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Instruments and Methods

Development of a new multiple sampling trawl with autonomous opening/closing net control system for sampling juvenile pelagic fish

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ABSTRACT

A new multiple layer sampling trawl with an autonomous net opening/closing control system was developed to sample pelagic juvenile fish quantitatively. The new trawl system, based on the Matsuda–Oozeki–Hu Trawl (MOHT), has a rigid-frame 3.3 m high and 2.35 m wide and five nets of 11.0 m length with a rectangular mouth of 2.22 m $\times$ 1.81 m (4 m^2 mouth area; large-scale prototype). A cambered V-shape depressor is hung below the frame and two bridles are attached at the midpoint of the side frames. A net-release controller is used, which not only controls the net release mechanism but also records the net depth, temperature and flow rate during net towing. The controller sends stored command signals to the net release mechanism as depth settings and/or time settings and does not require any commands from the surface through a conducting cable or by acoustic signals. Two other models were constructed before the construction of the large-scale prototype, which are a small-scale prototype (2 m^2 mouth area) for testing the net release mechanism and a 1/4-scale model of the large-scale prototype for flume tank tests. Flume tank tests with the 1/4-scale model showed that the frame leaned forward at a tilt angle from 5 to 15 degrees at towing speeds from 0.8 to 1.4 m s^{-1}. Opened nets closed smoothly and sequentially nets were completely opened when the trigger was released by the command. Net depth rarely changed even during changes in towing speed. Sea trials both by the small-scale and the large-scale prototype demonstrated the same towing characteristics expected from the flume tank tests. The newly developed multiple layer opening/closing MOHT (MOC-MOHT) is considered to be suitable for quantitative layer sampling of juvenile fish.

1. Introduction

Accurate stock assessments of pelagic fishes are supported both by precise catch data from fisheries and by quantitative fish sampling from research cruises. Fishing quotas are assigned based on the results of stock assessments with consideration of recent population recruitment levels. Estimations or predictions of the recruitment are, however, difficult due to uncertainty related to their natural mortality rates. Quantitative sampling of juvenile and pre-mature pelagic fishes (here termed "young fishes") is one of the most effective tools for understanding survival processes and for reducing uncertainty in estimation of natural mortality rates. A major reason for difficulties in sampling young fishes is that they are sparsely distributed and have sufficient swimming capability to evade nets (Heath and Dunn, 1990). Further non-homogeneous horizontal and vertical distribution means that conventional oblique tows by single nets tend to underestimate their densities (Heath, 1992). Previous studies demonstrated that effective sampling of juvenile fish can be performed by towing a large effective mouth opening net at a constant depth as fast as possible (Dunn et al., 1993; Aoki et al., 2000; Itaya et al., 2001; Oozeki et al., 2004). Because of their large mouth area, midwater trawls with a stratified layer sampling system are appropriate for sampling young fishes (Pearcy et al., 1977; Pearcy, 1980; Engås et al., 1997), however, midwater trawls have several disadvantages for quantitative sampling because of their variable mouth opening and non-uniform mesh size. High-speed stratified layer sampling nets, with large fixed mouth opening and uniform size of mesh, are required for quantitative assessment of the density of young fishes.

Historically a wide variety of net devices have been used for sampling marine organisms (*e.g.*, Wiebe and Benfield, 2003) but new acoustic and optical technologies have the potential to replace traditional net survey methods in systems in the near future. These newly innovated sampling instruments can differentiate marine organisms to species levels and supply

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high-resolution spatio-temporal data. Sampling gears targeting young fishes will be the last beneficiaries of such recent innovations because of present technical limitations. Young fishes distribute too sparsely for the limited water volume surveyed by optical sampling devices and are too large to be successfully identified. Conversely young fishes are too small to be differentiated to species level by acoustic sampling instruments. Meanwhile, demands for high-resolution distribution data of young fishes are increasing for analyses comparing with zooplankton distribution data obtained from the acoustic and optical sampling devices. Therefore, additional progress of the quantitative stratified layer sampling devices targeting young fishes is still required, even though progress in multiple net systems and/or closing cod-end systems has slowed after the mid 90s (Wiebe and Benfield, 2003).

It is still difficult to conduct quantitative stratified layer sampling for young fish, although a variety of sampling gears have been employed, *e.g.* the multiple opening/closing net and environmental sensing system (MOCNESS: Wiebe et al., 1976, 1985), the rectangular midwater trawl (RMT: Baker et al., 1973; Roe and Shale, 1979; Dimmler and Klindt, 1990), the Bedford Institute of Oceanography net and environmental sampling system (BIONESS: Sameoto et al., 1980) and the large opening–closing high speed net and environmental sampling system (LOCHNESS: Dunn et al., 1993). The MOCNESS has been widely used for zooplankton and micronekton sampling, however, the effective mouth area varies according to the towing speed due to the towing position in relation to the position of the attached bridles. Mouth shape of the RMT is also unstable because of the flexibility of the side wires connecting the upper and lower sections of the frame and the attachment of the bridles to the top of the frame as in the MOCNESS. This design has a disadvantage that the frame angle fluctuates considerably depending on the towing speed and the area of net opening is not stable. The BIONESS and LOCHNESS systems have horizontal bars with net stacking structures and mouth openings that are maintained vertical over a wide range of towing speeds. The BIONESS is, however, designed for plankton sampling including fish larvae although it has a small mouth area (1 m^2). The LOCHNESS has a large frame appropriate for fish sampling, however, the weight of the whole system exceeds 2 t and heavy dropping bars each weighing 100 kg must be set up using a crane mounted on the research vessel. Moreover, most multiple layer-sampling gears employ a conducting cable winch or an acoustic communication system for controlling opening/closing nets during the operation. It means that the usage of existing multiple layer sampling systems is limited by the facilities available on the research vessel. Ability to sample data to estimate young fish distribution will be greatly improved by increasing the portability of the multiple layer sampling systems that do not require specific facilities on research vessels.

