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## Examples of ocean wave spectra estimated from ERS-1 SAR images

Li-Guang LEU<sup>\*\*\*</sup> Yi-Yu KUO<sup>\*\*</sup> and Cho-Teng LIU<sup>\*\*\*</sup>

**Abstract :** ERS-1 SAR (Synthetic Aperture Radar) images were used to derive ocean wave spectra. Because of the simplicity in bottom topography and availability of sea truth data, Hwalien coastal region east of Taiwan was selected as the site for comparing the satellite SAR-derived and the *in situ* surface wave spectra. Two-dimensional (2D) wavenumber spectra were derived from the digital SAR images through the Fourier transformation in the space domain. The wavelengths, wavenumber, wave period and the direction of dominant wave systems were then calculated from the spectral peaks. To verify these SAR-derived wave characteristics, the wavenumber spectra were converted to the frequency power spectra for direct comparison with simultaneously observed *in situ* wave spectra. Two cases were studied. The difference between the SAR-derived wave directions and those measured by the directional wave rider buoy was about 8° and 26°, and about 3.5% and 16% for the wavelength. Since the significant wave height measured by the wave-rider was only 0.73 m and 1.65 m, we can conclude that using satellite SAR to observe the ocean waves is a feasible approach with acceptable accuracy, even over a relatively calm sea.

### 1. Introduction

Observing ocean surface waves using conventional instruments, e.g., the wave gauges, wave-riders, and ultrasonic wave meter, is relatively difficult at sea. Such difficulty includes deploying, monitoring and retrieving these instruments, thereby hindering efforts to acquire continuous wave data. The amount of surface wave data is much less than expected owing to the loss, damage, and malfunction of the instruments. Besides, most conventional wave instruments record the temporal change of sea surface elevation to derive the surface wave spectra, only a few can observe the spatial characteristics of wave fields. In contrast, the remote sensing technique can obtain the information of ocean wave-field at synoptic scale,

subsequently making it complementary to the conventional methods.

Synthetic Aperture Radar (SAR) images have been used to observe ocean surface waves (GONZALES *et al.*, 1979) since launching of the satellite SEASAT in 1978. The visible bands of System Probatoire d'Observation de la Terre (SPOT) can be used to image ocean surface wave-field (POPULUS, 1991); however, it functions only in the daytime and on a cloud-free day. SAR is an active radar. The microwave pulses sent out by the radar can penetrate the cloud and moisture in the air, and interact with the ocean surface waves – regardless of the time of the day or the weather conditions. Hence, SAR images can be used for monitoring the wave-field of rough seas, especially near regions where typhoons frequently occur. This capability is quite useful for the safe and economic design of coastal marine structures. Despite some successful applications of SAR images in previous case studies on bottom topography, eddy, internal wave, current and boundary, ship wakes, a definitive algorithm has as not yet been derived for imaging ocean surface waves by SAR. The SAR image spectrum

\* Energy & Resources Laboratories, Industrial Technology Research Institute, Bldg. 24, 195-6, Chung-Hsing Rd. Sec. 4, Hsinchu, Taiwan 310, Republic of China

\*\* Institute of Civil Engineering, National Chiao-Tung University, Hsinchu, Taiwan, Republic of China

\*\*\* Institute of Oceanography, National Taiwan University, Taipei, Taiwan, Republic of China.

is actually not representative of the spectrum of sea surface displacement. The power spectra of SAR image is only a transformation of a directional slope spectrum of sea surface through a modulation transfer function (MTF) (ALPERS and HASSELMANN, 1978). The SAR imaging of the sea surface is conceivably affected by the surface wave motion ; however, its mechanism is not yet fully understood (ALPERS *et al.*, 1981 ; HASSELMANN, 1985 ; ALPERS and BRÜNING, 1986). Many studies on how surface wave motions affect SAR imaging mechanism are still underway.

Earlier studies of the wave-field with satellite sensors were under taken primarily on the open seas. Relatively few successful observations were made of ocean surface waves near shore by satellite SAR. The images of apparent wavelike pattern were not easily obtained at low sea conditions in which the significant wave height was below 2 meters (GONZALES, 1979). The simple dispersion relation for deep water waves used in transferring the wave-number power spectra to the frequency power spectra. However, the general dispersion relation must be used in a coastal region.

In this study, two SAR images over the eastern coast of Taiwan are analyzed and compared with *in situ* wave data recorded simultaneously by a wave-rider. The wave-rider was located about 1 km offshore from the Hwalien Harbor on the east coast of Taiwan (Fig. 1). The water depth is about 26 m at the site of wave-rider. The waves are considered as intermediate water waves because the wavelength of swell east of Taiwan is normally around about one hundred meters. The significant wave heights were below 2 meters at the time of SAR observation. Subscenes of the SAR images (Fig. 2) covering the site of the wave-rider are extracted for the study. Also, pre-processing techniques such as detrend and low pass filtering are used to improve the signal to noise ratio (SNR) and to enhance the spectral characteristics. Figure 3 provides the data processing flow chart and also compares both spectra derived from SAR images and *in situ* wave data.

## 2. Data and pre-processing

### 2.1. ERS-1 SAR data and *in situ* data

The European Space Administration (ESA) launched the first European Remote Sensing Satellite (ERS-1) in July 1991, with the primary mission of ocean survey and research. The SAR scans and receives radar echoes from the sea surface at an angle of 23° off-nadir with an altitude of 785 km. The microwave used by SAR is C-band at 5.3 GHz. Every full scene of SAR images spans an area of around 100 km × 100 km. All pixels are nearly square with a size of 12.5m by 12.5m. The ERS-1 SAR images used in this study were received by the Ground Station at the Center for Space and Remote Sensing Research (CSRSR), National Central University in Chungli, Taiwan. Obtaining the image for averaging four looks is the major objective. The geometrically uncorrected four-look images are generally referred to as georeference or slant range data. SAR images have two modes : descending and ascending. In the descending mode, the satellite passes over Taiwan at about 2 : 30 Universal Time Coordinated (UTC), or 10 : 30 Taiwan Local Time (TLT). The original SAR images are reversed in the east-west direction, similar to a mirror image of the map. In the ascending mode, ERS-1 passes over Taiwan at about 14 : 30 UTC, or 22 : 30 TLT. Before re-mapping, the SAR images are turned upside down from a regular map view. In this study, two images were acquired from CSRSR. The acquisition time of SAR images and their orbit numbers are (a) descending orbit 12358, track 189 on November 26, 1993, 2 : 25 UTC, or 10 : 25 TLT, and (b) ascending orbit 122, track 31 on November 15, 1993, 14 : 19 UTC, or 22 : 19 TLT.

The Institute of Harbor and Marine Technology (IHMT) of Taiwan collected the *in situ* wave data. A wave-rider buoy was deployed at (24°0'00"N, 121°38'24.5"E), outside of the east breakwater of Hwalien Harbor. The sampling rate of the wave-rider was 1.28 Hz and the sea surface elevation was recorded for twenty minutes at two hour intervals. The data were then transmitted in at VHF frequency to the receiver in a building near the coast. Next, wave data were translated and transferred to a personal computer for recording. Acceleration of

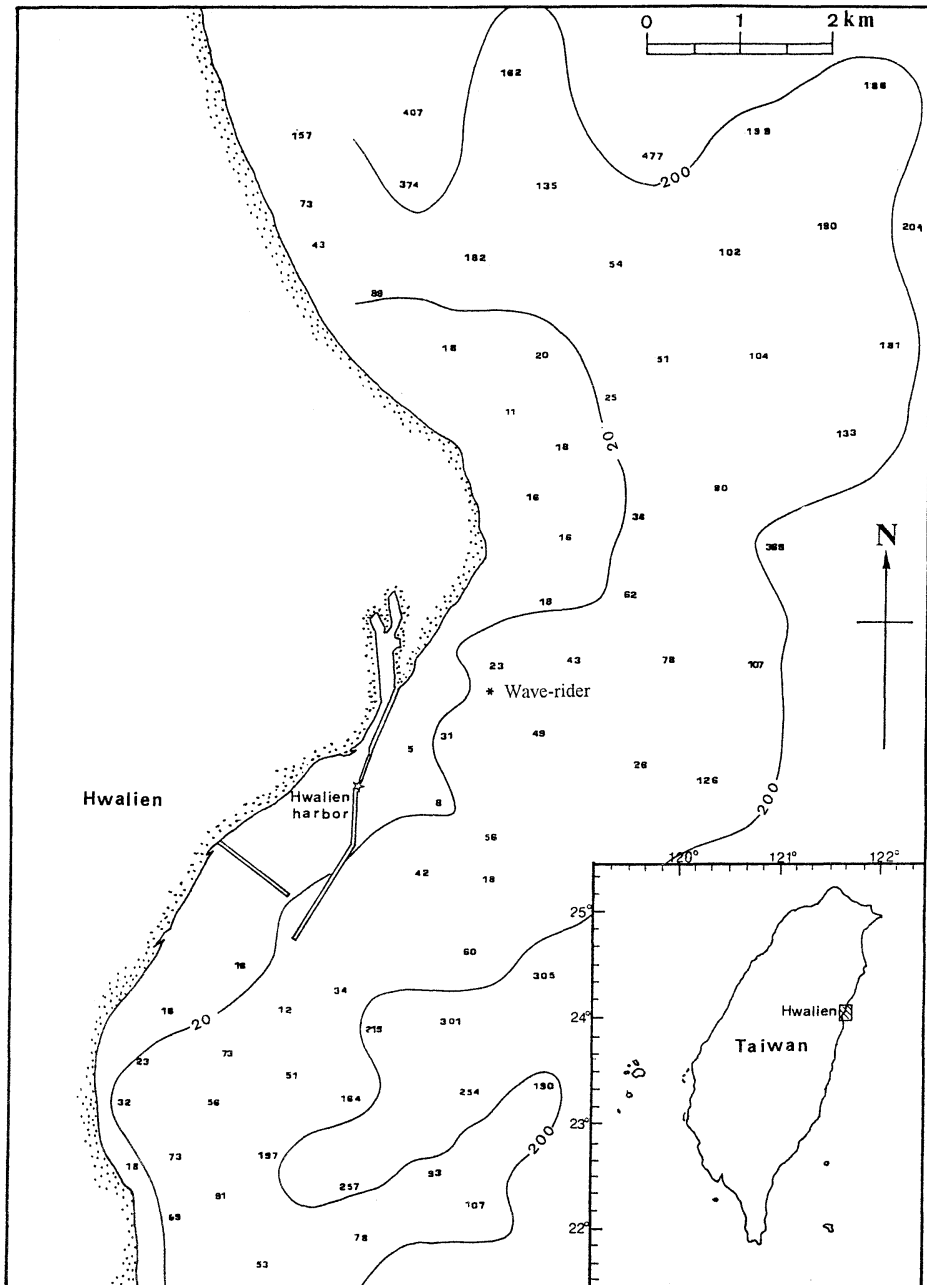
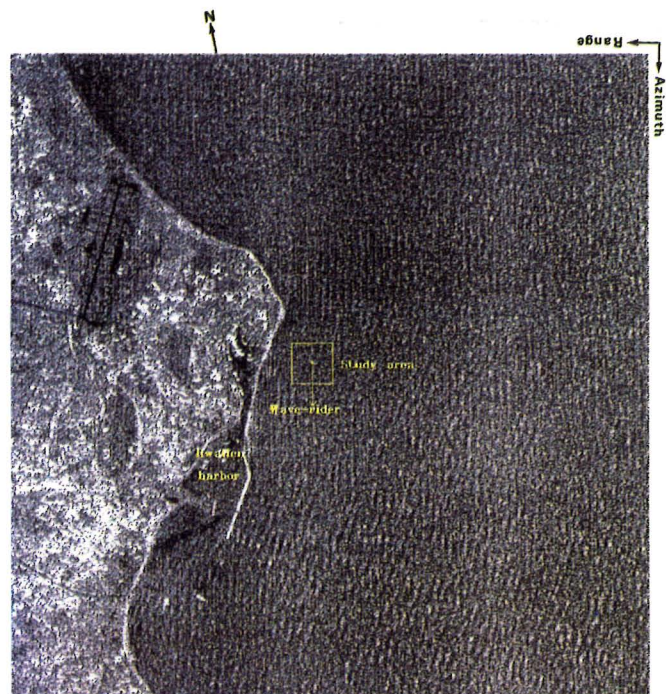


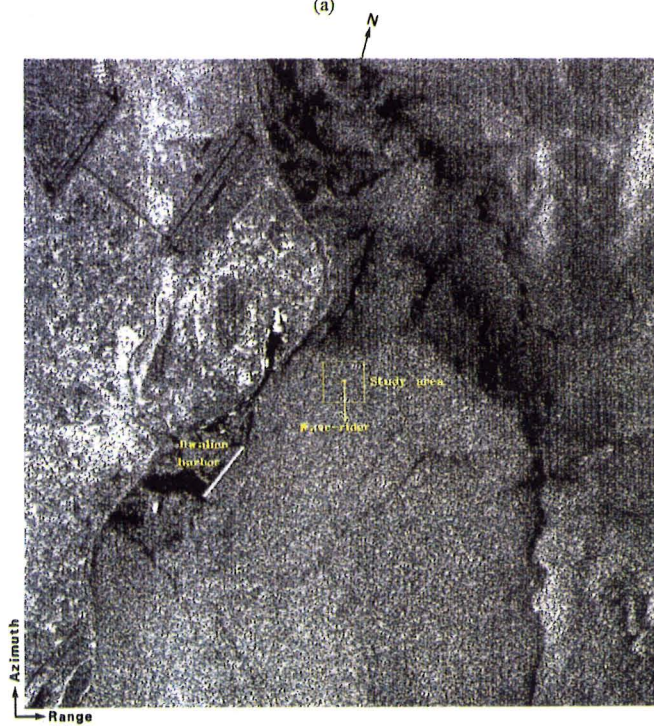
Fig. 1. The location of wave-rider and the bathymetry near Hwalien. Depths are in meters.

the buoy was measured by two fixed accelerometers in the horizontal x and y directions, and by an accelerometer mounted on a gravity stabilized platform in the vertical z direction. Also, the sea surface elevation was derived from the heave motion of the buoy. Moreover,

the wave direction was derived from the horizontal acceleration of the buoy. Two sets of *in situ* wave data were collected on (a) November 26, 1993, 10 : 30 TLT, and (b) November 15, 1993, 22 : 24 TLT.



(a)



(b)

Fig. 2. ERS-1 SAR images over Hualien of Taiwan for case (a) descending orbit 12358 on November 26, 1993, and case (b) ascending orbit 122 on November 15, 1993

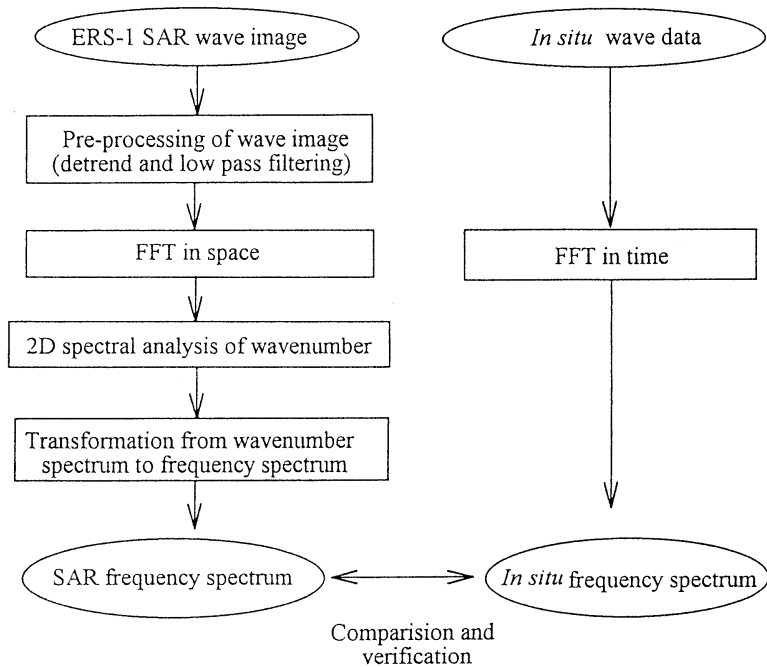


Fig. 3. Flow chart of data processing and their comparison of spectra derived from ERS-1 SAR images and *in situ* wave data.

