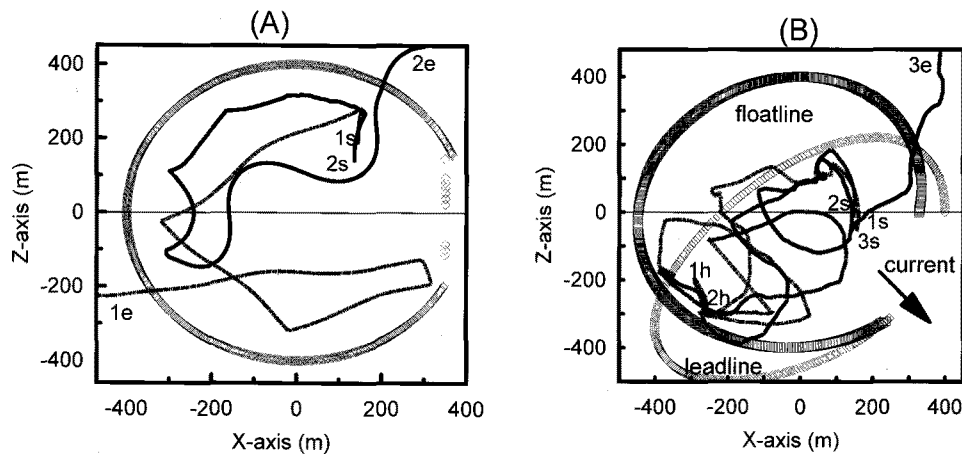


Fig. 8. Examples of horizontal skipjack tracks when calculated for the sinking mode with the sinking response threshold $R_K=0.9$ under constant $S_S=S_V=0.7$ for escape underneath the lead line when no current (A) and when two layer currents (B).

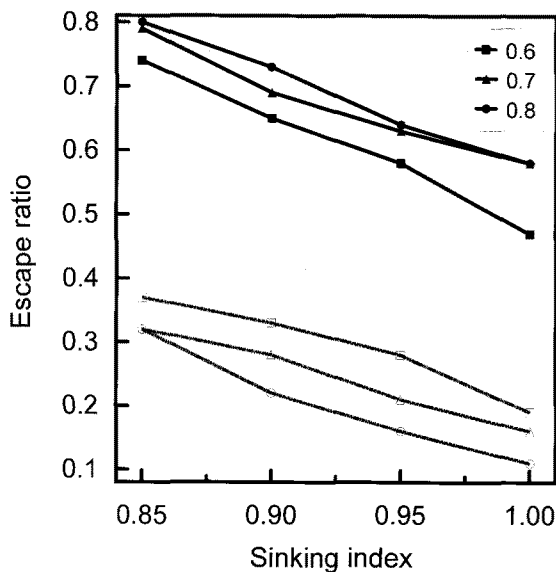


Fig. 9. The escape ratio while sinking response (dotted line with empty symbols) with total escape ratio (solid line with filled symbols) in relation to the sinking response threshold $R_K=0.85-1.0$ with $S_S=S_V=0.6-0.8$.

the skipjack school in relation to the geometry of the purse seine are shown in Fig. 10. The full animations can be viewed at <http://mirbada.gsnu.ac.kr/purse-behaviour/>.

Discussion

The simulated moving tracks, variation in swimming speed, swimming direction, and escape behavior were all similar to the results of field observations of skipjack schools (Kim, 2007) or mackerel schools

(Misund, 1993). Therefore, this model might be used to predict the probability of success as well as how to drive a fish school to prevent escape by modifying relevant stimuli. The ratio of schools caught to those escaping in relation to school size in this model can be controlled by the main behavioral parameters such as stimulus-response thresholds by adapting catch data from fishing operations (Kim and Huh, 1987; Ben-Yami, 1994; Trigueros-Salmeron and Ortega-Garcia, 2001; Marcelo, 2003). Our model adapted the fish school response to multiple stimuli using a response threshold algorithm with a chaotic behavior equation differing from the response area concept of Inada and Kawachi (2002), Zheng et al. (2005), and Goodwin et al. (2006) for natural movements of fish schools. However, school formation of skipjack was not included in this model because of the lack of field observation data. Therefore, school formation and movements of skipjack during the capture process in purse seine operations need to be observed quantitatively to estimate response distance with sensitivity, swimming speed, and turning maneuvers. The meandering curves of simulated tracks by skipjack schools are similar to field observations for skipjack (Kim, 2007) or mackerel (Misund, 1992; 1993) in both the herding case and the escape case. The model also revealed very complex and irregular variation in tracks through variation of swimming speed and turning direction by changing relevant parameters of response thresholds. The mean swimming speed of skipjack schools for herding and escape ranged from 1.9-2.3 m/s in the simulations and 1.7-2.2 m/s in field observations respectively. These speed ranges are considered to be just below the maximum aerobic