In this study, we aimed to establish a quantitative sampling gear for young fishes at a specific layer depth with an autonomous net opening/closing control system, which allowed easy operation on research vessels without any special facilities. The new multi-layer sampling trawl has the same net-depth stability as the Matsuda–Oozeki–Hu Trawl (MOHT) under rough sea conditions (Hu et al., 2001b; Oozeki et al., 2004) and is named the multiple layer opening/closing MOHT (MOC-MOHT). We constructed one scale model and two prototypes (large-scale and small-scale). Flume tank tests on a 1/4-scale model of a large-scale prototype were conducted to investigate the performance of the autonomous net opening/closing system as well as its towing characteristics. Sea trials using the small-scale prototype (2 m^2 mouth area) and the large-scale prototype (4 m^2 mouth area) were conducted to verify the achievement of the designed performance.

2. Materials and methods

2.1. Large-scale prototype

The MOC-MOHT has a rigid frame maintaining a near-vertical attitude over a range of towing speeds (1.0–2.25 m s^{-1}) with five nets (Fig. 1). The main frame with a vertical bar of net stacking structure was 3.3 m high and 2.35 m wide, and was constructed of square cross section stainless steel tubes welded together. Two vertical stainless steel tubes each were placed at the back and front on both sides of the frame. The two frontal tubes supported four horizontal dropping bars as guides with plastic rollers at both ends. The other two tubes at the back held the side panels of nets with plastic rollers (Fig. 1). A net release mechanism was located at the center of the upper frame and a net-response sensor was located inside the bottom of the left side frame for detecting closures of nets. A flowmeter was placed at the center of the lower frame. Four floats were set inside the upper frame.

A cambered V-shape depressor (Hu et al., 2000) with an aspect ratio 6.0 and a camber ratio of 15% was hung below the frame by four mutually parallel cables (8 mm diameter 2.0 m-long; Fig. 1). The wingspread of the depressor was 2.44 m, and its wing area 0.99 m^2. Mass of the depressor was 50 kg in air. Two 10 m-long bridles were attached at the midpoint of the two sides frames. The mass of each dropping bar was 21.8 kg and the total mass of the frame without the depressor was approximately 490 kg in air.

The shape of the mesh parts were the same, all 11.0 m long with a rectangular mouth of 1.81 m $\times$ 2.22 m for the five nets (Fig. 2). Nets were constructed of square mesh consisting of a bar length of 1.95 mm and a twine diameter 0.36 mm (1.59 mm pores) knotless ultra-high-strength polyethylene (Toyobo, Japan; Dyneema SK60) with four Dyneema ropes, which were sewn at the edge of the four panels for supporting the net. The nets were attached to the frame using black nylon canvas supports. The upper and lower parts of the canvas wrapped around the dropping bars and the side canvases of the nets were attached to the two vertical guide tubes with plastic rollers via 5 cm-wide black nylon webbing (automobile seatbelt material). The mouth canvas part of the first net was different in shape from the other four nets, with the nets numbered from the bottom to the top based on opening order during operation. Preliminary tests in a flume tank indicated that an approximately 10° tilt angle of the frame to the towing direction was necessary to ensure simultaneous net closures and openings. Therefore we adopted a design in which the angle of the leading edge of the mouth of the net balanced the turning moment produced by drag on the net (Hu et al., 2008). Net edge angles of the large-scale model were calculated as 15° (1st net) and 2° (2nd to 5th nets) and were defined by the shape of the side nylon canvas to facilitate exchange and/or repair of nets (Fig. 2).

The underwater control unit equipped with a depth and a temperature sensor was also used to retrieve flowmeter count signals and net closing signals (Fig. 3). A magnetic switch was equipped for starting/ending sampling data recording. Commands of net opening/closing were stored in the control unit via a Data read/write unit on deck. Data during the towing, including depth, temperature, flowmeter counts, net releasing and closing time, were also stored in the control unit and transferred to a PC via the Data read/write unit on deck. The control unit itself detected the behavior of the net system (sinking or rising) by comparing the present depth of the system with transit depths, and sending trigger signals to the net releasing motor when the target depth was attained. Permissible range of depth also could be set to allow for depth fluctuation of the net. Several setting options can be programmed in the software as follows: (1) depth-setting with transit depth for detecting sinking or rising; (2) time-setting for