## 2.2. SAR wave image pre-processing

Some appropriate filterings are necessary before the wave spectral analysis of the satellite images can be performed. A low pass filter was used to remove the high frequency noises that are typical in SAR images: a high pass filter was applied to remove the trend of grayness in the satellite images. The echo strength recorded by the SAR varies from pixel to pixel, as in the case of the distance between the satellite and the sea surface. The noises in the satellite images are regarded as a random error. A moving average with a 3 by 3 mask is sufficient to reduce the random error. The removal of noise improves the SNR of the satellite-derived surface wave systems. The nearshore wave-field is normally inhomogeneous owing to the topographic steering of the swell. Taking a small subscene of the wave image is preferable in the sense that the wave-field is nearly homogeneous in the subscene, thereby yielding stable statistics and power spectra of the wave system. The detrend of wave images may make SAR images of a wavelike pattern more easily observed and manifest a small variation of

signals thereby, producing an enhanced wave power spectra.

The digital counts of SAR images represent the radar backscattering crosssection of the sea surface. Assume that the gradual change of gray tone in an image can be expressed as

$$X_t(m_1, m_2) = a + bm_1 + cm_2 \quad (1)$$

where  $a$ ,  $b$ ,  $c$  are constants, and  $m_1$ ,  $m_2$  fall within 0 to  $N-1$ , and  $(m_1, m_2)$  is the position in the image of  $N$  by  $N$  pixels. The spatial 2D linear least square method is used to obtain the trend of wave image. The detrended image is obtained after removing the main trend image. If the matrix of original digital image is expressed as  $X_0(m_1, m_2)$ , the matrix of detrended image is written as

$$X(m_1, m_2) = X_0(m_1, m_2) - X_t(m_1, m_2) \quad (2)$$

The process of detrending may not be enhanced for every wave-field image. Detrending may occasionally more effective in obtaining the actual wave pattern in images with an uneven backscattering cross-section. However, manipulating the later processing of the SAR

images after detrending and deriving the enhanced wavenumber power spectra are highly desired.

### 3. Methodology

#### 3.1. Spatial fourier transform

A SAR image is a 2D sampling of the backscattering strength of satellite radar echoes of the sea surface over an area of 100 km by 100 km. The subscene covers the wave-rider location with a relatively uniform wave pattern so that a reliable conclusion can be derived from the comparison between the SAR data with *in situ* wave data. All of the pixels are assumed here to be squares of length  $d$  on each side. As shown in equation (2), let  $X(m_1, m_2)$  be the digital value of a pixel located at  $(m_1, m_2)$  within the subscene of  $N$  by  $N$  pixels. Here, the 2D Discrete Fourier Transform (DFT) is used to derive the wavenumber spectra from the SAR images. DFT defines

$$E(n_x \cdot k_0 \cdot n_y \cdot k_0) = \frac{1}{N^2} \sum_{m_2=0}^{n-1} \left[ \sum_{m_1=1}^{n-1} X(m_1, m_2) \cdot e^{-in_x \cdot k_0 \cdot m_1 \cdot \Delta x} \right] \cdot e^{-in_y \cdot k_0 \cdot m_1 \cdot \Delta x} \quad (3)$$

where

$$k_0 = 2\pi / D$$

$D = N \cdot d =$  the linear size of the subscene of the SAR image

$$d = 12.5 \text{ meters}$$

$$N = 64 \text{ in following studies}$$

$$n_x \cdot k_0 = k_x = \text{wavenumber in } x \text{ direction}$$

$$n_y \cdot k_0 = k_y = \text{wavenumber in } y \text{ direction}$$

$$n_x \text{ and } n_y = 1, 2, 3, \dots, N$$

Computations were performed via Fast Fourier Transforms (FFT), thereby, subsequently limiting the choice of  $N$  to the power of 2, i.e.  $N = 2^p$  ( $p = 1, 2, \dots$ ). The power spectra were acquired in correspondence to the wavenumbers in the  $x$  and  $y$  directions, respectively. The units for the wavenumber coordinates are

$$\delta k_x = \delta k_y = 2\pi / D = 2\pi / (N \cdot d).$$

#### 3.2. Wavenumber spectrum

In the 2D wavenumber spectrum, the spectral peak  $(n_x, n_y)$  represents the dominant wave characteristics, i.e.,

$$\frac{2\pi}{L} = K = \sqrt{K_x^2 + K_y^2} \quad (4)$$

$$\tan \theta = \frac{K_y}{K_x} = \frac{n_y}{n_x} \quad (5)$$

where  $K$  is the wavenumber of dominant wave.  $K_x$  and  $K_y$  are their components in  $x$  and  $y$  directions so that

$$L = \frac{D}{\sqrt{n_x^2 + n_y^2}} = \text{the wavelength of dominant wave} \quad (6)$$

$$\theta = \tan^{-1}\left(\frac{n_y}{n_x}\right) = \text{the wave direction of dominant wave counter-clockwise from } k_x \quad (7)$$

A one-dimensional wavenumber power spectrum can be derived by integrating the 2D wavenumber power spectrum in all directions. The spectral peak of a one-directional wavenumber power spectrum shows the wavelength of the dominant wave system. The variations of wave slopes shown in the SAR digital image were not the absolute wave heights. On the other hand, wave height can be calculated from *in situ* data via zero-up crossing method or spectral analysis. Following careful calibration of the wavenumber spectra with many simultaneously collected SAR and *in situ* data, the wave height may be calculated from the spectra of SAR images. The wave height can still not be accurately derived from SAR data since the effects of wave motion mechanism in SAR images remain unclear.

#### 3.3. Frequency power spectrum

Time-series data analysis is the conventional approach of observing ocean waves with wave-rider buoys. The wavenumber power spectra are derived from SAR images of spatial data, thereby making a direct comparison with the frequency power spectra derived from *in situ* wave data nearly impossible. The wavenumber power spectra should be transformed to frequency power spectra, while the reverse can not be done because of the difference in the number of independent variables. The wavenumber power spectra in the Cartesian coordinate system and in the polar coordinate system have the following relationship (TUCKER, 1991):



$$\phi(k, \theta) = k \cdot \phi(k_x, k_y) \quad (8)$$

where  $\Psi$  is the wavenumber power spectrum derived from SAR images,  $k$  is the wavenumber of ocean surface waves in SAR images and  $k = \sqrt{k_x^2 + k_y^2}$

The total wave energy computed from the frequency( $f$ ) domain and the wavenumber( $k$ ) domain should be equal, i.e.,

$$\int_0^\infty \int_0^{2\pi} \phi(f, \theta) \cdot df \cdot d\theta = \int_0^\infty \int_0^{2\pi} \phi(k, \theta) \cdot dk \cdot d\theta \quad (9)$$

where  $\phi(f, \theta)$  is SAR directional frequency power spectrum, and is determined in the following derivation

Therefore,

$$\phi(f, \theta) = \phi(k, \theta) \cdot \frac{dk}{df} \quad (10)$$

By combining (8) and (10), the relationship between directional frequency power spectrum and wavenumber power spectrum is

$$\phi(f, \theta) = \phi(k_x, k_y) \cdot k \cdot \frac{dk}{df} \quad (11)$$

$\frac{dk}{df}$  in equation (11) can be calculated via the wave dispersion relation :

$$\omega^2 = (2\pi f)^2 = gh \tan h(kh) \quad (12)$$

where  $\omega$  is the angular frequency of wave

$g$  is the acceleration of gravity

$h$  is the water depth of the study area

By considering the case of uniform water depth  $h$ , the omnidirectional frequency power spectrum  $\Phi(f)$  can be calculated by integrating the directional frequency power spectrum over all directions :

$$\Phi(f) = 1/(2\pi) \int_0^{2\pi} \phi(f, \theta) \cdot d\theta \quad (13)$$

The forms and peaks in frequency power spectra of SAR images and *in situ* wave data are compared in the following to assess the feasibility of using SAR images to estimate the characteristics of ocean wave-field over coastal zone.

#### 4. Case studies

The SAR images of Hwalien over the east coastal region of Taiwan were chosen to analyze the wave-field characteristics. A wave observation station was located at the offshore of

Hwalien harbor. Comparing the SAR images with *in situ* wave data simultaneously collected in the same study area was relatively easy. CSRSR provided the ERS-1 SAR images over Hwalien. Two ERS-1 SAR images were acquired during the phase C (35 day repeat cycle) of ERS-1 operation.

SAR images of Figs. 2a and 2b show the different sea states of case (a) and (b). The sea states near Hwalien are largely affected by the north-east monsoon during the autumn and winter seasons. The wave height is usually about 1 m to 2 m and, in 1993, was larger than 2 m at only about 30% of the time. The wave period is generally 6 sec to 8 sec. The worst sea states appear from August to October when the typhoons approach from the east. Figure 1 shows the location of Hwalien in Taiwan and the nearshore bottom topography. The water depth changes rapidly offshore. The wave-field in the coastal zone is relatively localized. The wave spectra observed by the wave-rider may not be representative for a large SAR image. On the other hand, the wavenumber power spectra lose their statistic characteristics if the subscene is too small to contain a sufficient number of waves. A subscene of 64 pixels by 64 pixels (or 800 m by 800 m) is considered optimal, based on our previous experimental studies. Twodimensional wavenumber power spectra were derived via FFT of the SAR data in the space domain. Figure 4 shows the wavenumber power spectra of case (a) and (b). Results obtained from the case studies and the comparison between SAR data and *in situ* wave data are discussed below.

##### 4.1. Case(a) : wave field on November 26, 1993

The 2D wavenumber power spectrum in Fig. 4a was derived from the Fourier transform of a 800 m by 800 m subscene of the satellite image in Fig. 2a. The spectral peak located at  $(n_x, n_y) = (2, 5)$  represents the primary wave system east of Taiwan on November 26, 1993. The direction of  $k_x$  axis is  $12.9^\circ$  in a clockwise direction from the south for all descending pass of ERS-1, as in case (a). The wave came from a  $68^\circ$  counter-clockwise direction of  $k_x$  or  $125^\circ$  from the north. The wavenumber of the primary wave system is  $4.23 \times 10^{-2}$  rad/m, corre-

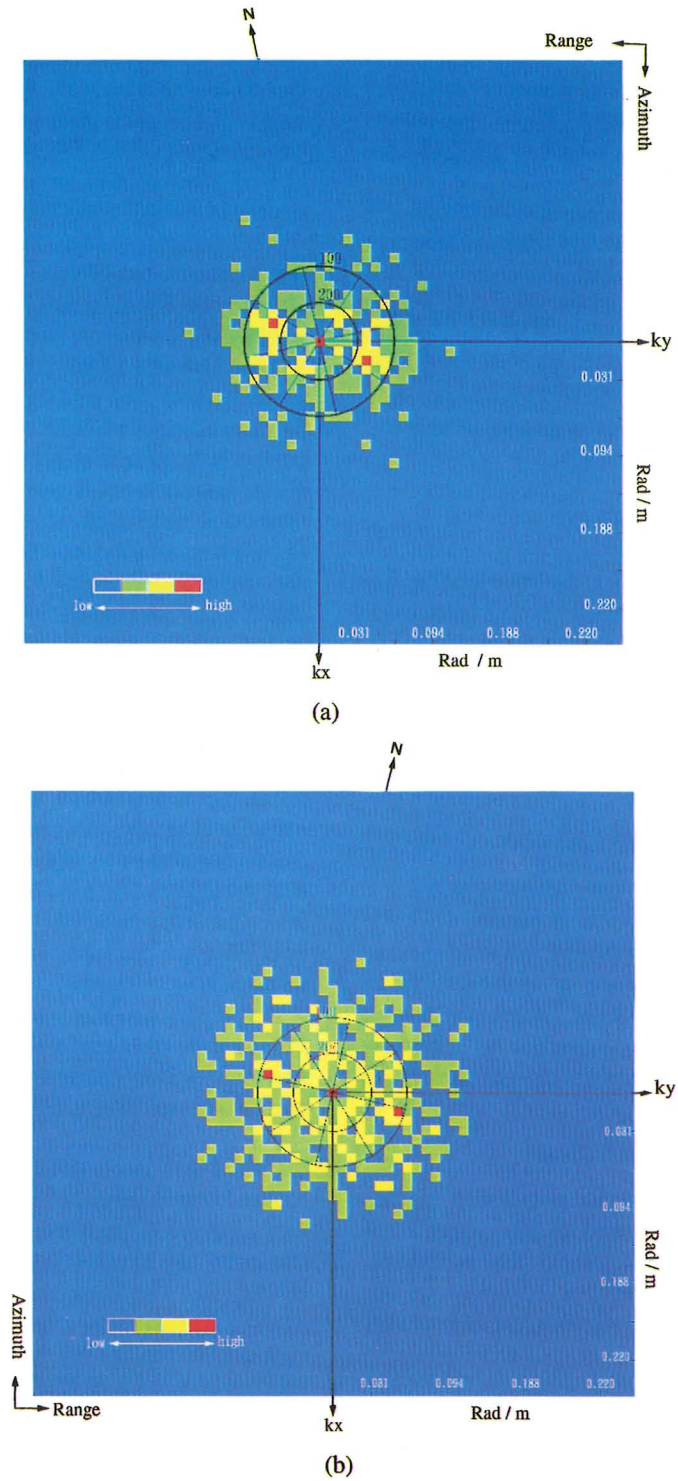


Fig. 4. SAR wavenumber power spectra of Hwaiien coastal zone for case (a) and (b). The inner and outer circles denote the loci of wavelength 200 m and 100 m, respectively.

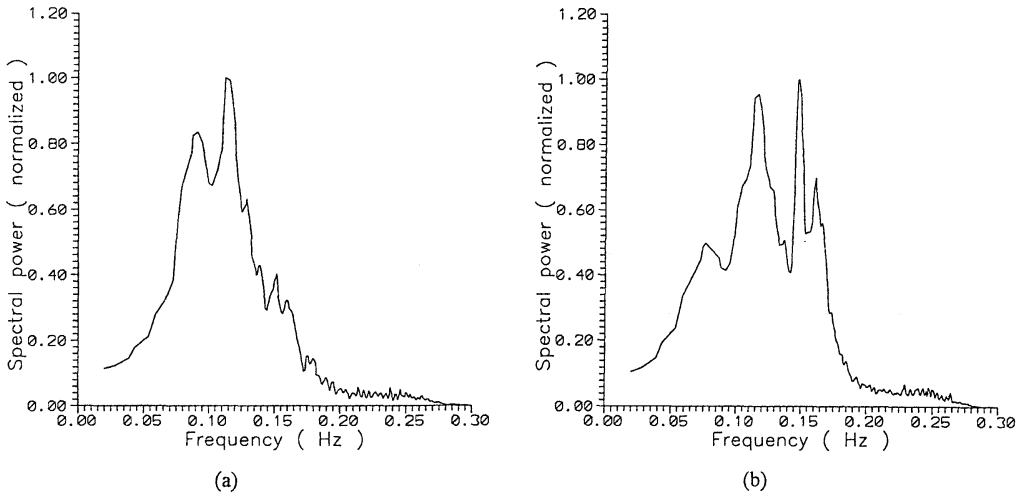


Fig. 5. SAR frequency power spectra of Hwaiien coastal zone for case (a) and (b).

sponding to 149 m in wavelength. This 2D wavenumber power spectrum was transformed to the omnidirectional frequency power spectrum by integrating the power spectra of equal-wavelength waves in all directions. Figure 5a clearly reveals two separate peaks (fp) in the frequency power spectrum : one is at 0.092 Hz and the other is at 0.113 Hz. The wave system with fp=0.092 Hz in the omnidirectional frequency power spectrum matches the wave system of  $(n_x, n_y)=(2, 5)$  in the 2D wavenumber spectrum. The other one with fp=0.113Hz (wavelength=110m) does not distinguish itself in the 2D wavenumber power spectrum. Further analysis reveals a large but narrow spectral peak appearing at the wavenumber  $(n_x, n_y)=(-2, 7)$  in Fig. 4a. This wave system came from  $106^\circ$  in a counter-clockwise direction from the  $k_x$  axis, or  $87^\circ$  in a clockwise direction from the north.