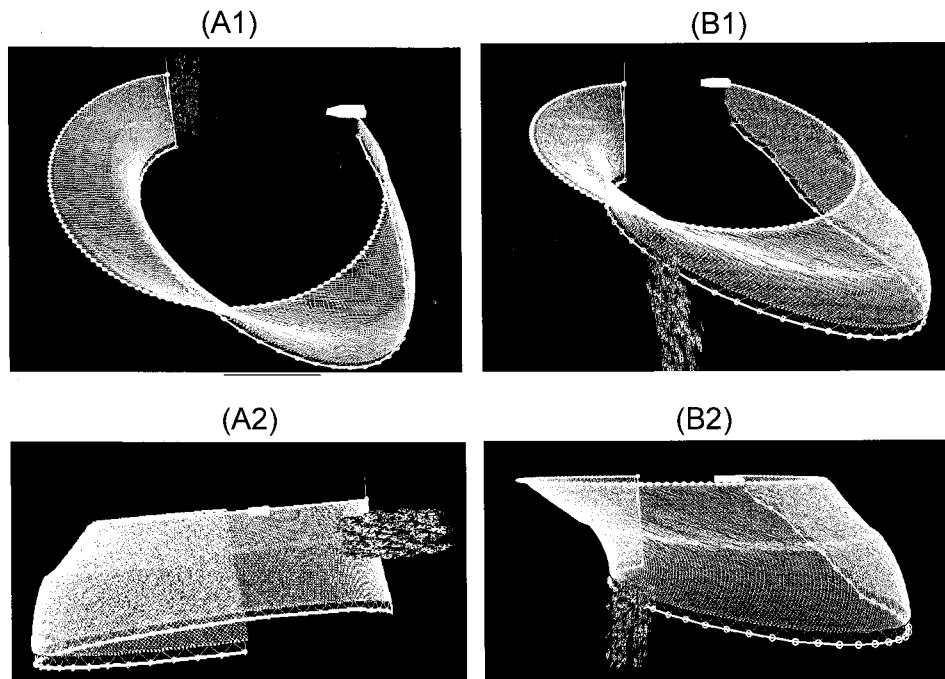


Fig. 10. Two examples of still images from the 3-D animation of a skipjack school showing herding response in relation to the geometry of the purse seine. A skipjack school escapes between the wing-ends (A1,2) data from a skipjack school in Fig. 2(A) and a school escapes underneath the leadline (B1,2) in Fig. 4(A).

swimming speed of skipjack of 4.6 body lengths (BL)/s (Syme and Shadwick, 2002), while maximum burst swimming speed is about 20 BL/s (Yuen, 1970). The swimming speed of skipjack schools in BL/s in pelagic purse seining was similar to that of Atlantic mackerel during purse seining (Misund, 1992; 1993). The frequency of the swimming speed of a skipjack school fit a gamma distribution for all cases of simulation and observation, and herding or escaping, similar to the natural schooling model of Inada and Kawachi (2002). The maximum sinking speed of skipjack in natural diving movements from the observation results by Schaefer and Fuller (2007) was estimated to be at least 2.3 m/s. Therefore, the sinking speed of skipjack when encountering a net was estimated with coefficient $\beta=0.5$ in Eq (14) as half of the prolonged horizontal swimming speed reported by Kim and Wardle (1998) because of the lack of observed data on sinking speed in skipjack capture processes. Examples of sinking speed by the simulation revealed a reasonable range of 0.8-1.6 m/s lower than the maximum sinking speed. However, direct observation of the sinking speed of skipjack in purse seining is necessary in the future. The variation of turning direction of skipjack schools in simulations and observations was normally distributed, with peak frequencies of -30-0 and range between ± 100 similar

to the maximum individual direction in a fish-schooling model (Inada and Kawachi, 2002). The visual sensitivity of skipjack requires more detailed study on visual contrast thresholds and fast frequency thresholds considering water temperature (Fritsches et al., 2005), which were not included as a factors in the visual sensitivity model proposed by Kim (1998). The sound stimulus and sensitivity of skipjack, which, like mackerel (Misund, 1993), lack a swimbladder, was expressed by the simple formula of Eq (2) in this model. However, a more realistic model for sound reception and response should be formulated as sound pressure and distribution by the purse seiner (Urlick, 1996) in relation to sound reception and sensitivity to sound along lateral lines (Scholik and Yan, 2002).

In conclusion, this model could be extended for any kind of purse seine operation, both coastal and pelagic, to predict the catch ratio for different underwater conditions, different species, or different net designs by adjusting the present model and by adapting more detailed and relevant parameters as mentioned above.

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