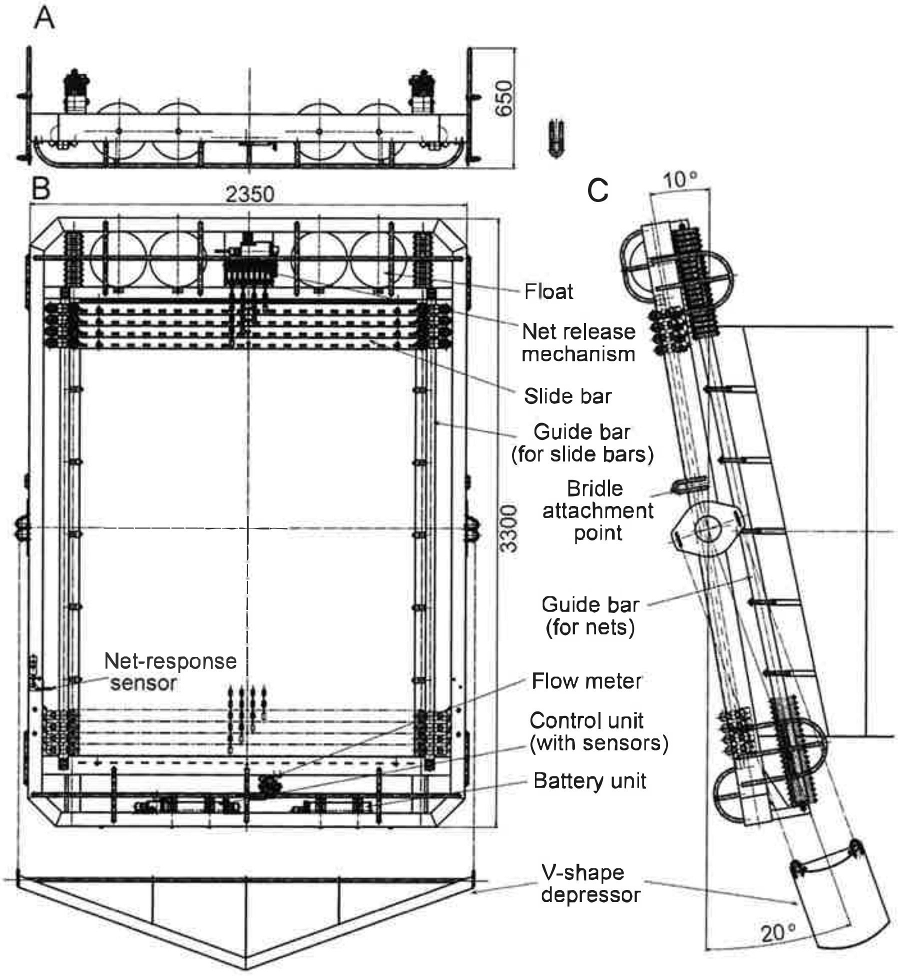

Fig. 1. Global design of the frame for a large-scale prototype (A: front view; B: upper view; C: side view).

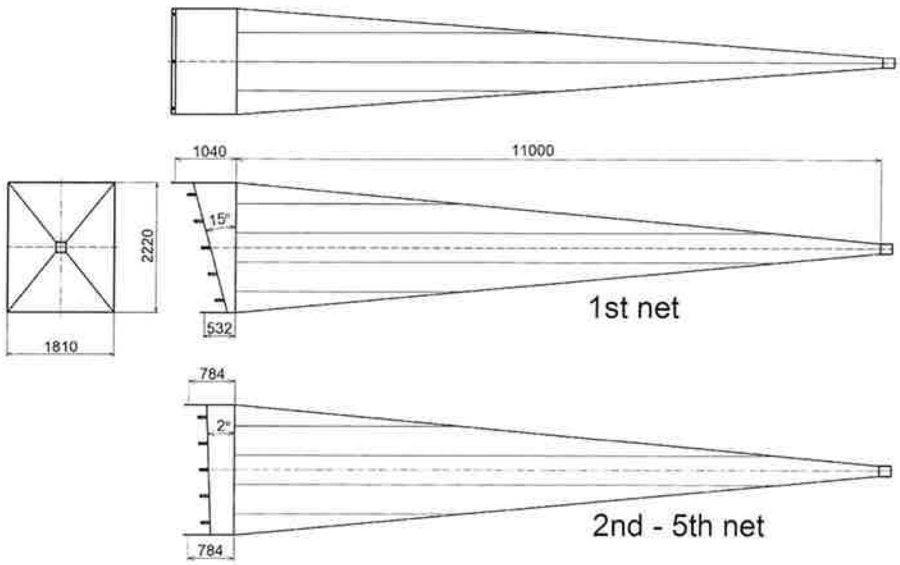

Fig. 2. Profile of the net arrangement for a large-scale prototype.

operation after an elapsed time; (3) flowmeter count setting for operation when a given flowmeter count is reached; (4) combination setting of "and/or" relative to any two of the three inputs listed above. Variable parameters and the planned trajectory are shown at the command setting, and measured trajectory with a temperature plot, including flowmeter counts, net releasing and closing time, are also shown in the software after retrieving the data.

2.2. Small-scale prototype

A small-scale prototype model of half the net mouth area with four nets and the same net control system was used to test the validity of the opening/closing net system. The main frame had a 1.9 m height and 1.8 m width, and the wingspread of the cambered V-shape depressor was 1.93 m and its wing area was 0.62 m^2. Two 8 m-long bridles were attached at the midpoint of the two side frames. The mass of each dropping bar was 18 kg and the total mass of the frame without the depressor was approximately 210 kg in air. Four nets, 8.0 m long with a rectangular mouth of 1.35 m × 1.5 m, were constructed using the same mesh as the large-scale prototype. Net-cutting angles were designated as 12°, 4°, 3° and 1° in order of net number.

2.3. Model experiment in a flume tank

Model experiments using the 1/4-scale model of the large-scale prototype (1/4-scale model) were conducted in a flume tank at the Tokyo University of Marine Science and Technology. The 1/4-scale model equipped with four nets of the same mesh as the large-scale prototype and the net release mechanism was controlled electrically from outside the tank. The main frame had a 0.85 m height and 0.78 m width, and the wingspread of a cambered V-shape depressor was 0.64 m and its wing area was 0.068 m^2. Two 2.5 m bridles (2 mm in diameter) of the 1/4-scale model were connected to a 1.0 m towing wire and the other end of the wire was fixed to the surface of the tank upstream. Performance of the net opening/closing control system was monitored at flow velocities from 0.8 to 1.4 $m\,s^{-1}$. It was estimated that these flow velocities during the model experiment corresponded to 1.11–1.95 $m\,s^{-1}$ in the large-scale prototype by scaling according to the modified Tauti's law (Hu et al., 2001a). Tilt angle of the frame was recorded every second by an electrical inclinometer (AI-CMP, Alec Electronics, Japan) attached to the left side of the frame. The frame behavior during the experiment was recorded from outside the tank by a digital video camera.