To verify the SAR-derived wave system, *in situ* wave data acquired by the wave-rider were analyzed. Figure 6a shows two peaks of frequency power spectrum : one with a frequency of 0.095 Hz and the other with a frequency of 0.11 Hz. Those peaks correspond to wave periods of 10.53 sec and 9.09 sec, and wavelengths of 141m and 114m, respectively. The solid line in Fig. 6a represents the dominant direction of propagation for each wave frequency. For the above mentioned spectral peaks, the wave directions are  $105^\circ$  and  $95^\circ$  from the north.

Table 1 lists the wave-field characteristics as derived from SAR images and from *in situ* measurements. The differences in wavelength were 5.7% (8m difference) in the primary wave system and 3.5% (4m difference) in the secondary wave system. The differences of wave direction were  $20^\circ$  and  $8^\circ$ , respectively. In Figs. 5a and 6a, clearly indicates that their spectra shapes are compatible, despite the small difference in the relative magnitude of the spectral peaks. At 25% level of the spectral maximum, the wave energy in the SAR spectrum ranges between 0.06 and 0.16 Hz. Moreover, the wave energy in the wave-rider spectrum ranges between 0.08 and 0.12, with the significant wave height and the wave period being 1.65 m and 8.4 sec, respectively.

4.2. Case(b) : wave field on November 15, 1993

Figure 4b shows another example of applying 2D wavenumber power spectrum SAR image. A primary wave system on November 15, 1993 is represented by the spectral peak at  $(n_x, n_y)=(2, 7)$ . Table 1 lists wave directions, wavelengths, and wave periods. Two spectral peaks in the omnidirectional frequency spectrum (Fig. 5b) are (1) fp=0.113 Hz corresponds to the wave system  $(n_x, n_y)=(2, 7)$  in 2D wavenumber power spectrum, and (2) fp=0.147 Hz does not appear clearly in the wavenumber spectrum. If we limit the search along a circle with a wavelength of 70 m in Fig.

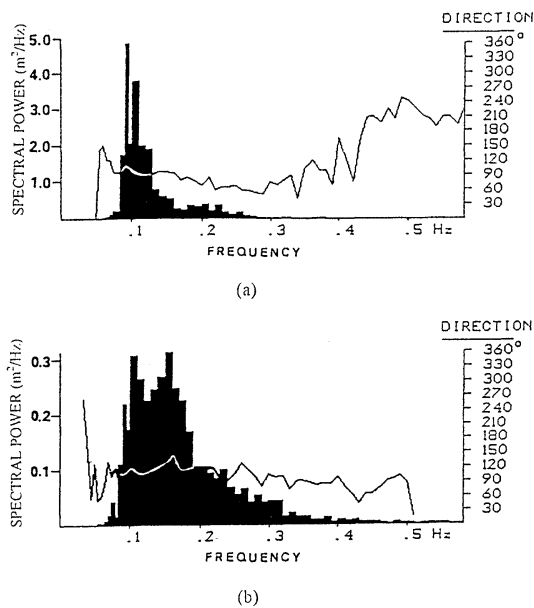


Fig. 6. Frequency power spectra of Hwaiien coastal zone derived from *in situ* wave data for case (a) and (b). Solid lines denote wave directions varying with wave frequencies.

4b, then the secondary wave system is found at  $(n_x, n_y) = (8, 8)$ . The  $k_x$  axis is  $12.9^\circ$  in the counter-clockwise direction from the south for a SAR image of ascending pass of ERS-1. Therefore, this wave system came from a  $45^\circ$  counter-clockwise direction from  $k_x$  axis, i.e.,  $122^\circ$  clockwise direction from the north.

Two spectral peaks were found in the frequency power spectrum (Fig. 6b) of *in situ* wave data. Case (b) of Table 1 lists the wave

characteristics analyzed from SAR image and *in situ* wave data. The differences in wavelength and wave direction are 7.6% (or 9m) and  $26^\circ$  for the primary wave system, respectively, and 16% (or 10 m) and  $20^\circ$  for the secondary wave systems. A comparison of both frequency power spectra in Figs. 5b and 6b reveals that their spectral peaks correspond well to each other. The primary wave energy was concentrated within the frequency of 0.09~0.17 Hz in SAR power spectrum and 0.09~0.19 Hz in the power spectrum of *in situ* data. Both spectrum curves were strikingly similar. The sea state was relatively calm with the significant wave height measured by the wave-rider being 0.73 m at a period of 6.6 sec.

## 5. Conclusions

Microwave remote sensing of the earth's surface has nearly all-weather imaging capabilities, and is insensitive to natural illumination (day or night) or atmospheric conditions (clear or cloudy sky, calm or windy weather). Satellite SAR can image the surface wave-field in severe sea states and obtain information regarding wave characteristics over a vast region. This study has verified the feasibility of using SAR to observe the ocean wave-field over intermediate water depth with a significant wave height below 2 meters. Experimental results demonstrate that an appropriate size of SAR image should be carefully determined for spectral analysis. A subscene of 800 m by 800 m was selected such that the power spectra

Table 1. Comparison of Hwaiien wave characteristics derived from ERS-1 SAR and *in situ* wave data for case (a) of November 26, 1993, and case (b) of November 15, 1993.

Sensors	dominant wave systems	wavelength (m)	wave direction (degree)	frequency (Hz)	period (sec)
case (a)					
ERS-1/SAR	primary	149	$125^\circ$	0.092	10.9
	secondary	110	$87^\circ$	0.113	8.9
Wave-rider	primary	141	$105^\circ$	0.095	10.5
	secondary	114	$95^\circ$	0.110	9.1
case (b)					
ERS-1/SAR	primary	110	$93^\circ$	0.113	8.9
	secondary	71	$122^\circ$	0.147	6.8
Wave-rider	primary	119	$119^\circ$	0.107	9.4
	secondary	61	$142^\circ$	0.160	6.3

shows stable features. Dispersion relation of deep water waves can be applied in the open sea ; however, the full wave dispersion relation should be used for the coastal zone. High pass and low pass filters were necessary in the pre-processing of SAR images to remove the trend and noises and to improve the SNR of the spectra peaks.

A comparison of main waves derived from SAR images and from *in situ* observation revealed that the difference in wavelength is about 3.5% to 16% (i.e. 4m to 10m) for wavelength of 60 m~150 m, and the difference in wave direction is about 8° to 26°. This finding demonstrates that ERS-1 SAR images are sufficient to examine wave characteristics such as the wavelengths and directions. In these case studies, SAR spectra and *in situ* wave spectra correlated well with each other. Also, the wave energy distribution (spectral shape) and the spectral peaks in the frequency domain were very similar.

Because the power spectra was derived from the SAR images of radar backscattering cross section of the sea surface, the wave height information is combined with other forcings such as the surface wind velocity. Therefore, the wave height could not be estimated directly from the SAR images unless a calibrated MTF is available for corresponding the surface waves and SAR frequency power spectra. Determining the wave height by SAR data is to be addressed in our near future study.

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## Minimum daytime brightness recognized by Japanese spiny lobster

Takashi KOIKE\*, Kooji HAYASHI\* and Yutaka NAGATA

**Abstract:** The Japanese spiny lobster shows nocturnal habit, and a clear diurnal variation is observed in its activity. We reproduced diurnal brightness variation in our experimental tank by setting a 12-hour bright period (daytime) and a 12-hour dark period (nighttime), alternatively. The lobster was habituated in the condition of the  $3.3 \times 10^2$  lx daytime brightness and of the 0 lx nighttime brightness for several days prior to each experimental run. Then, the daytime brightness was changed to 0 lx, and the lobster was put into a long-lasting dark condition (control run). The lobster sustains its diurnal variation pattern even after the change of condition, but the variation period tends to be shortened. Several similar experiments were conducted by decreasing the changing rate of the daytime brightness, and compared with the results of the control run. When the daytime brightness is changed to lower than a threshold value, the lobster behaves just as in the control run. When the brightness is larger than this threshold value, the activity variation of the lobster occurs just in phase with the brightness variation, and no change in variation period occurs. The threshold brightness was shown to be about  $2.3 \times 10^{-5}$  lx, and this value would be understood as the minimum daytime brightness recognized by the lobster.

### 1. Introduction

Spiny lobsters show nocturnal habit (*e.g.*: SUTCLIFFE, 1956; IWAI and HAYASHI, 1990; LIPCIUS and COBB, 1994). They move actively at night, and are almost at rest at daytime. KOIKE *et al.* (1993, 1995) investigated the diurnal variation of activity of Japanese spiny lobsters *Panulirus japonicus* in a small water tank, and showed that the nighttime activity is strongly controlled by underwater brightness. Spiny lobsters move actively under nighttime brightness less than  $2.3 \times 10^{-5}$  lx just as in a pitch-dark condition (0 lx). The nighttime activity is considerably suppressed if the nighttime brightness is set to be higher than  $5.2 \times 10^{-3}$  lx. KOIKE *et al.* (1993, 1995) adapted  $3.3 \times 10^2$  lx as the standard daytime brightness in their experiments, but they showed that the diurnal activity variation is almost unchanged if the daytime brightness is kept higher than  $3.5 \times 10^{-2}$  lx. However, the lower limit of the daytime brightness that spiny lobsters are able to identify as the daytime was not obtained.

A lobster was kept in the standard conditions of  $3.3 \times 10^2$  lx daytime brightness and of 0 lx nighttime brightness for several days as a habituation period. Then, the daytime brightness was lowered to a prescribed value. Even if the daytime brightness is changed to 0 lx, and if the lobster is kept in pitch-dark condition thereafter, the lobster preserves the similar diurnal variation pattern as in the habituation period. After several days, however, the transition time from low activity to high activity period tends to shift gradually, and occurs earlier and earlier day after day.

It was shown that the shift of the transition time occurs when the daytime brightness is lowered to a finite values smaller than a threshold value. Above this threshold value, the diurnal variation of the lobster activity occurs just in phase with given brightness variation. The threshold brightness was shown to be about  $2.3 \times 10^{-5}$  lx, and this value would be understood as the minimum daytime brightness recognized by the lobster.

\* Faculty of Bioresources, Mie University, Kamihama-cho, Tsu. Mie 514, Japan

### 2. Experimental procedure

Our experiment was conducted in small water

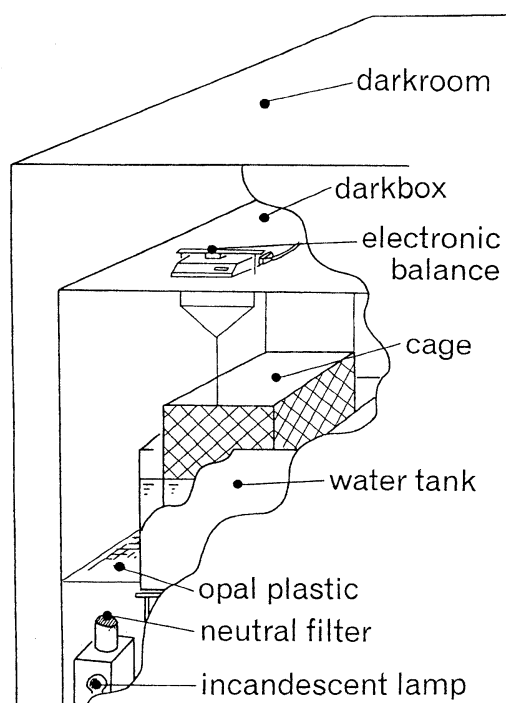


Fig. 1. Schematic view of the experimental apparatus.

tanks in the Fisheries Research Laboratory of the Mie University which is located in Zaga Island in Ago Bay, Mie Prefecture. The tanks are kept in the dark box as shown schematically in Fig. 1. Each lobster was kept in a cage of 40 cm length, of 30 cm width and, of 30 cm depth. The cage is hung by three wires, one of which is connected to an electric balance. The variation of its tension caused by lobster movements is measured and recorded automatically. The water in the tank is replaced by sea water pumped up from the depth of about 5 m at the rate of 3 l per min. The water is drained from two outlets placed near the water surface and near the bottom of the tank,

respectively, in order to keep the water inside clean. We use incandescent lamps as light source. Only the reflected light from the ceiling is allowed to reach the tank surface, and the downward light flux at the surface at the center of the tank is used as a measure of the brightness. The light intensity is adjusted by putting various semitransparent neutral filters on front of lamps. The lamps are switched on at 6:00 and off at 18:00 by using a timer. The daytime is modeled by 12 hours bright period with a constant brightness, and the nighttime by 12 hours period of 0 lx.

The tension of the wire averaged over 9 sec recorded for every 15 sec. By assuming that the tension change larger than 2 gw indicates a significant lobster movement, the occurrence frequency of such changes is used as a measure of the lobster activity. The 2 gw change in tension corresponds to the movement of the lobster of 250 gw (about 25 gw in the sea water) over the distance of 3.2 cm in the longitudinal direction. The apparatus and the experimental procedure are the same as used in the previous papers (KOIKE *et al.* 1993, 1995).

The combination of the daytime and nighttime brightnesses for each experimental run is shown in Table 1, together with other experimental parameters. The nighttime brightness is fixed to be 0 lx throughout our experiments. The daytime brightness is set to be 0 lx in run 1 (control run),  $6.8 \times 10^{-8}$  lx in run 2,  $2.3 \times 10^{-5}$  lx in run 3,  $5.2 \times 10^{-3}$  lx in run 4, and  $3.5 \times 10^{-2}$  lx in run 5, respectively. The lobster was kept in the standard condition of the  $3.3 \times 10^2$  lx daytime brightness for more than 1 week (habituation period) prior to the experiments of run 1 through run 3. The behaviors of the lobster in run 2 through run 5 will be discussed in comparison with that in the control run (run 1).

Table 1. Experimental conditions of the five experimental runs conducted in the present study.

Run No.	Brightness(lx)		Water temp. (°C)	Dates	
	daytime	nighttime			
1	0	0	19.0-22.4	May.28-Jul.15	1993
2	$6.8 \times 10^{-8}$	0	21.7-22.5	Jul. 3-Jul.25	1993
3	$2.3 \times 10^{-5}$	0	19.6-23.7	Sep.21-Oct.31	1993
4	$5.2 \times 10^{-3}$	0	22.5-27.8	Jul. 1-Jul.15	1990
5	$3.5 \times 10^{-2}$	0	23.1-26.0	Jun.17-Jun.30	1990

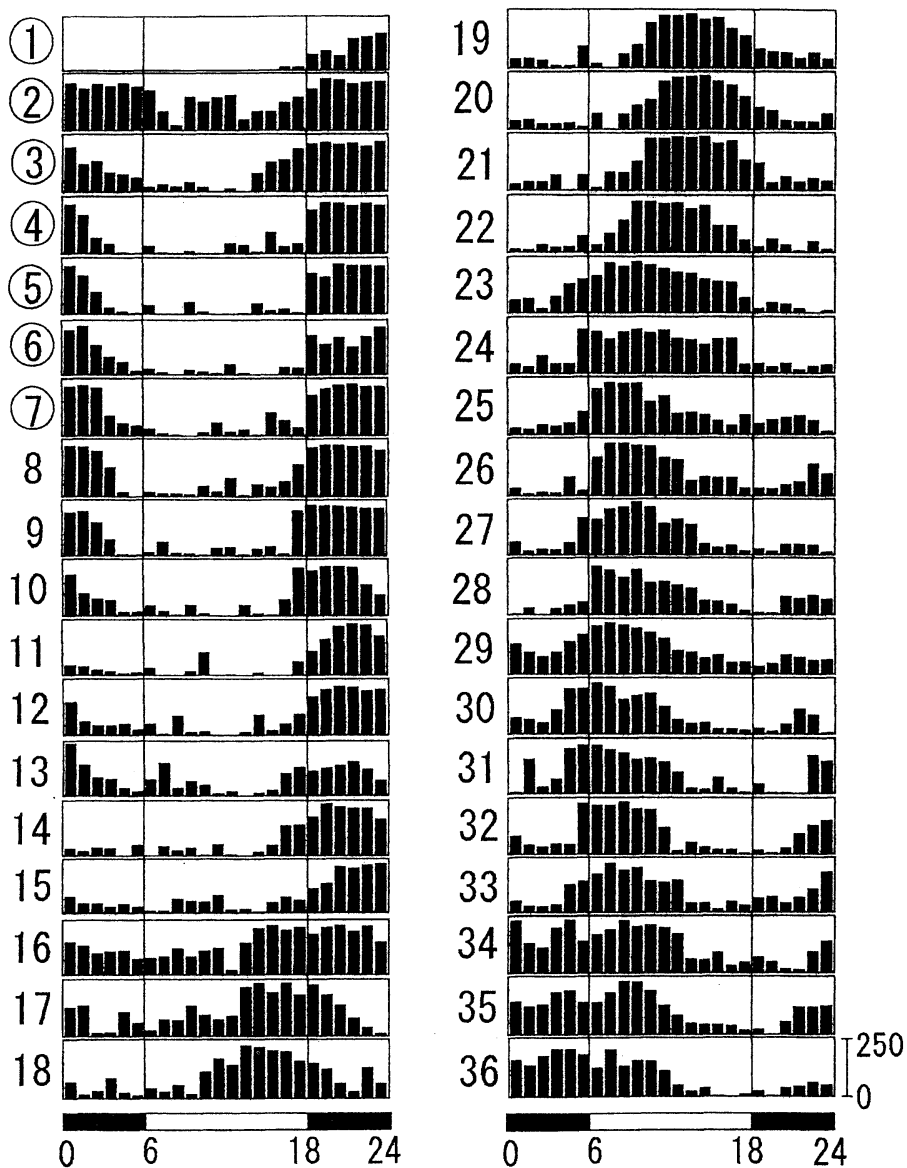


Fig. 2. Daily variation of the diurnal activity change of the lobster in run 1. The activity frequency per hour is taken in the ordinate, and its scale is shown at the under right corner. The time of day is taken in the abscissa. The nighttime is shown with black horizontal bars and the daytime with white bars. The numerals attached on left side of each figure show the day number, and those with circle indicate that they are in the habituation period.

We used the lobsters which had been caught in the sea off Wagu of the Shima Peninsula, Mie Prefecture. Only the male lobsters having carapace length from 7.0 to 8.5 cm and having weight from 250 to 350 gw. The lobsters can be usually used more than one year. No significant change is observed in their moving

characteristics, though the magnitude of activity frequency strongly depends on water temperature as discussed later. The same lobster was used in the experiments of run 1 through run 3, but the lobsters used in run 4 and run 5 were different to one another. The lobster in the tank is fed with 150–250 gw living mussels



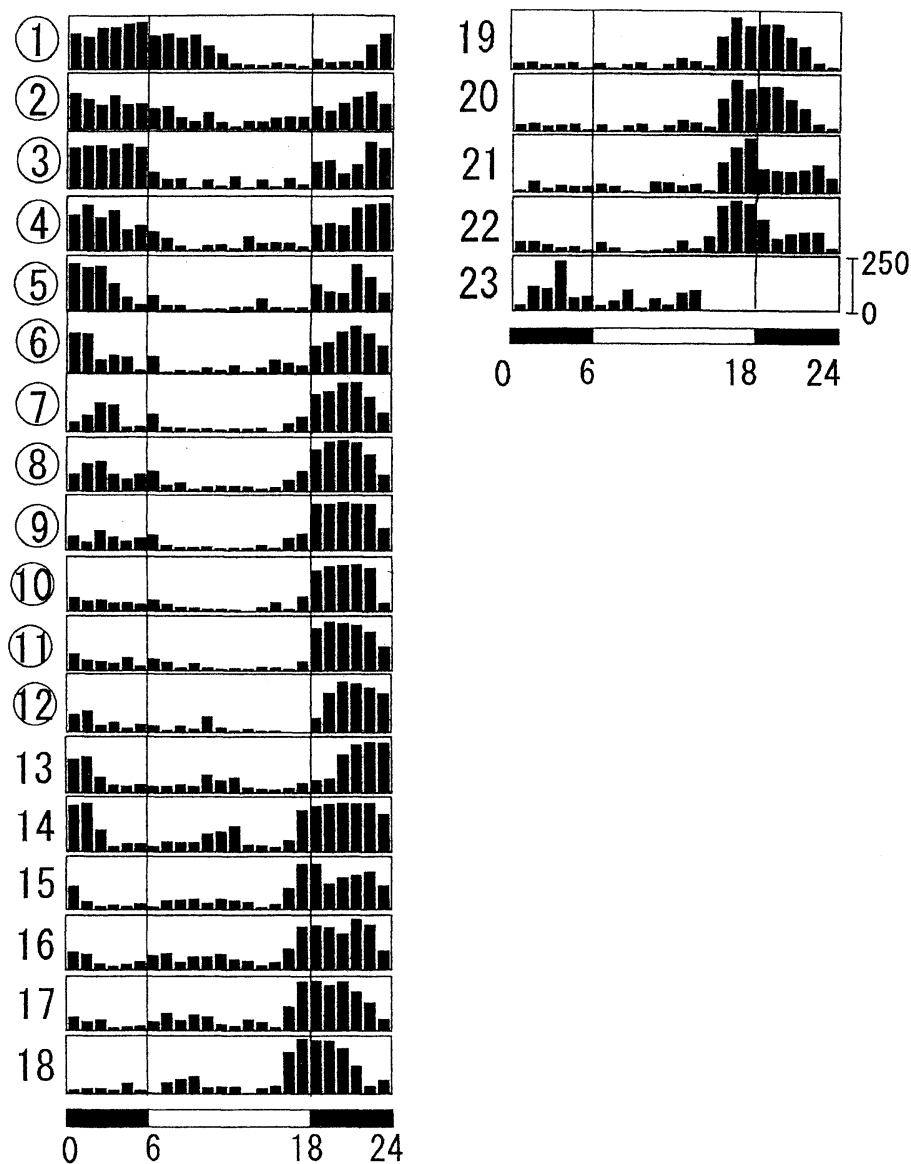


Fig. 3. The same as in Fig. 2, except for run 2.

*Mytilus edulis* once a week. The weight of the mussels ranges from 3 to 10 gw, and their shells are partly broken so as that the lobster can easily eat them. The mussels are sometimes found living three days after, but all of the mussels have been eaten up before the next feeding time. The feeding was made in the middle of the day, and the water temperature in the tank was measured with a thermistor at the time of feeding.

### 3. Diurnal variation of the lobster in the standard condition

The diurnal variations of the lobster activity are shown in Fig. 2 for the period from May 28 to July 2, 1993 (run 1) and in Fig. 3 for the period from July 3 to July 25, 1993 (run 2), respectively. The first 7 days in run 1 and the first 12 day in run 2 are the habituation period in the standard condition. The pattern of the diurnal variation appears to be disturbed for a few

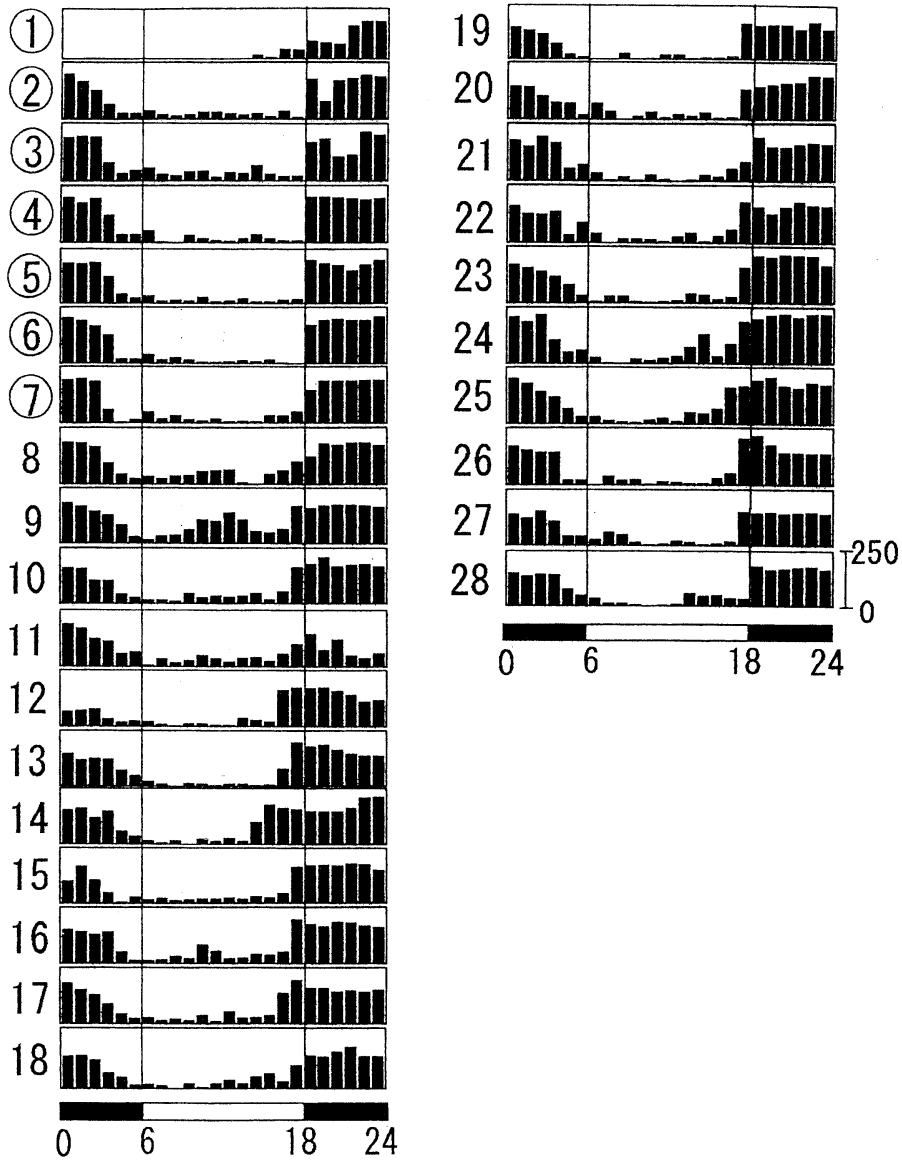


Fig. 4. The same as in Fig. 2, except for run 3.

days until the lobster becomes familiar with its new circumstance. Then, the lobster activity usually shows a clear diurnal variation in phase with the diurnal brightness variation. The length of the habituation periods adopted in our present experiments is arbitrary and depends mainly on the time needed for set up our experimental apparatus. The data taken in the first few disturbed days are included in our analysis as it does not affect on our

experimental results significantly.

The diurnal activity variations measured in the period from September 21, 1993 to October 31, 1993 (run 3) are shown in Fig. 4. The lobster had been kept in the standard condition for about 1 month, but the data is available only the last 7 days due to a trouble in our recording system. The diurnal activity variations for these 7 days are shown as in habituation period in the figure.

Table 2. Activity frequencies per hour for nighttime (N) and for daytime (D) for each habituation period and for each sub-period of one week length. The sub-period in each run may be shorter than one week, and 4 days (\*) or 6 days (\*\*). The standard deviations are also shown. The variation periods (in hour) obtained by the periodogram analysis are shown in parentheses. The brightness conditions are reproduced in the left side columns.

Run No.	Brightness (lx)	habituation	first week	second week	third week	fourth week
1	N 0	155.0±25.2	128.5±27.8	81.8±38.9	45.1±6.9	91.1±11.9
	D 0	38.2±32.3 (24.0)	37.4±7.8 (24.0)	129.5±37.2 (22.8)	144.7±14.3 (23.6)	111.2±14.6 (23.8)
2	N 0	119.5±9.8	104.7±25.9	49.3±7.3 *		
	D 6.8×10 <sup>-8</sup>	25.7±5.4 (24.0)	58.3±9.9 (23.4)	53.2±20.4 * (23.8) *		
3	N 0	136.4±30.9	127.3±21.0	128.0±10.1	145.7±16.0	
	D 2.3×10 <sup>-5</sup>	19.8±7.2 (24.0)	46.6±16.1 (23.8)	34.1±9.2 (24.2)	37.6±8.8 (24.0)	
4	N 0		86.8±9.7	66.8±11.0		
	D 5.2×10 <sup>-3</sup>		19.5±10.8 (24.0)	12.6±2.4 (24.0)		
5	N 0		62.4±13.4	81.2±13.5 **		
	D 3.5×10 <sup>-2</sup>		14.7±4.8 (24.0)	9.4±1.3 ** (24.0) **		

The diurnal activity variations for these habituation periods give a pattern with very low activity in daytime and with high activity in nighttime. The activity frequency averaged separately for daytime and for nighttime for each habituation period is shown in the left-hand side column of Table 2, together with its standard deviation. It can be seen that the activity frequency in nighttime is remarkably higher than that in daytime. The magnitude of the activity frequency, however, appears to be changeable run by run even for the same lobster. Activity frequencies accumulated for 24 hours are calculated for the days when the water temperature was measured. In Fig. 5, the accumulated frequencies in the habituation (standard) condition are plotted against the water temperature. The data of the previous experiments and of run 4 and run 5 are also included, as the lobster shows a clear diurnal variation patterns as just as in the standard condition. The data are well aligned near a straight line, and the activity decreases linearly with temperature increase. The straight line drawn in Fig. 5 is obtained by the least square method, and is given by

$$F = 9569 - 301T$$

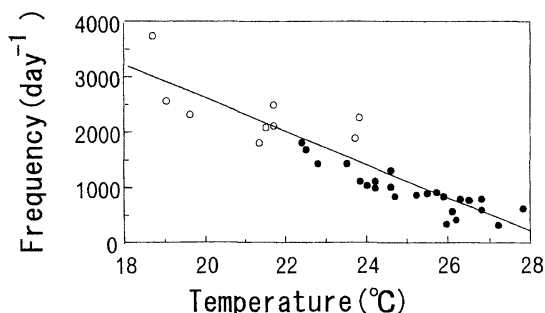


Fig. 5. Relation between the water temperature (°C) and the accumulated activity frequency per day. The straight line in the figure is obtained by the least square method. Data points shown with white circles are obtained in the present experiments, and those with black circles in the previous experiments.

where  $F$  is the activity frequency per day, and  $T$  the water temperature in °C. This relation could not be applicable for lower temperatures as the lobster activity is very low in winter time. The relation suggests that the lobster activity is determined mainly by water temperature. This might be resulted partly from the facts that we used male lobsters of medium sizes only and that significantly inactive

lobsters are intentionally removed prior to the experiments. The individuality of the lobster appears not to affect our present experimental results significantly.

The transition from the low activity to the high activity occurs just when the light is turned off (at 18:00). However, the transition from the high activity to the low activity does not always coincide with the time when the light is put on (at 6:00). The lobster used in run 1 through run 3 tends to stop its activity a few hours before the start of the daytime. The lobsters used in runs 4 and 5 tend to continue to move for a little while after the light is on. The transition time from high activity to low activity may depend on individuality of lobsters.