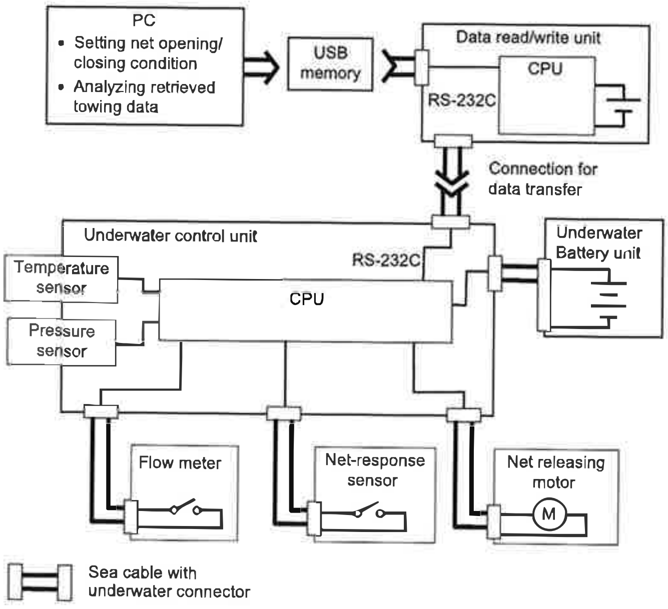

Fig. 3. Block diagram of underwater control unit with sensors.

2.4. Open sea trials by the small-scale prototype

Open sea trials of the small-scale prototype were conducted in Sagami Bay by the RV Soyo-maru in November 2007 and September 2008 (Table 1). The small-scale prototype was towed via a 9.0 mm diameter wire cable. Two spherical floats (diameter: 40 cm, maximum depth rating: 1000 m, total buoyancy: 294 N) were attached at the top of the frame to reduce the weight-in-water of the frame.

Data on the properties of the small-scale prototype were mainly collected in November 2007. Tilt angles of the frame were measured with the electrical inclinometer (AI-CMP, Alec Electronics, Japan) while each net was opened at 100 m warp length and 1.0, 1.5 or 2.0 $m\,s^{-1}$ towing speeds (net speed to water). Towing depth of the net was measured by records stored in the control unit, a miniature depth logger (MDS-MkV/D, Alec Electronics, Japan) and a net depth sensor (Scanmar, Norway) under several warp lengths of 110, 200, 300, 400 and 500 m at three towing speeds of 1.0, 1.5 and 2.0 $m\,s^{-1}$.

Several types of tow, including step oblique tows at 200 m and 100 m, oblique tow from surface to 300 m depth and yo-yo tows from surface to 50 m depth, were tested in September 2008 based on the relationships between warp length and towing depth obtained at the November 2007 cruise (Table 2). All towing was conducted at the net speed of 2.0 $m\,s^{-1}$ through the water. Net opening/closing commands were set by the "OR" combination of depth and elapsed time.

2.5. Open sea trials of the large-scale prototype

Open sea trials of the large-scale prototype were conducted in Sagami Bay by the RV Hakhou-maru in May 2010 and by the RV Kaiyo-maru in November 2010 (Table 1). The large-scale prototype was towed at a speed of 2.0 $m\,s^{-1}$ and four spherical floats (diameter: 30 cm, maximum depth rating: 1200 m, total buoyancy: 323 N) were attached at the top of the frame to reduce the weight-in-water of the frame.

Oblique tows from the surface to 200 m depth were repeated in order to compare layer isolation of specimens between daytime and nighttime at the same area in May 2010. The tilt angles of the frame were recorded every second by the electrical inclinometer (AI-CMP, Alec Electronics, Japan) attached to the left side of the frame. Records of towing trajectories and net opening/closing timings were obtained from the control unit. Wire out and tension were monitored by sensors on the trawl winch. Specimens in each net were preserved in 5% formalin and were sorted to the family level.

Table 1
Open sea trials by the small-scale prototype (net mouth size 2 m^2) and the large-scale prototype (net mouth size 4 m^2) of the MOC-MOHT.

Date	Ship	Net		Speed ($m\,s^{-1}$)	Towing method
		Mouth size (m^2)	Layer		
4–7 November, 2007	RV Soyo-maru	2	4 nets	2.0	Step oblique, oblique, yo-yo
13–15 September, 2008	RV Soyo-maru	2	4 nets	2.0	Step oblique, oblique, yo-yo
11 May, 2010	RV Hakhou-maru	4	5 nets	2.0	Oblique
18–21 November, 2010	RV Kaiyo-maru	4	5 nets	2.0	Oblique

Table 2
Typical command settings for net opening/closing during open sea trials. All tows were conducted at a net speed to water of 2.0 m s^{-1}. "OR" combination setting was used between depth and elapsed time. Permissible range of depth was set as ±1 m in all tows. All nets were closed at the time of retrieving in September 2008.