In order to describe the periodicity of the diurnal variation of the lobster activity objectively, a periodogram analysis (see, for sample, TABATA, 1991; WADA, 1983) is applied for the data in each habituation period, and the obtained period is given in parenthesis in each column of Table 2. The period in each habituation period is exactly 24.0 hours.

#### 4. The behavior of the lobster after the daytime brightness is changed to 0 lx

We shall see how the behavior of the lobster is changed after the daytime brightness is lowered to 0 lx (from the 8-th day to the 36-th day in Fig. 2: run 1). For the first several days, the lobster keeps its diurnal variation pattern as just as in the habituation period even in pitch dark condition. Then, the transition time from low activity to high activity shifts earlier and earlier day by day. On the 18-th day, the high activity period occurs from 6:00 to 18:00: the phase of the diurnal activity variation becomes just opposite to that of the original brightness variation.

After the 21-th day, the diurnal pattern of the activity variation appears to be disturbed: the length of the high activity period tends to increase and that of the low activity to decrease, and the peak of the high activity appears sometimes twice a day (on the 32-th and 33-th days in Fig. 2). For this period, the phase shift of the variation pattern is hardly recognized.

We divided the period, after the day when

the 24 hours pitch-dark condition starts, into several sub-periods having the length of a week (the length of the last sub-period of each run may be shorter than one week). The activity frequency and its standard deviation for the daytime (defined as from 6:00 to 18:00 also in the pitch-dark condition for convenience' sake) and the nighttime (defined as from 18:00 to 6:00) are calculated for each sub-period, and shown in Table 2. The shift of the diurnal activity variation mentioned above is recognized as increases of daytime activity and decreases of nighttime activity.

The periodogram analysis was applied also for each sub-period, and the obtained period of the diurnal variation is shown for each column in Table 2. No phase shift occur in the first week of run 1, and the period is just 24.0 hours. The period in the second week decreases to 22.8 hours indicating that the transition time moves earlier and earlier. The periods in the third and fourth weeks are also shorter than 24.0 hours, but the period tends to increase toward the 24.0 hours as the time elapses.

The phase shift and the shorter variation period seen in the second and third weeks might suggest that the diurnal activity variation of Japanese spiny lobster is strongly controlled by the brightness conditions, and the 24.0 variation period is not their inherent nature. However, the variation period increases gradually again near to 24.0 hours, if it is kept long enough in a pitch-dark condition, though the variation pattern tends to become ambiguous. The further elaborated experiments would be needed to get definite conclusions.

#### 5. Minimum daytime brightness recognized by Japanese spiny lobster

If we change the daytime brightness to a level lower than the minimum brightness recognized by a Japanese spiny lobster after keeping a lobster in the standard condition, the lobster in the tank would exhibit just as the same behavior as described in the previous section. The daytime brightness is lowered to  $6.8 \times 10^{-8}$  lx from the 13-th day in run 2 (Fig. 3). Though some disturbance is seen for the first few days, the transition time from low activity to high activity shifts clearly earlier and

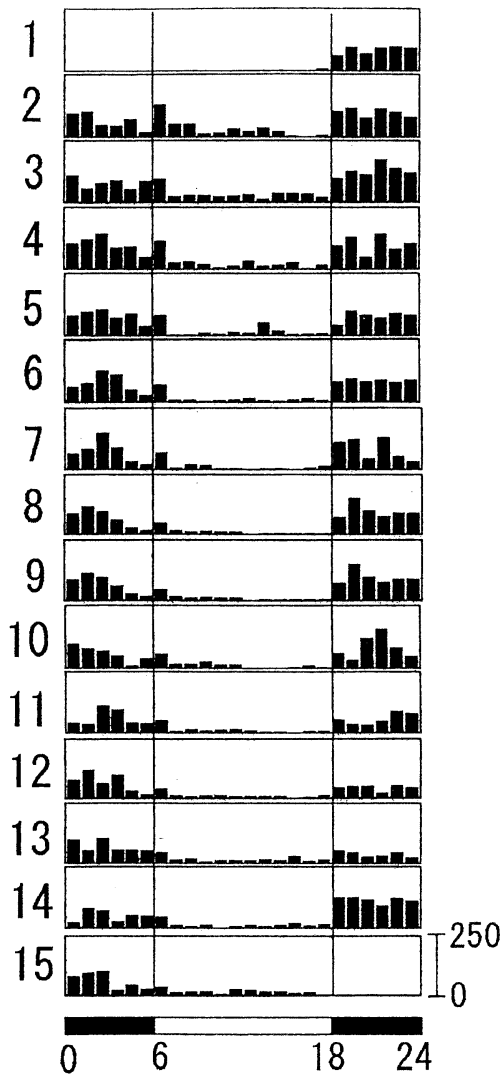


Fig. 6. The same as in Fig. 2 except for run 4. No habituation period is set in this run.

earlier after the 14-th day. The activities for daytime (6:00–18:00) and for nighttime (18:00–6:00) and their standard deviations for each one-week sub-period are shown in Table 2, together with the period obtained from the periodogram analysis. The behavior of the lobster in run 2 is very similar to that in run 1. We conclude that the lobster cannot identify the brightness of  $6.8 \times 10^{-8} \text{ lx}$  as daytime.

The daytime brightness is lowered to  $2.3 \times 10^{-5} \text{ lx}$  from the 8-th day in run 3 (Fig. 4). The variation pattern for the first few days are

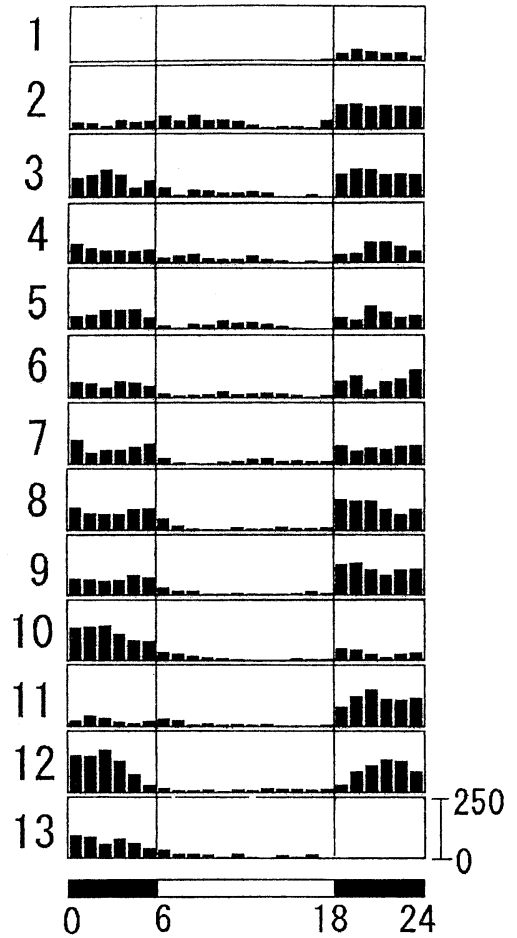


Fig. 7. The same as in Fig. 2 except for run 5. No habituation period is set in this run.

disturbed, and the lobster activity is rather high even in daytime, especially in the 8-th and 9-th days. The shift of the transition time from high activity to low activity shifts forwards from the 12-th day to the 14-th day. However, the transition time goes back and occurs at 17:00 in the 15-th day (one hour before the brightness change). The similar forward shift is observed in the period from the 15-th day to the 18-th day, but the transition backs again and occurs at 17:00 in the 19-th and 20-th days. In general, the transition time is not exactly in

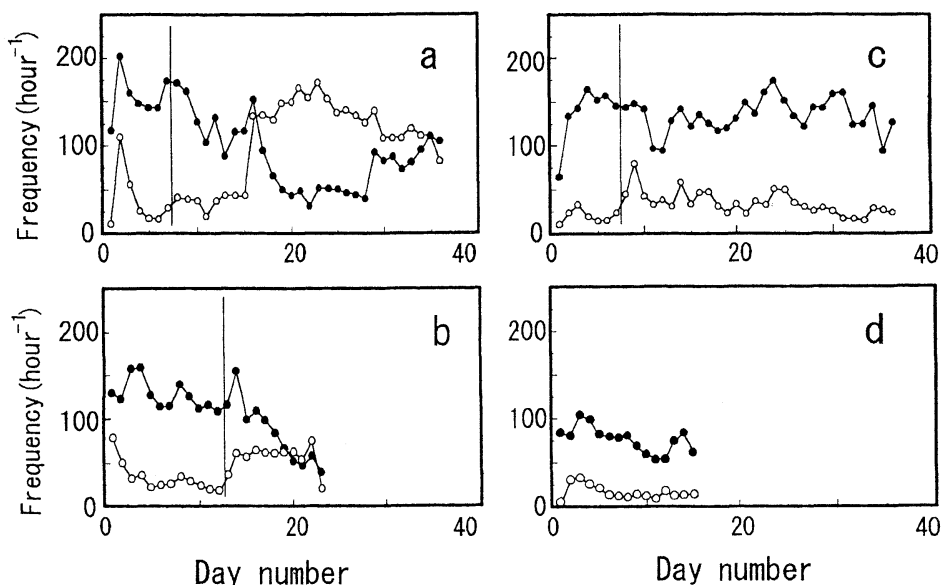


Fig. 8. Temporal changes of the lobster activity frequencies per hour averaged over nighttime (black circles) and over daytime (white circles) for each day: **a** is for run 1, **b** for run 2, **c** for run 3, and **d** for run 4, respectively. The day number is taken in the abscissa. The left-hand side of the vertical line indicates the habituation period.

phase to the brightness variation. These results suggest that the lobster appears to be confused, but identifies more or less the brightness of  $2.3 \times 10^{-5} \text{ lx}$  as daytime.

The diurnal lobster activity variations for the daytime brightness of  $5.2 \times 10^{-3} \text{ lx}$  (run 5) and of  $3.5 \times 10^{-2} \text{ lx}$  (run 6) are shown in Figs. 6 and 7, respectively. Though no habituation period is set for these experiments, and though some disturbed patterns appear for the first few days, the transition from low to high activity occurs always at 18:00, namely at the time that the light is put off. The difference between daytime and nighttime activity and the variation period are as just as in the standard condition (Table 2). We conclude that the lobster recognizes these brightness as daytime.

## 6. Summary and conclusion

The change of the diurnal variation pattern of the Japanese spiny lobster for the various daytime brightness is investigated in the experimental tank. The results are summarized in Fig. 8 where day to day variations of the lobster activity frequencies in daytime and in nighttime are shown for each experimental

runs. The variation patterns for the daytime brightness of  $2.3 \times 10^{-5} \text{ lx}$  and of  $5.2 \times 10^{-3} \text{ lx}$  are almost identical to that in the habituation period. When the daytime brightness is lowered to  $6.8 \times 10^{-8} \text{ lx}$ , the transition time from low to high activity is shifted earlier and earlier, and the nighttime activity (18:00–6:00) decreases on reflecting such phase change. For the case of  $2.3 \times 10^{-5} \text{ lx}$  daylight brightness, the clear shift of the transition time is not observed, but the transition time is somewhat variable day by day. This brightness value appears to be detected by the lobster but with some perplexity. Our results suggest that the minimum daytime brightness recognized by Japanese spiny lobster is about  $2.3 \times 10^{-5} \text{ lx}$ . This is consistent with the result given by KOIKE *et al.* (1993, 1995) where they reported that the lobster activity in nighttime is very high if the nighttime brightness is lower than this value. It is also consistent to the results given by ARCHIGA and ATKINSON (1975): they reported the brightness value of  $10^{-5} \text{ lx}$  as the minimum brightness recognized by Burrowing prawn *Nepherops norvegicus*.

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## Seagrasses and epiphytes in Thale Sap Songkhla, Southern Thailand

Saowapa ANGSUPANICH\*

**Abstract** : Seagrass biomass in Thale Sap Songkhla was monthly investigated from December 1992 to November 1993. Seagrasses were found in only 2 areas in Thale Sap Songkhla. *Halodule pinifolia* and *Halophila ovalis* were obtained on the sandy bottom 1300 m from the mouth of Thale Sap Songkhla while *Halophila beccarii* inhabited the area close to the western shoreline of Thale Sap Songkhla. *Halophila beccarii* and *Halodule pinifolia* were found almost throughout the year, with average annual biomass of 95.3 and 84.1 g(d.w.)m<sup>-2</sup>, respectively. *Halophila ovalis* was the least abundant species and could be found during only 6 months in the year (March to September). The maximum biomass of three species of seagrasses was in the light rainy period during July to August (southwest monsoon) while the minimum was in the heavy rainy period during October to December (northeast monsoon). Most epiphytes found on the three species of seagrasses were benthic diatoms. The dominant was *Cocconeis* sp. Old leaves of seagrasses tended to have more epiphytes than young leaves.

### 1. Introduction

Seagrass bed is well-known to be important for fisheries (KLUMPP *et al.*, 1989). Juvenile spotted seatrout used seagrass beds as their major habitat (MCMICHAEL and PETERS, 1989). The seagrass distribution and diversity have been investigated along the coast of Andaman Sea and Gulf of Thailand (POOVACHIRANON, 1988; LEWMANOMONT *et al.*, 1991). However, the seagrass community survey in Songkhla Lake is limited.

Songkhla lake is located between latitudes 7°08' N and 7°50' N, and between longitudes 100°07' E and 100°37' E (Fig. 1). It is the only lake in Thailand and covers a total area of 986.8 km<sup>2</sup> (98680ha), divided into 3 parts: Thale Noi, Thale Luang and Thale Sap Songkhla (the low-ermost part of Songkhla Lake, connecting with the open sea) (BROHMANONDA and SUNGKASEM, 1982). The salinity of water in Thale Sap Songkhla is brackish to seawater according to seasons. The average depth at the middle of Thale Sap Songkhla is 1.2 m. The deepest area is about 8.0-8.8 m measured at Pak Khat and

the mouth of Thale Sap Songkhla (RAKKHEAW, 1994).

The present study was designed to investigate the distribution and seasonal variation of seagrasses in Thale Sap Songkhla.

### 2. Materials and methos

Surveys and samplings of seagrasses in Thale Sap Songkhla were done during low tide using a Tamura grab of 0.05 m<sup>2</sup> in surface area. This particular grab, with serrated teeth, was suitable for sampling small seagrasses growing on the soft bottom. Random samplings were done around the shore and the middle of the lake to locate areas covered by seagrasses. After the areas were found, they were then sampled every month from December 1992 to November 1993. Ten replicate samplings were done for each sampling site. Samples were washed through a series of sieves with 5 mm and 1 mm apertures. Seagrasses and their epiphytes were identified. Each species of seagrasses was washed in 5% phosphoric acid (BROUNS, 1987), then dried at 60-80 °C for 48 hours to determine their dry weights. Measurement of seagrass blade length was also carried out.