Date	Towing method	Command setting				Remarks
		Layer	Transit depth (m)	Target depth (m)	Elapsed time (min)	
4–7 Sept, 2008	Step oblique (200, 100 m)	1st	190	200	15	Fig. 5A
		2nd	190	180	22	
		3rd	110	100	35	
		4th	90	80	42	
	Oblique (0–300 m)	1st	250	300	10	Fig. 5B
		2nd	200	150	13	
		3rd	125	100	16	
		4th	10	0	19	
	Yo-yo (0–50 m)	1st	10	20	15	Fig. 5C
		2nd	10	20	22	
		3rd	10	20	35	
		4th	10	20	42	
11 May, 2010	Oblique (0–200 m)	1st	180	200	13	Fig. 6 day
		2nd	120	100	23	
		3rd	80	70	33	
		4th	40	30	43	
	Oblique (0–200 m)	1st	180	200	18	Fig. 6 night
		2nd	120	100	28	
		3rd	80	70	38	
		4th	40	30	48	
18–21 Nov, 2010	Oblique (0–200 m)	1st	140	150	10	Fig. 7A
		2nd	160	150	15	
		3rd	110	100	20	
		4th	60	50	25	
	Oblique (0–200 m)	1st	140	150	10	Fig. 7B
		2nd	160	150	15	
		3rd	110	100	20	
		4th	60	50	25	
	Oblique (0–1000 m)	1st	490	500	30	Fig. 7C
		2nd	510	500	35	
		3rd	310	300	60	
		4th	160	150	68	

Portability and usability of the net system was mainly tested by operators and crews other than developers of the system in November 2010. Oblique tows from the surface to 200 m or 1000 m depth were repeated for testing the operational reliability. Examples of net opening/closing command settings are shown in Table 2.

3. Results

3.1. Characteristics of the frame in a flume tank

Frame attitudes of the 1/4-scale model are shown in the case of each net opened at a flow velocity of 1.4 m s^{-1} (Fig. 4 upper panel) and of Net-1 opened at a flow velocity from 0.8 to 1.4 m s^{-1} (Fig. 4 lower panel). These pictures indicated that the frame maintained almost the same tilt angle, inclining slightly forward and that the cambered V-shape depressor kept almost the same attack angle, despite net opening events and flow velocity increase from 0.8 to 1.4 m s^{-1}. The tilt angles of the frame when nets 1, 2, 3 and 4 were opened were 4.7–7.9°, 6.1–8.9°, 5.5–8.2° and 1.6–4.8°, respectively, at flow velocities ranging from 0.8 to 1.4 m s^{-1}. The variations in the tilt angle of the frame were within approximately 3° at the range of flow velocities tested. Furthermore, variations of the tilt angle as successive nets opened decreased at flow velocities faster than 1.1 m s^{-1}.

The frame inclined forward considerably when a slide-bar was released, and then moved back to the previous inclination within 2–3 s after the releasing commands at the same time as the net closing. Maximum forward inclining frame angles were observed in response to the release of slide bars and increased with the velocity; angles of 17.4°, 17.2° and 16.0° were observed at the setting velocity of 0.8 m s^{-1}, and 27.6°, 30.0° and 28.1° at the setting velocity of 1.4 m s^{-1}.

3.2. Open sea trials by the small-scale prototype

Open sea trials in November 2007 indicated no significant difference between the records stored in the control unit, a miniature depth logger (MDS-MkV/D) and a net depth sensor (SCANMAR). Tilt angle of the frame increased slightly with an increase in the towing speed, but there were no significant differences in the tilt angle of the frame between the successive four nets opened at the towing speeds tested. The average tilt angles were 5.5°, 8.8° and 11.9° at the towing speeds of 1.0, 1.5 and 2.0 m s^{-1}, respectively. Although the tilt angles obtained at the sea trials were slightly larger than the values observed in the flume tank experiments, the difference in tilt angle between the flume tank experiment and the sea trial was within approximately 5°.

Nine hauls of the small-scale prototype were conducted in September 2008 and the autonomous opening/closing control system ran smoothly for several types of towing pattern. Three typical results of the towing trajectories with net opening/closing records are shown in Fig. 5. "Depth-or-time" settings were adopted in all tows and the time settings being used as a backup

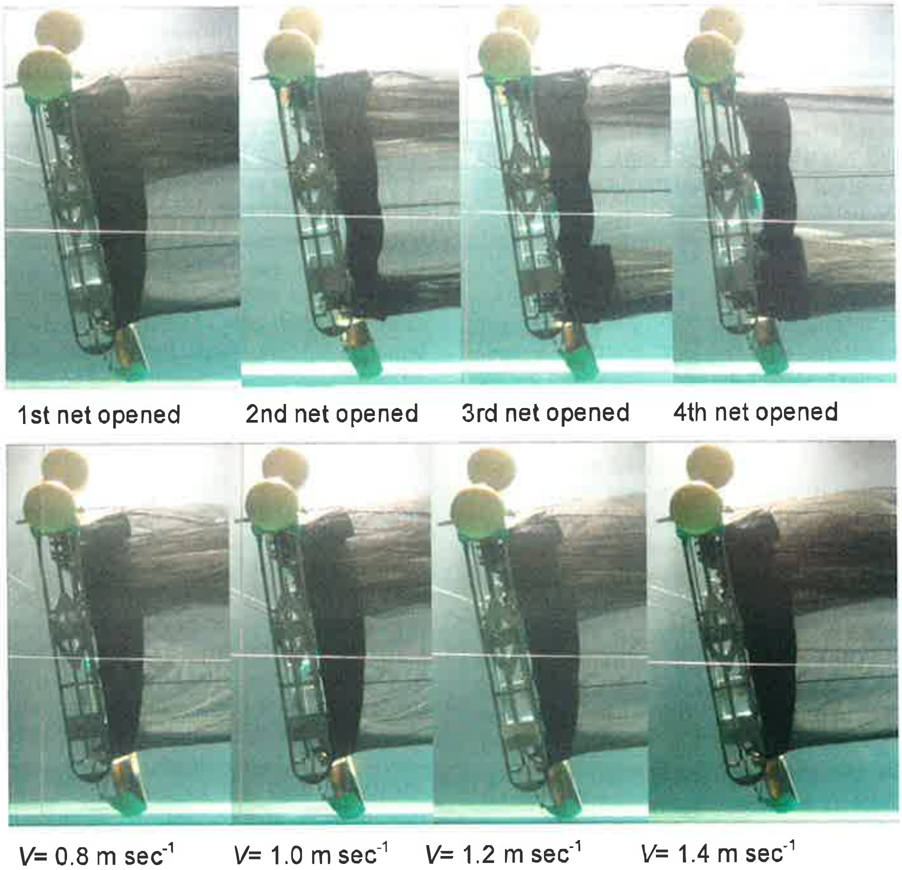

Fig. 4. Frame characteristics of the 1/4-scale model as different nets opened at a flow velocity of 1.4 m s^{-1} (upper panel) and at different flow velocities with the first net opened (lower panel) in the flume tank. Horizontal white lines are a marker line at the observation window of the flume tank.