\*Department of Aquatic Science, Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand



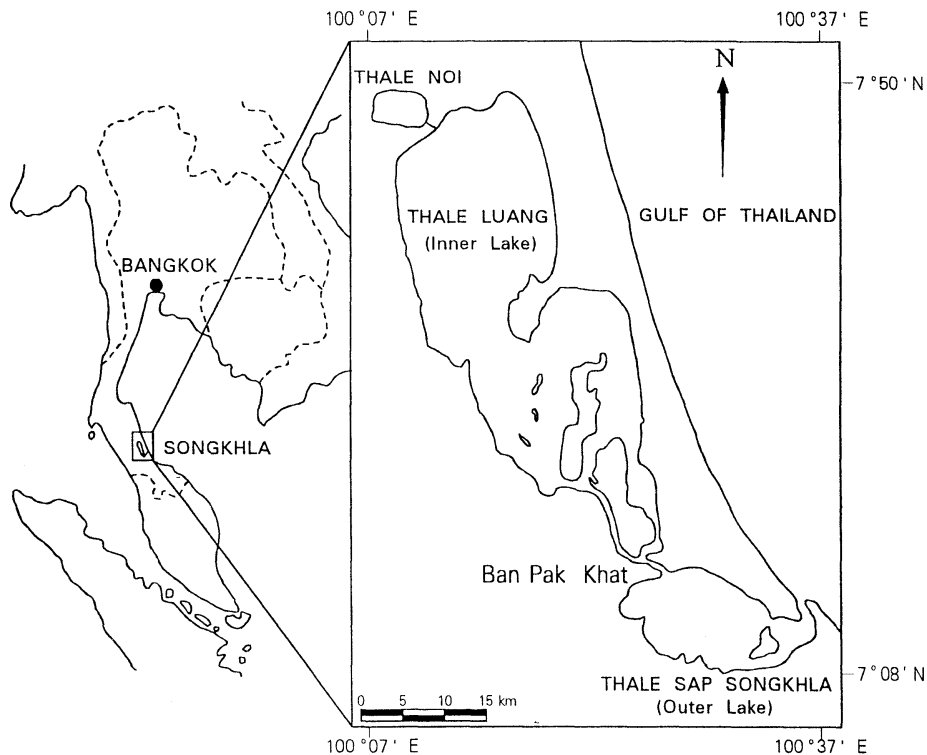


Fig. 1. Map showing Songkhla Lake and the study area (Thale Sap Songkhla).

### 3. Results

The distribution and abundance of seagrasses in Thale Sap Songkhla are shown in Fig. 2.

#### a. Species and distribution

Seagrasses were found in only 2 areas in Thale Sap Songkhla. The first area was the sandy bottom 1300 m from the mouth of Thale Sap Songkhla (area I). Seagrasses were patchily distributed in a narrow area. Two species of seagrasses, *Halodule pinifolia* and *Halophila ovalis*, inhabited the area. The other area was close to Ban Hua Hat shoreline (area II) where the water was rather stagnant and only *Halophila beccarii* was found in a narrow strip.

#### b. Biomass and seasonal variation

*Halophila beccarii* was the most abundant species, and could be found almost throughout the year, with biomass in the range of 0–204.8 g (d. w.)  $m^{-2}$  (annual average 95.3 g (d. w.)  $m^{-2}$ ). Biomass of other species was 8.7–224.0 g (d. w.)

$m^{-2}$  (annual average 84.1 g (d. w.)  $m^{-2}$ ) for *Halodule pinifolia* and 0–10.7 g (d. w.)  $m^{-2}$  (annual average 2.7 g (d. w.)  $m^{-2}$ ) for *Halophila ovalis*. *Halophila ovalis* was the least abundant species and could be found during only 6 months in the year (March to September). The young leaves occurred in March when the salinity increased.

The maximum biomass of three species of seagrasses was in the light rainy period during July to August (southwest monsoon) while the minimum was in the heavy rainy period during October to December (northeast monsoon). The blade length of seagrass was much longer in the SW monsoon season than those in the NE monsoon season (Table 1). During a heavy rain period, the salinity was very low and blades of seagrasses became soft, yellowish brown and rotten. Only the rhizome was collected in some case.

*Halophila beccarii* could be found in a wide range of salinity from freshwater to brackish water. *Halodule pinifolia* could also be found in

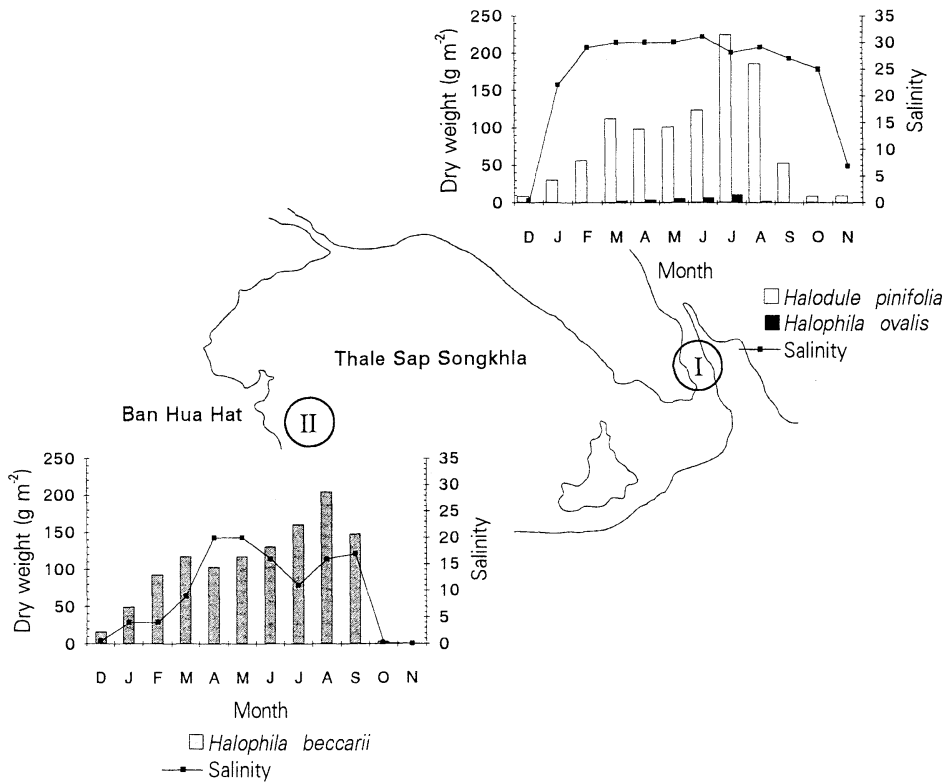


Fig. 2. Distribution and seasonal pattern of seagrass biomass in relation to salinity (PSU) at areas I and II.

Table 1. Length (cm) of blade plus petiole of seagrasses distributed in Thale Sap Songkhla.

Species	SW monsoon	NE monsoon
<i>Halodule pinifolia</i>	18.5–35.0 (July)	2.0–8.0 (December)
<i>Halophila ovalis</i>	3.0–8.0 (July)	2.3–3.9 (March)
<i>Halophila beccarii</i>	3.0–4.8 (August)	1.5–2.2 (December)

a wide range of salinity from brackish water to seawater. *Halophila ovalis* could tolerate only a narrow range of salinity.

### c. Epiphyte diversity

Most epiphytes were diatoms, *Tabellaria* sp., *Cocconeis* sp. and *Nitzschia* spp., while some branching algae and other diatoms could also be found sporadically (Table 2). *Cocconeis* sp. was the most abundant diatom with *Tabellaria* sp. ranked the second. The latter was often

found on leaves of *Halophila beccarii* inhabiting the area hardly perturbed by tidal current and boat transportation. *Nitzschia* spp., *Pleurosigma* sp. and branching algae were rarely found. *Cocconeis* sp. was more abundant in the dry season (February–April) compared to the wet season and *vice versa* in *Tabellaria* sp. During the SW monsoon season, especially in July, the number of epiphyte species increased, but the cell number of each species was low. Mature leaves also tended to have more epiphytes than young leaves.

*Tabellaria* sp., a rod-shaped diatom, grew by attaching new cells to the existing ones forming filaments in all directions (Fig. 2 a and b). On the contrary, *Cocconeis* sp. was an oval-shaped solitary diatom which attached firmly to the leaf surface (Fig. 2 c). It never formed filaments or attached newly formed cells to the existing ones. For the branching algae, attachment to the leaf margin was observed (Fig. 2 d).

Table 2. Epiphytic microalgae on seagrasses collected from Thale Sap Songkhla.

Months	Taxa	Host <sup>1</sup>	Density <sup>2</sup>
December '92	<i>Tabellaria</i> sp.	Hb	High
January '93	<i>Tabellaria</i> sp.	Hb	Rare
February '93	<i>Cocconeis</i> sp.	Hp	Rare
March '93	<i>Cocconeis</i> sp.	Hb, Hp	Medium
	<i>Cocconeis</i> sp.	Ho	Rare
	<i>Cocconeis</i> sp.	Hb, Hp	High
April '93	Branching algae	Hp	Rare
	<i>Tabellaria</i> sp.	Hp, Hb	Rare
June '93	<i>Nitzschia</i> spp.	Hp, Ho	Rare
	Branching algae	Hp	Rare
	<i>Tabellaria</i> sp.	Hp, Ho, Hb	Rare
July '93	<i>Cocconeis</i> sp.	Hp, Ho, Hb	Rare
	<i>Pleurosigma</i> sp.	Hp, Ho, Hb	Rare
	<i>Nitzschia</i> spp.	Hp, Ho, Hb	Rare
	Branching algae	Hp	Rare
	<i>Cocconeis</i> sp.	Hp, Ho, Hb	Rare
August '93	<i>Nitzschia</i> spp.	Hp, Hb	Rare
	Branching algae	Hp	Rare
	Branching algae	Hp	Medium
September '93	<i>Cocconeis</i> sp.	Hp, Ho, Hb	Rare
	<i>Nitzschia</i> sp.	Hb	Rare
	Branching algae	Hp	Medium
October '93	<i>Cocconeis</i> sp.	Hp, Hb	Rare
	<i>Tabellaria</i> sp.	Hb	Rare
	Branching algae	Hp	Medium
November '93	<i>Cocconeis</i> sp.	Hp	Medium

<sup>1</sup> Hb, *Halophila beccarii* ; Hp, *Halodule pinifolia* ; Ho, *Halophila ovalis*

<sup>2</sup> Density of epiphytes on surface area of leaves

#### 4. Discussion

##### a. Distribution and biomass of seagrasses

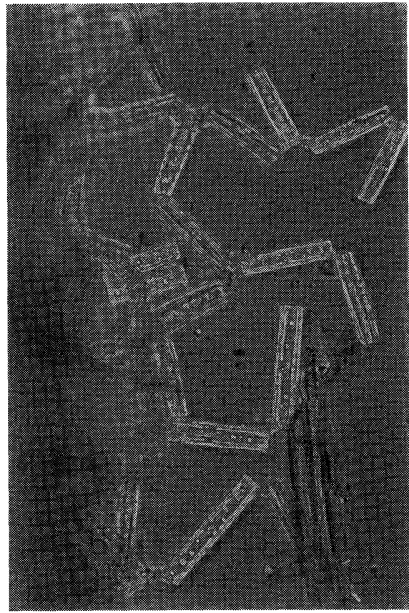
In the present study, only 3 species of seagrasses were found in Thale Sap Songkhla: *Halodule pinifolia*, *Halophila beccarii* and *Halophila ovalis*. LEWMANOMONT *et al.* (1991) surveyed the coastal area in the Gulf of Thailand just north of the mouth of Songkhla Lake and found 4 species of seagrasses. Three of the 4 species in their study were the same as those found in the present study. The other species was *Ruppia maritima* reported in a lagoon in India where salinity was in the range of 18–38 (VIRNSTEIN and CARBONARA, 1985). *Halophila beccarii* was found in only one area and as the sole species in Thale Sap Songkhla. The substrate in the particular area was silt with little fine sand which was quite different from the substrate close to the mouth of the lake where *Halodule pinifolia* and *Halophila ovalis* were

found. The substrate in the latter area was mostly coarse sand with shells in certain parts (CHATUPOTE *et al.*, 1994). The relationship between seagrass species and substrate compositions found in the present study agreed with various reports (den HARTOG, 1970; WALKER and PRINCE, 1987; LEWMANOMONT *et al.*, 1991; PARTHASARATHY *et al.*, 1991). In addition, it was found that pH and phosphorus in sediment at area II (*Halophila beccarii* area) were lower than those at area I (*Halodule pinifolia* area) (CHATUPOTE *et al.*, 1994). These two parameters may relate to seagrass diversity.

Seasonal variation of salinity in Thale Sap Songkhla affected not only seagrass distribution but also its growth and seasonal variation in abundance. *Halodule pinifolia* could be found throughout the year with low abundance in the heavy rainy period and good growth in the light rainy period. In July, its blade length



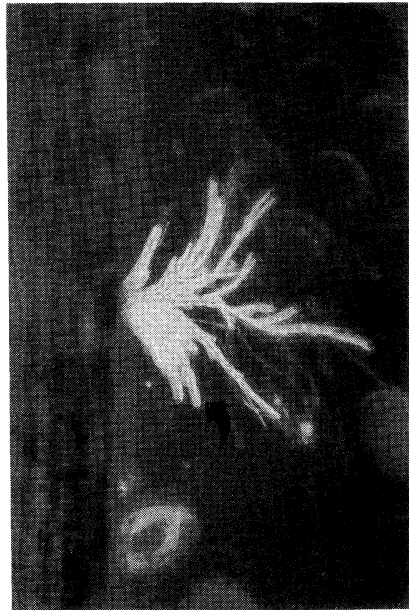
a. *Halophila beccarii* with thick growth of *Tabellaria* ( $\times 6.7$ )



b. *Tabellaria* ( $\times 200$ )



c. *Cocconeis* ( $\times 1000$ )



d. Branching algae ( $\times 100$ )

Fig. 3. Epiphytes on seagrass leaves.

was much longer than that in December and longer than what had been reported by LEWMANOMONT *et al.* (1991). *Halophila ovalis*, on the other hand, was found in only 6 months of a year. During 5 months of the rainy season, its stem above the substrate was rotten and died, only to grow again from the rhizome when salinity in the lake started to increase in early summer. Results of laboratory experiments showed that *Halophila ovalis* would not develop an apex, and died when salinity was 5, but would develop new leaves when salinity was 20 (ANGSUPANICH, unpublished data). Other two species in the genus *Halophila*, *H. decipiens* and *H. johnsonii* raised in 5 died within 3 days (DEWES *et al.*, 1989). Water temperature did not seem to be the cause of death in *H. ovalis*, as it was found in both tropical and temperate zones, indicating its tolerance to a wide range of temperatures (PHILLIPS and MENEZ, 1988).

The annual average biomass of *Halodule pinifolia* in Thale Sap Songkhla and Ban Tub Lamu, Phang-nga was similar, 84.1 and 93.6 g (d. w.)  $m^{-2}$ , respectively. On the other hand, the biomass of *Halophila ovalis* in Thale Sap Songkhla was only 1/15 that in Ban Tub Lamu. However, in Ban Tub Lamu, *Halophila ovalis* was also the least abundant species of seagrasses, with average biomass of 40.0 g (d. w.)  $m^{-2}$  (LEWMANOMONT *et al.*, 1991).

#### b. Epiphyte diversity

Epiphytes found on the 3 species of seagrasses in Thale Sap Songkhla were small benthic algae. Both solitary and branching forms of benthic algae were found and most of them were diatoms, which agreed with a study by THURSBY in 1978 (cited by HARLIN, 1980), who reported the attachment of *Cocconeis* sp. on *Halodule* sp. *Cocconeis* sp. also distributed more widely than *Tabellaria* sp. which was found only in *Halophila beccarii*. Salinity may be the limiting factor for the growth of *Tabellaria* sp. However, on an equal area of seagrass blade, *Tabellaria* sp. had higher cell numbers compared to *Cocconeis* sp., because *Tabellaria* colonies protruded in all directions. Old blades of seagrass in the present study also tended to support higher numbers of epiphytes

than young ones, which agreed well with what had been found in *Thalassia hemprichii* (HEIJS, 1984) and *Enhalus acoroides* (BROUNS and HEIJS, 1986). MCROY and GOERING (1974) reported that nutrients in the sediment could be passed from the seagrass root to blade and later to epiphytes. Epiphytes also could absorb 15–100% of the phosphorus released from the seagrass leaves (PENHALE and THAYER, 1980 cited in HEIJS, 1984). It is possible that an old leaf tends to release larger amounts of nutrients than a young leaf.

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## Macrobenthic fauna in shrimp-farms adjacent mangroves, Kradae Chae Canal, Ban Don Bay, Southern Thailand

Saowapa ANGSUPANICH\* and Sanit AKSORNKOAE\*\*

**Abstract:** An investigation was made into the fate of macrobenthic fauna in shrimp-farms adjacent mangroves, Kradae Chae Canal, Southern Thailand, to examine the fauna between the mangrove floor and mangrove cut-down floor. The density and diversity of macrobenthic fauna per m<sup>2</sup> were higher on mangrove floor than those on mangrove cut-down floor. The species composition of benthic fauna at the former in each season ranged from 16-17 species while at the latter ranged from 1-12 species. Polychaetes and crustaceans were predominant. Most abundant of these two groups were capitellid polychaetes and grapsid crabs. The latter was dominant only in the wet season. Although the density of benthic fauna found on mangrove floor was high (1088-2080 individuals m<sup>-2</sup>), the species composition of crustaceans and molluscs was low compared to other typical mature mangrove forests.

### 1. Introduction

Macrobenthic communities in mangrove areas have been studied in Thailand both on the west coast (FRITH *et al.*, 1976; FRITH, 1977; CHATANANTHAWAJ and BUSSARAWIT, 1987) and on the east coast (SRISUCHAT, 1981). Some previous studies have focussed on the effects of off-shore tin mining on benthic communities (PRASERTWONG, 1984; HYLLEBERG *et al.*, 1985).

The present work was undertaken to study the benthic communities at shrimp-pond construction area along Kradae Chae Canal, Ban Don Bay. The study was required because of the increasing exploitation of mangrove areas for aquaculture; a comparative study of benthic fauna between the mangrove floor and mangrove cut-down floor might provide a basis for estimation of the importance of mangroves to benthic communities.

### 2. Materials and Methods

#### *Study area*

Kradae Chae Canal is located in Ban Don Bay, Suratthani Province (9° 12'N, 99° 25'E). The water temperature and salinity ranges in the

year of the study were 24-33°C and 16-34 ppt, respectively. The depth of the canal ranges from 0.7 to 4.0 m., and the linear distance from the canal mouth to the upper stream is 4 km. On both banks of the canal, there are sparse populations of mangrove trees and scattered group of houses, among which many shrimp ponds have been constructed.

For this study, six stations were established along the canal (Fig. 1). These stations differ by their distance from the seawater entry point into the canal. Stations 1-5 were within the canal, while station 6 was located at the mouth of the canal adjacent to one of the few remaining stands of mangrove, with approximately 50 cm of water remaining at low tide.

Six samples were collected along the bank of each station during the dry (March) and wet (October) seasons, using a 0.05 m<sup>2</sup> Tamura grab. This method was found to be most suitable for this type of environment. The samples were sieved consecutively through 3 orders of screens of 5 mm, 1 mm and 0.5 mm mesh. The macrobenthic fauna were removed with forceps, and the 0.5 mm mesh screen residue was also collected. The samples were fixed in 10% rose bengal formalin and transferred to 70% ethyl alcohol before identification.

\* Faculty of Natural Resources, Prince of Songkla University, Hatyai, Songkhla 90112, Thailand

\*\* Faculty of Forestry, Kasetsart University, Bangkok, Bangkok 10900, Thailand



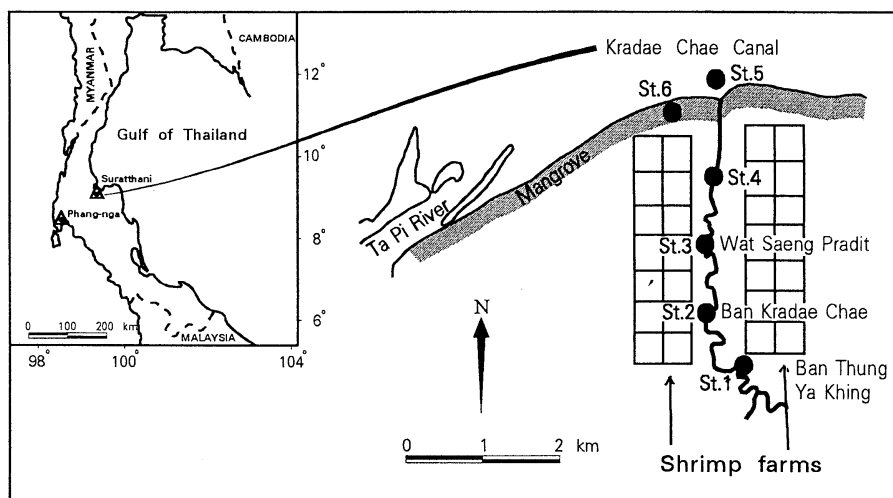


Fig. 1. Location of stations in the study of benthic fauna at Kradae Chae Canal.

### Results and Discussion

Table 1 shows the distribution of benthic fauna in Kradae Chae Canal in the dry season. A total of 5 phyla (Platyhelminthes, Annelida, Arthropoda, Mollusca and Chordata) consisting of 23 species were identified, including 9 species each of polychaetes and crustaceans with *Heteromastus* sp. and *Eupogebia* sp. respectively as the dominant. The remainder was composed of 3 species of pelecypod, 1 species of eel and 1 species of flat worm. The number of species obtained at each station ranged from 1 to 17. The lowest fauna diversity was found at station 5 (1 species), while the highest was at station 6 (17 species). The total density of benthic fauna at each station ranged from 42 (St. 5) to 8560 (St. 2) individuals per m<sup>2</sup>.

Table 2 shows the distribution of benthic fauna in Kradae Chae Canal in the wet season. A total of 5 phyla (Coelenterata, Platyhelminthes, Annelida, Arthropoda and Mollusca) containing 22 species were identified. Crustacea showed the highest number of species (12 species) followed by Polychaeta (6 species). Grapsidae was the most abundant crustacean, with Spionidae as the dominant polychaete. The number of species found at each station ranged from 1 to 16. The lowest fauna diversity was found at station 1 (1 species) while the highest was once again found at station 6 (16 species). The total density of fauna at each

station ranged from 14 (St. 1) to 1088 (St. 6) individuals per m<sup>2</sup>.

Total macrobenthic fauna (33 species) for the study area (Sts. 1–6) in two seasons consisted of Coelenterata (1 species), Platyhelminthes (1 species), Polychaeta (10 species), Crustacea (15 species), Insecta (1 species), Pelecypoda (3 species), Gastropoda (1 species) and fish (1 species). Twelve species were found in both seasons. The total species composition of fauna between the dry and the wet season was not significantly different while their abundance was greater in the dry than in the wet season.

The average abundance and the diversity of benthic fauna varied widely among the stations, with both higher in the mangrove forest area (St. 6) than in the canal (Sts. 1–5) where the mangroves have been cut down.

The diversity of benthic fauna at Stations 1–5 was slightly less than that at the sand and mud flat biotopes of Koh Surin Nua (11 species) while that at Station 6 was slightly higher but less than that at the mangrove biotope of Koh Surin Nua (38 species) which has been recognized as a low species diversity area (FRITH, 1977).

The average abundance of benthic fauna found in Kradae Chae area was similar to that in the reports of previous studies in other coastal and mangrove areas, such as the west

Table 1. Diversity and density (individuals m<sup>-2</sup>) of benthic fauna at 6 stations in the Kradae Chae Canal, Suratthani on March 7, 1993.

Taxa	St. 1	St. 2	St. 3	St. 4	St. 5	St. 6
<b>Platyhelminthes</b>						
Unidentified sp.	—	—	—	—	—	8
<b>Annelida</b>						
Capitellidae						
<i>Capitella</i> sp.	96	231	—	—	—	—
<i>Heteromastus</i> sp.	—	—	65	108	42	926
Eunicidae						
Unidentified sp.	—	—	4	—	—	65
Nephtyidae						
<i>Nephtys</i> sp.	4	4	4	8	—	8
Nereidae						
Unidentified sp. 1	4	4	—	—	—	—
Unidentified sp. 2	—	4	11	4	—	—
Opheliidae						
Unidentified sp.	—	—	—	—	—	8
Sabellidae						
Unidentified sp.	—	—	—	21	—	215
Spionidae						
Unidentified sp.	—	11	8	—	—	172
<b>Arthropoda</b>						
Cyclopoida						
Unidentified sp.	—	—	—	—	—	8
Amphipoda						
<i>Eriopisa</i> sp.	—	18	4	—	—	115
Unidentified sp. 1	—	—	—	—	—	86
Unidentified sp. 2	—	—	—	—	—	46
Isopoda						
<i>Apanthura</i> sp.	—	4	—	—	—	158
<i>Spheroma</i> sp.	—	—	—	—	—	21
Caridea						
Unidentified sp.	8	—	—	—	—	—
Anomura						
<i>Upogebia</i> sp.	—	8	—	—	—	194
Brachyura						
Grapsidae						
Unidentified sp. 1	—	—	—	—	—	8
<b>Mollusca</b>						
Pelecypoda						
<i>Modiolus</i> sp.	—	—	—	—	—	21
Unidentified sp. 1	8	8276	—	—	—	—
Unidentified sp. 2	—	—	—	—	—	21
<b>Chordata</b>						
Eel larvae (1 species)	—	—	4	—	—	—
Total density	120	8560	100	141	42	2080
Number of species	5	9	7	4	1	17

Table 2. Diversity and density of benthic fauna at 6 stations in the Kradae Chae Canal, Suratthani on October 16, 1993.

Taxa	St. 1	St. 2	St. 3	St. 4	St. 5	St. 6
<b>Coelenterata</b>						
Anemone	—	—	—	4	—	—
<b>Platyhelminthes</b>						
Unidentified sp.	—	—	—	—	—	10
<b>Annelida</b>						
Capitellidae						
<i>Heteromastus</i> sp.	—	—	100	206	10	260
Nephtyidae						
<i>Nephtys</i> sp.	—	4	10	—	—	—
Nereidae						
Unidentified sp. 1	—	—	—	14	4	2
<i>Dendronereis</i> sp.	14	—	—	24	36	36
Sabellidae						
Unidentified sp.	—	—	—	4	—	—
Spionidae						
Unidentified sp.	—	—	—	364	—	300
<b>Arthropoda</b>						
Acarina						
Unidentified mite	—	—	—	—	—	10
Cyclopoida						
Unidentified sp.	—	10	—	—	—	—
Amphipoda						
<i>Eriopisa</i> sp.	—	—	—	24	—	36
Unidentified sp. 1	—	4	—	14	—	18
Isopoda						
<i>Apanthura</i> sp.	—	—	—	4	—	10
Mysidacea						
Unidentified sp.	—	20	—	40	10	30
Caridea						
Unidentified sp.	—	4	—	—	—	—
Penaeidea						
<i>Penaeus</i> (post larvae)	—	—	—	—	—	26
Anomura						
<i>Upogebia</i> sp.	—	—	—	4	6	54
Brachyura						
Grapsidae						
Unidentified sp. 1	—	—	—	—	20	264
Unidentified sp. 2	—	—	—	—	—	20
Ocypodidae						
Unidentified sp. 1	—	—	—	—	—	6
<b>Mollusca</b>						
Pelecypoda						
Unidentified sp. 2	—	—	—	—	—	6
Gastropoda						
<i>Cerithidea</i> sp.	—	—	—	4	—	—
Total density	14	42	110	706	86	1088
Number of species	1	5	2	12	6	16

coast of Thailand (CHATANANTHAWAJ and BUSSARAWIT, 1987), Ao Nam-Bor shore, Phuket (FRITH *et al.*, 1976), Ko Yao Yai, Phuket (NATEEWATHANA and TANTICHODOK, 1980), Ko Maphrao, Phuket (TANTICHODOK, 1981) and Phang-nga Bay (PAPHAVASIT and SETTI, 1981), but the diversity was very low compared to those areas.

Although the abundance of macrofauna on the mangrove forest floor at Station 6 did not appear significantly different from that found in typical mangrove areas, the number of species is comparatively low, particularly for crabs and molluscs (FRITH, 1977; PAPHAVASIT and SETTI, 1981) and amphipods (BUSSARAWICH *et al.*, 1984). This may be due to several factors: there is information that crabs have been over-harvested for food processing (personal communication by fishermen), and there is a difference in the forest floors. The mangrove floor of the collecting site is often submerged during low tide. The presence of mangrove trees and associated microhabitats accounts for the high diversity and abundance of grapsid crabs within the habitat, such as beneath dead wood, among rotting vegetation, and on prop roots and tree trunks (FRITH *et al.*, 1976). Although these crabs feed on mangrove leaves, mangrove seedlings and fine plant and animal detritus, members of Grapsidae are well adapted to aerial breathing and are able to withstand longer exposure periods, an adaptation which allows them to colonize the more landward intertidal areas (MACNAE, 1968). Some grapsid crabs, *Chiromanthes indiarum* and *Helice leachi*, were notably more abundant in the landward rather than the seaward mangrove forest areas (FRITH, 1977). The low species diversity of grapsid crabs at Station 6 may therefore be due to the mentioned factors.

It is noteworthy that the members of several gastropod families such as Littorinidae, Neritidae, Assimineidae and Potamididae, which are dominant in the mangrove biotope (FRITH *et al.*, 1976; PAPHAVASIT and SETTI, 1981; SHOKITA *et al.*, 1983), were not encountered in the present study. The type of substrate (FRITH, 1977) and inundation during low tide might, to some extent, be attributable to the absence of some gastropods. The majority of gastropods

found within the mangrove environment are able to breathe air and thus withstand long exposure periods (BERRY, 1972). This adaptation may allow them to be active during low water periods and to colonize the more landward shore areas (FRITH *et al.*, 1976). Then, tree-dwelling gastropods are often observed in mangrove microhabitats as leaves, prop roots, tree trunks and branches (FRITH *et al.*, 1976; FRITH, 1977; SHOKITA *et al.*, 1983; COOK and GARBETT, 1989). Unfortunately for the present study, the tree-dwelling animals have not been investigated. Thus, in this case a comparative discussion with previous reports may be difficult.

At Stations 1-5, it was found that the polychaete population was dominant while crustaceans were rare. This was different from Station 6 where crustaceans were more abundant in both density and diversity. Such levels of polychaetes with reduced numbers of crustaceans reflect high pollution or stress in the environment; the opposite state results in the reverse condition (AMIO, 1979). Although capillid polychaetes have been found in mangroves in Malaysia (SASEKUMAR, 1974), on Phuket Island (FRITH *et al.*, 1976) and on Koh Surin Nua (FRITH, 1977), Capitellidae, such as *Capitella capitata*, have been recorded as an indicator species for organically polluted waters (KIKUCHI, 1991). CHAREONPANICH *et al.* (1994) suggested that *Capitella* sp. I has the ability to be utilized as an effective biological treatment for poor oxygenated sediment below fish net pen culture areas. The treatment of organically polluted sediment is particularly appropriate (CHAREONPANICH *et al.*, 1993). It would seem, therefore, that the presence of other species of Capitellidae such as *Capitella* sp. and *Heteromastus* sp. within Kradae Chae Canal may be due to the enrichment of organic matter from shrimp ponds and households there. Especially in the dry season, the capitellid population was more abundant than in the wet season.

The density and diversity of benthic fauna in general within the Kradae Chae Canal (Sts. 1-5) itself were markedly low, with the exception of Station 2 (dry season) where the highest total density was found. This included a large

number of small dead bivalves (8 mm in length). Dredging of the canal for water pumping to shrimp ponds was the major factor in the reduction of benthic fauna. Recolonization should be possible if the dredging is prevented. Tidai currents would serve as a source of larval stock and food, with the stations closer to the sea being colonized faster than the inner stations. Estimation of the time required for complete recolonization will need further study. Coastal areas affected by off-shore tin mining need to be allowed more than one monsoon period for full recolonization by benthic polychaetes (HYLLEBERG *et al.*, 1985).