except for a step oblique tow (Table 2). For the step oblique tow, the first bar dropped at a depth setting of 200 m during the descent, the second bar dropped at 211 m by the time setting, the third bar dropped at 100 m during ascent triggered by the depth setting and then the fourth bar dropped at 108 m by the time setting (Fig. 5A). In the subsequent oblique tow, the first bar was released at a depth of 300 m during the descent and then the following three bars were released at depths of 150, 100 and 0 m during the ascent (Fig. 5B). In the case of the yo-yo towing from the surface to 50 m, a wire was veered out to a length of 160 m and then repeatedly hauled in 20 m (Table 2). The slide bars were released at 10 m depth during each ascent giving four consecutive oblique tows from a single cast (Fig. 5C). During these operations, nets closed within 3 s of the commands signals. The tilt angles of the frame remained at an appropriate angle, approximately from 20° to 25°, except during veering of the warp (Fig. 5A, B). Instantaneous forward tilting of the frame was also observed when the slide bars were released.

3.3. *Open sea trials by the large-scale prototype*

Eight hauls of the large-scale prototype were conducted in May 2010 and the autonomous opening/closing control system ran smoothly except for one towing mistake of the winch control. During these operations, nets closed within 3 s after the commands released. Two typical results of the oblique towing trajectories in daytime (15:22–16:01) and the nighttime (21:17–21:58) are shown with net opening/closing records in Fig. 6. "Depth-or-time" settings were adopted at the oblique towing with the time settings as a backup (Table 2). Warp length required for the expected net depth was calculated by the following equations based on the data obtained previously during this cruise

$$\text{Velocity} = 1.5\ \text{m s}^{-1} \quad D = 0.393L + 0.371 (n = 3, r^2 = 0.999) \quad (1)$$

$$\text{Velocity} = 2.0\ \text{m s}^{-1} \quad D = 0.340L - 26.02 (n = 5, r^2 = 0.998) \quad (2)$$

where D is the net depth (m), and L is the warp length (m). In both oblique tows, the first bar was released at a depth of 200 m at the sinking pass and then the following three bars were released at depths of 100, 70 and 30 m during the floating pass, respectively (Fig. 6 day and night, upper panel).

Layer isolation of the large-scale prototype was analyzed by individual number per filtered volume for anchovy larvae and juveniles (Fig. 6A), lantern fish larvae (Fig. 6B) and lantern fish juveniles and adults (Fig. 6C) both in the daytime and nighttime. Anchovy larvae and juveniles concentrated in the surface layer from 30 m to 0 m in the nighttime (93.2 individuals 1000 m^{-3}), whereas they dispersed from 100 m to the surface in low abundance in the daytime. Abundance of the lantern fish larvae observed mainly in the surface layer from 30 m to 0 m in the nighttime (2.2 individuals 1000 m^{-3}), whereas lantern fish juveniles and adults mainly distributed in the mid-depth layer from 100 m to 70 m (5.9 individuals 1000 m^{-3}) with a wide distribution from 200 m to the surface. In the daytime, no lantern fish were sampled.

Ten hauls of the large-scale prototype were conducted in September 2010 and the autonomous opening/closing control system ran smoothly, even with the operators and crews using this system for the first time. Three typical results of the oblique towing trajectories are shown in Fig. 7. "Depth-or-time" settings were adopted for the oblique towing with the time settings used as a backup (Table 2). Warp length required for the expected net depth was calculated by Eqs. (1) and (2). In both oblique tows from the surface to 200 m depth, the first bar was released at a depth of 150 m during the descent and then the following three bars were released at depths of 150, 100 and 50 m during the ascent (Fig. 7A and B). In the first oblique tow, the net maintained almost constant depth at the beginning because of the slow veering speed (Fig. 7A). In the oblique tows from surface to 1000 m depth, the first bar was released at a depth of 500 m during the descent and then the following three bars were released at depths of 500, 300 and 150 m during the ascent (Fig. 7C). During these operations, nets closed within 3 s after the

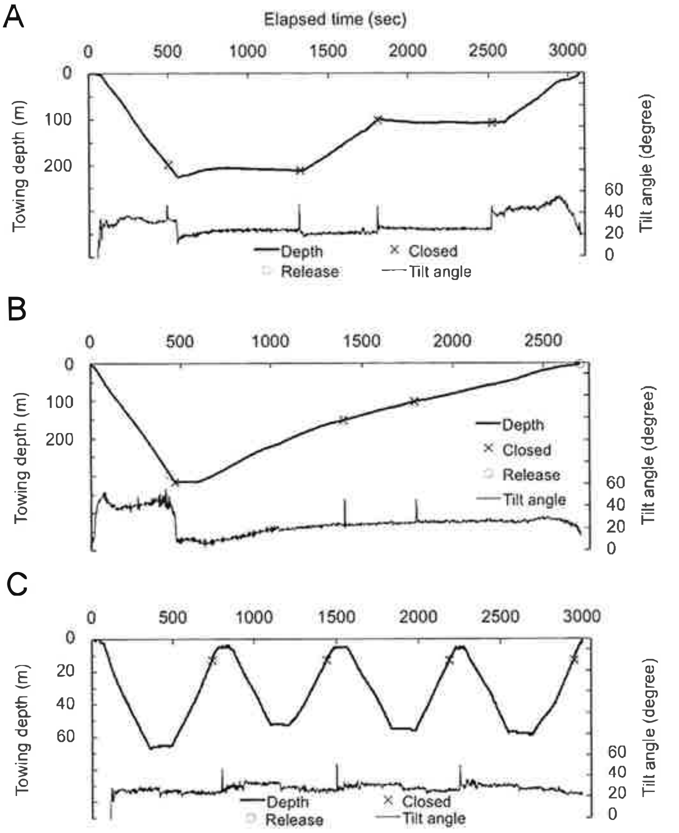

Fig. 5. Towing records and tilt angle of the small-scale prototype at a step-oblique tow (A), an oblique tow (B) and a yo-yo tow (C) under at a towing speed of 2.0 m s^{-1} in September 2008.

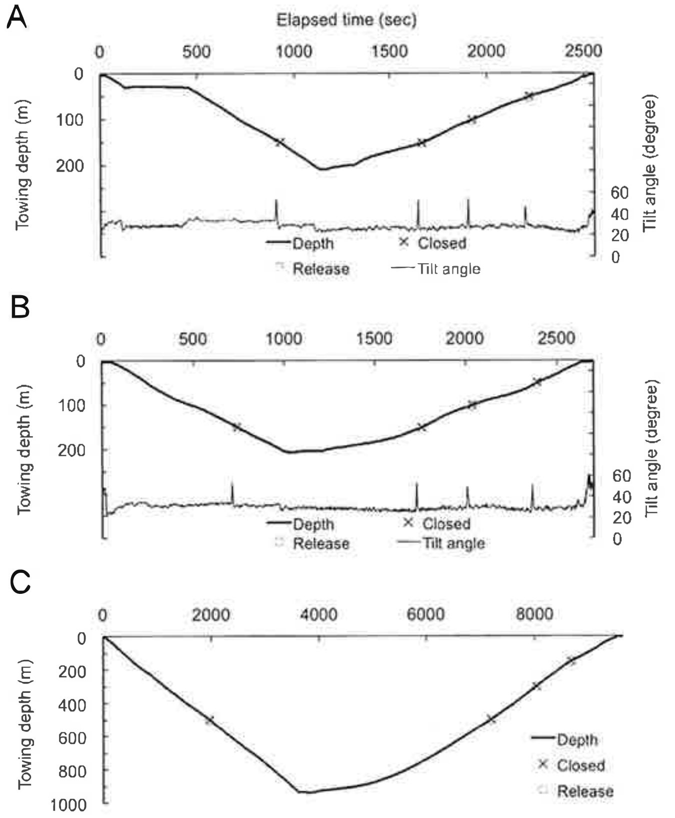

Fig. 7. Towing records and tilt angle of the large-scale prototype at shallow oblique tows (A, B) and a deep oblique tows (C) under at a towing speed of 2.0 m s^{-1} in November 2010.

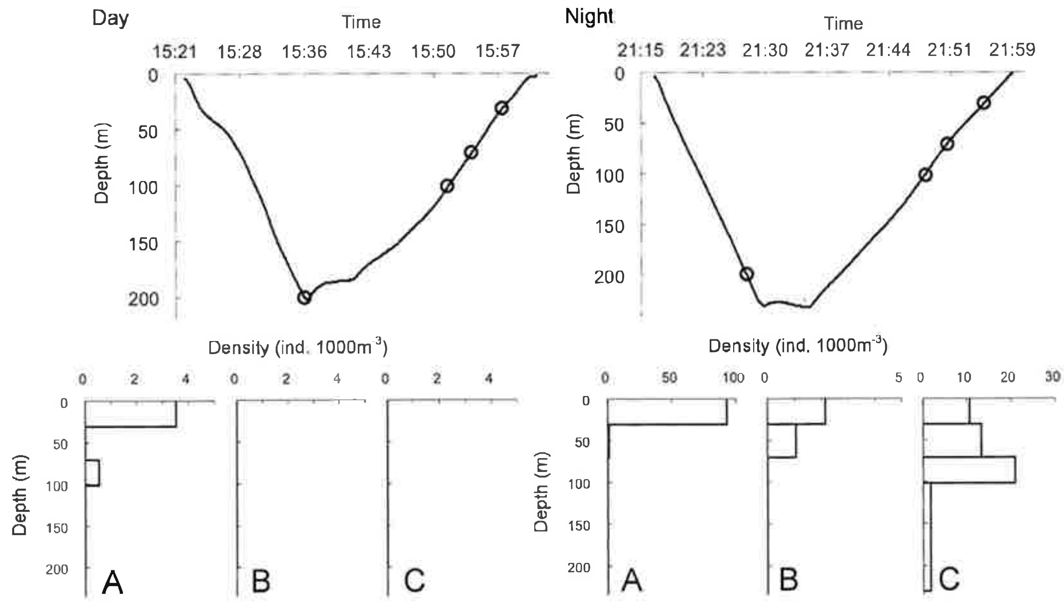

Fig. 6. Towing records of the large-scale prototype at oblique tows at the daytime (15:22–16:01) and the nighttime (21:17–21:58) at a towing speed of 2.0 m s^{-1} in May 2010 (upper panels). Vertical distributions of anchovy larvae and juveniles (A), lantern fish larvae (B) and lantern fish juveniles and adults (C) are shown in density (individuals 1000 m^{-3}) on day and night (lower panels).

commands were released and the tilt angle of the frame was maintained at 20–30° in the oblique tows from surface to 200 m depth (Fig. 7A and B).

4. Discussion

We developed an autonomous multiple layer opening/closing MOHT (MOC-MOHT), which does not require any commands from the vessel via a conducting cable or acoustic signals. Command settings are easily programmed for several types of towing even by first-time users to operate the net opening/closing control system and no errors due to the system occurred in the sea trials. High controllability, with respect to the frame behavior was observed both in the flume tank experiments and sea trials, contributed to the successful samplings in the step oblique tows and oblique tows during the sea trials.

In order to operate the MOC-MOHT effectively, knowledge is required of the relationship between warp length and towing depth of the net at a given towing speed. The results obtained from the sea trials demonstrated significant correlation between the warp length and net depth at all towing speeds. Normally the net towing speed can be assumed to be equal to the ship speed through the water and this is now easily obtained on research vessels. The relationship derived from the sea trials ensured good controllability of this trawl minimizing operational risk *e.g.*, non-closure of a net due to insufficient warp length. Towing depth of the net varied with towing speed because of the frame weight in water, although the main frame and the cambered V-shape depressor were based on the MOHT (Hu et al., 2001b; Oozeki et al., 2004). In the sea trial of the large-scale prototype, we simply attached four floats with a total buoyancy of 323 N at the top of frame to facilitate handling and operations on deck. Oozeki et al. (2004) suggested that, as in the MOHT, reducing the frame weight in water would decrease the differences observed in towing depth caused by fluctuations in the towing speed. The effect of towing speed on the towing depth was thus considered to be due to the frame weight in water. Conversely, it is possible to improve depth stability by reducing the frame weight in water close to zero by attaching floats, but this might be reflected in difficulties associated with operations on deck. Consequently, it appears that the use of materials such as light alloys in the frame could be employed to optimize the performance of this sampling trawl.

Overshoot movement of trawl depth was, generally, accompanied by veering out a long warp (Hu et al., 1994). Although the MOHT indicated no serious overshoot movement, it may be difficult to accurately control the net depth, while employing a depth setting command for opening/closing nets during a step-oblique tow or oblique tow. In order to solve this problem, we adopted incorporation of the option of being able to set passage depth and permissible range of depth for reaching the target operational depth. Opening command of the deepest layer should be set to activate during the descent, as shown in the cruise in November 2010 (Table 2; Fig. 7), instead of the ordinary method adopted in the May 2010 cruise (Table 2; Fig. 6) to avoid the trouble of shortage of warp length. Furthermore, the combination of depth-and-time or depth-or-time settings will enable the success of step oblique samplings.

To control the behavior of the frame with four or more nets attached, newly designed nets with a net-cutting angle on the side part of nets were suggested (Hu et al., 2008). The net-cutting angle of each net was theoretically calculated based on several parameters including, the drag on the closed net, lift and drag on the open net and the structure of the frame. Tests of the 1/4-scale model with four nets in the flume tank indicated that the frame leaned slightly forward but that the tilt angles were all within 10° at a wide range of flow velocities for all cases of open nets (Fig. 4). Although a slight increase in tilt angle was observed with increasing tow speed, an average value of 11.9° was observed at 2.0 m s^{-1} in the sea trial of the small-scale prototype. It is very important for reliable quantitative sampling of larvae and juveniles that no significant differences were observed in the tilt angle of the frame when any of the four nets were opened at the same towing speed. As described above, the simple net design with net-cutting angle described here was well suited for application as a multi-sampler with a bridle attached at the midpoint of the side frame in the same way as in the MOHT.

Dynamic responses of the frame characteristics were observed in both the model experiments and sea trials when the slide bars were released (Figs. 5 and 7). These dynamic responses facilitate the movement of the lightweight slide bars, and thus contribute to the reliability of net opening/closing. The observed changes in the tilt angle of the frame suggested that fluid resistances on the opened net was temporarily directed to the lower portion of the net when a slide bar was released, because the bridles were attached to the midpoints of the two opposite sides of the frame. Frame inclination recovered within several seconds after the dynamic responses and did not affect the sampling efficiency and the specimen isolation. Contamination of specimens was naturally not detected during the mechanism of opening/closing whole nets same as MOCNESS (Wiebe et al., 1976) and no contamination of specimens was confirmed on the comparison of oblique samplings between daytime and nighttime.

The MOHT, which was the base of the MOC-MOHT constructed in this study, indicated improved sampling of micronekton, as it sampled 10 times more than the 10 m^2 MOCNESS and 5 times more than the 900 m^2 Otter trawl with a Multisampler system in calibration tests (Yamamura and Yasuma, 2010). This improvement of sampling efficiency might be from the faster towing speed of more than 2.0 m s^{-1} and the higher filtering efficiency of the MOHT under fast towing speeds. Flume tank experiments of the MOHT indicated no significant difference between the flow rate inside and outside of the frame even at high water speeds (Hu, unpublished data). The MOC-MOHT inherited the towing ability at the fast speed and the sufficient filtering efficiency possessed in the MOHT. Therefore, reliable information of vertical distribution on young pelagic and mesopelagic fishes can be expected by the operational usage of the MOC-MOHT.

The MOC-MOHT was demonstrated to have several advantages over other multiple sampling trawls, high reliability of the autonomous net opening/closing system, right weight of the total system and the stability of the frame angle at the towing. The frame behavior controllability and net-depth stability of the MOC-MOHT permit the sampling of specific depth layers easily by the ship only equipped with a simple trawl winch and facilitate the study of the vertical migration patterns of juvenile fishes and mesopelagic species. The suitability of the system for undertaking the quantitative sampling of young fishes will be demonstrated shortly, and the potential benefits for studying marine ecosystem including young fishes and mesopelagic species might be considerable.

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