Although it has not yet been demonstrated that benthic fauna provide a supplementary source of protein in shrimp ponds, macrobenthos are a major natural source of food for penaeid shrimp (IKEMATSU, 1963). For shrimp, epifaunal suspension feeders and deposit-suspension feeders are preferred to infaunal deposit feeders (KUWABARA and AKIMOTO, 1986). Such species as macrobenthos *Perinereis quatrefagesi* have been used as food for cultured shrimp (HYLLEBERG *et al.*, 1986). Moreover, crustaceans, bivalves, gastropods and polychaetes have been reported as the most common food items in the guts of both juvenile and adult *Penaeus merguensis* (WASSENBERG and HILL, 1993). This suggests that benthic fauna are useful to shrimp production. The soft bottom under mangrove trees is more productive of benthic fauna. The present study suggests that there is a positive relation between the density of the mangrove trees and the density and diversity of benthic fauna produced. The low diversity of crustaceans on mangrove floor at Kradae Chae Canal found in this study seems to be different from the typical mangrove forest. The intensive research on the effect of shrimp-pond effluent on benthic fauna may be necessary.

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## 種苗幼魚の連続計数システムに関する研究

陳 滄\*・矢田 貞美\*・戸田 勝善\*

### Study on successive counting system for seedlings fry

HU CHEN\*, SADAMI YADA\*, and MASAYOSHI TODA\*

**Abstract:** In order to change the intermittent counting course into a successive counting course, a system constituted by alternately operating two suction rooms was produced. In this paper, relationship among the counting efficiency of the system and the time of ball valves rotating from opening condition to shutting condition, length of inside suction tube and suction velocity were described, and what an appropriate counting system was theoretically analyzed. The results are as follows.

1. When a fry was sucked in one course at suction velocity of 0.9 m/s, 1.2 m/s and 1.5 m/s, the suitable time of ball valves rotating from opening condition to shutting condition were 4.5 s, and 5.0 s, 5.5 s, and the suitable suction time of a fry were 32.5 s, 23.9 s, and 22.5 s.

2. When two or three fry were sucked in one course at suction velocity of 1.0 m/s, the suitable time of ball valves rotating from opening condition to shutting condition was 4.5 s, and the suitable suction time of fry were 24.5 s, and 24.8 s.

3. The system constituted with two suction rooms could count 4,800 fry per hour. If inside suction room was lengthen to 2.93 m, or fry sucked by three suction rooms with the ball valve which rotating time is 0.5 s, the system could count 38,400 fry per hour.

Depend on the studies as described above, the system could be considered as an effective and practical method of counting fry.

#### 1. はじめに

種苗の生け簀替え、出荷および放流時に魚数を把握する方法としては、一般に見掛けの魚と水の混合容積当たりの尾数を推定する方法、あるいは平均体重から尾数を推定する方法の何れかが採られているが、何れも経験と勘を要するうえ最大計数誤差は最大で50%もある。また、従来の光センサ式魚数計（藤本，1993）では、魚体重複と気泡に起因すると推定される計数誤差が多い場合には-48.6%から+17.2%の範囲にあるため、実用に耐えないから高性能な計数システムの開発が関係者から要望されている。

そこで、吸引室は外筒および内筒から構成され、内筒は吸引ホースから排出ホースまでの管路の一部に該当する間欠作動式計数システムを試作した（矢田ら，1993）。本システムでは、吸引ホースに設けた測定用矩形管によ

り高精度な計数が可能となったが、吸引・排出行程が交互に作動する間欠作動式なので単位時間当たりの計数能率は低い。

本報では、間欠作動式計数システムの高効率化を目的として吸引・排出行程を間欠作動式から連続作動式に改良するため、並列配置の2つの吸引室が交互に作動する計数システム（以後、連続計数システムと称する）を試作し、計数能率と、各バルブの開閉時間、吸引速度および内筒長等の関係について検討した。

#### 2. 実験方法および実験装置

##### 1) 実験装置

Fig. 1a に連続計数システムの概要を示す。吸引ホースから吸引された魚と水の混合水（以後、魚水と称する）は吸引側で分岐して、並列する2つの吸引室9および同10に入り、排出側で合流して排出ホースで排出される。開閉機構は吸引側3および同4、吸引側バルブ5および同6、排出側11および同12、排出側バルブ17および

\*東京水産大学海洋生産学科漁業工学講座  
〒108 東京都港区港南4-5-7

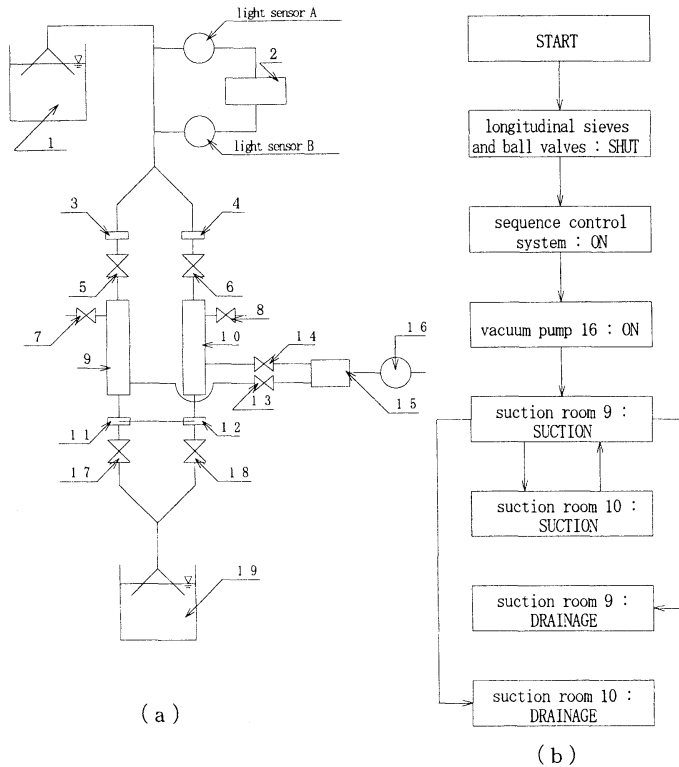


Fig. 1. System outline (a) and flow chart (b) of successive counting system. 1,19 : water tanks, 2 : speedometer, 3,4 : longitudinal sieves of suction side, 5,6 : ball valves of suction side, 7, 8 : admission valve, 9,10 : suction room, 11,12 : longitudinal sieves of exhaust side, 13,14 : change valves of suction room, 15 : tank for pressure control, 16 : vacuum pump, 17,18 : ball valves of exhaust side.

同18より構成される。篩の表面を被覆する魚体損傷防護材は、ゴムチューブから柔軟な多重ゴム網（厚さ6mm）に変更された。吸引室は既報と同じ構造と大きさの内筒および外筒から構成される。真空ポンプ16と2つの吸引室との連結を切替える電磁弁（以後、吸水切替弁13および同14と称する）の設置により、吸引室9および同10は交互に吸引する。吸引室内の魚水は自重により落下・排出させるため、各外筒に入気弁7および同8を設けた。篩、バルブ、入気弁および吸水切替弁の各作動はシーケンス制御した。なお、各行程における魚体の移送状況の観察を容易にするため外筒、内筒および吸引ホースは透明材を用いた。

既報（矢田ら、1993）の方法と同様に、魚体の吸引速度はホース吸引口から5mの位置に0.3m間隔でセンサAおよび同Bを設置し、速度計2（Takada Riken 製 TR 5821）により計測した。

## 2) 実験装置の作動行程と調整

Fig. 1 b にシーケンス制御される本システムのフローチャートを示す。システムの電源を入れると、真空ポンプ16が駆動され、所定の真空圧が得られる時間（以後、真空時間と称する）の経過後に、吸水切替弁13、吸引側バルブ5、吸引側篩3が順次開放され、魚水は吸引室9内に吸引される。吸引側バルブ5の設定開閉時間の経過後、同バルブ全閉後に入気弁7、排出側篩11および排出側のバルブ17が順次開放され、吸引室9内の魚水は排出される。吸引室9内の魚水の排出と同時に、吸水切替弁14、吸引側バルブ6および吸引側篩4が順次開放され、吸引ホース内の魚水は吸引室10内に吸引され、魚水の排出と同時に吸引室9が吸引を開始する。

なお半自動式のため本計数システムの電源を入れて真空ポンプを駆動し、手で吸引口を遊泳するコイの幼魚（体長42から59mm）まで移動させて頭部から吸引した。



以上のように、吸引室9および同10は吸引・排出を交互に繰返して魚水を連続的に吸引・排出する。その際、調圧タンク15により吸引速度を調整し、シーケンス制御の各吸引・排出側バルブの開閉時間および真空時間をそれぞれ実験方法に示す数値に設定した。

3) 実験方法

吸引速度を0.9, 1.2および1.5m/sの3段階に、また吸引側バルブの開閉時間を4.0sから6.0sまで0.5s間隔の5段階に設定し、幼魚を単尾ずつ吸引させ、吸引ホース内および吸引側篩の直前における魚体の移送状況について目視で観察した。本システムの計数能率について検討するため、魚水の吸引に必要な真空時間ならびに吸引室から魚水の排出に必要な排出側バルブの開閉時間をストップウォッチで計測した。また、魚体の吸引口から排出口までの吸引・所要排出時間（以後、所要計数時間と称する）を計測し、各吸引速度における吸引側バルブの好適な開閉時間、ならびに本システムの計数能率について検討した。

次に、同様な方法により、吸引速度1.0m/sで2および3尾の頭尾を相互に接して吸引させ、吸引側バルブの好適な開閉時間、ならびに本システムの計数能率について検討した。

3. 結果および考察

1) 単尾吸引時における所要計数時間

内筒内の真空圧は一定なので、回転バルブの開口断面と内筒内断面との重複断面（以後、ボールバルブの開口断面積と称する）を徐々に拡大すると、吸引ホース内の吸引速度は徐々に速くなる。それ故、ボールバルブの開口断面積と魚体の吸引速度の関係について検討する。

(1) ボールバルブの開口断面積と吸引速度

Fig. 2aに吸引中におけるボールバルブの開口状態の正面を、同図bに平面を示す。流れ方向のボールバルブ内径を $2R$ 、流れに垂直方向のボールバルブの内径を $2r$ 、ボールバルブの回転角を $\beta$ とすると、ボールバルブの内口半径は内筒と同じなので内筒の半径は $r$ となり、式(1)が成立する。

$$\left. \begin{aligned} EF &= R \cos \beta - r \\ CE &= r \sin \beta \\ CF &= CE - EF \end{aligned} \right\} \quad (1)$$

ボールバルブ開口の投影と同開口の中心線の投影の交差点をC、内筒内径の投影とボールバルブ開口の中心線

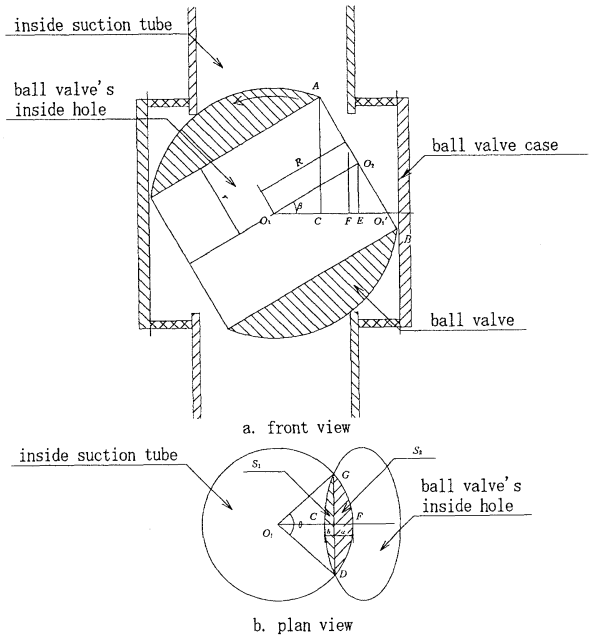


Fig. 2. Opening conditions of ball valve when fry was sucked by vacuum pump.  $\beta$  : rotation angle of ball valve,

$S_1$  : hole section area of opening ball valve,  $S_2$  : hole section area of opening inside suction tubem,

$\theta$  : angle formed by center  $O_1$  of inside suction tube and cross point  $D$  and  $G$  between  $S_1$  and  $S_2$ ,  $a$  : hole section length between opening ball valve and cross point  $D$  and  $G$ ,  $b$  : hole section length between opening inside suction tube and cross point  $D$  and  $G$ ,  $CF$  : hole section length of opening ball valve.

の投影の交差点をFとする。ボールバルブの開口断面長CFは、式(1)より式(2)で示される。

$$CF = r + r \sin \beta - R \cos \beta \quad (2)$$

また、ボールバルブ内口と内筒内径とが交差する垂直方向の投影点をD、Gとすると、バルブ開口からDGまでの断面長bと内筒の開口からDGまでの断面長aとの関係は式(3)で示される。

$$\left. \begin{aligned} b &= a \sin \beta \\ a + b &= CF \end{aligned} \right\} \quad (3)$$

ボールバルブの開口断面積 $S$ 、ボールバルブの開口投影面積 $S_1$ と内筒の開口断面積 $S_2$ は式(4)および(5)（スピーゲル、1984）で示される。

$$\left. \begin{aligned} S &= S_1 \\ S_1 &= S_2 \end{aligned} \right\} \quad (4)$$

$$S_2 = \frac{1}{2} r^2 (\theta - \sin \theta) \quad (5)$$

ただし、 $S_1$  と  $S_2$  の交差点 DG と内筒の中心  $O_1$  のなす角度を  $\theta$  とする。

式(2)、(3)、(4)および(5)より、ボールバルブの回転中における開口断面積  $S$  は式(6)で示される。

$$S = r^2 (2 \cos^2 \alpha \cdot \cos^{-1}(k_1 \cdot \tan \alpha) - k_1 \cdot \sin 2\alpha \cdot \sqrt{1 - k_1^2 \cdot \tan^2 \alpha}) \quad (6)$$

$$\text{ただし、} \alpha = \frac{\pi}{4} - \frac{\beta}{2}, k_1 = \frac{R}{r} \text{ とする。}$$

調圧タンクにより吸引室内は定圧に保持されるため、回転中のボールバルブの開口内の流速は、同ボールバルブの全開時の魚体の吸引速度と同じである。また、ボールバルブの形状および管内抵抗による水頭損失を無視すると、吸引ホース内の流量はボールバルブの開口内と同じなので、式(4)と連続の式(片岡, 1993)より、吸引側バルブが回転して開口断面積が増減する場合における吸引ホース内の瞬間吸引速度  $V$  (即ち、魚水の吸引速度) は式(7)で示される。

$$V = \frac{V_0}{\pi} (2 \cos^2 \alpha \cdot \cos^{-1}(k_1 \cdot \tan \alpha) - k_1 \cdot \sin 2\alpha \cdot \sqrt{1 - k_1^2 \cdot \tan^2 \alpha}) \quad (7)$$

ここで、吸引側バルブの全開時における魚水の吸引速度を  $V_0$  とする。

## (2) 吸引側バルブの回転当たり魚水の吸引距離

吸引側バルブの所要回転時間を  $t_1$  とすると、吸引側バルブの回転当たり魚水の吸引距離  $L_1$  は式(8)で示される。

$$L_1 = \int_0^{t_1} V \cdot dt \quad (8)$$

$t_1$  を実測に基づき 1.5s、計数  $k_1$  を式(6)より 1.25 とすると、式(7)および(8)より、本システムにおける実際の魚水の吸引距離  $L_1$  は式(9)で示される。

$$L_1 = 0.5592 V_0 \quad (9)$$

式(9)より、吸引速度がそれぞれ 0.9、1.2 および 1.5 m/s の場合における吸引側バルブの回転当たりの魚水の吸引距離は 0.50、0.67 および 0.84m となる。

吸引側バルブの回転に伴って、同バルブの開放および

閉鎖時における吸引ホース内の流速は徐々に増減し、吸引側バルブが全開すると、吸引速度は最大になる。すなわち、吸引室 9 および同 10 は交互に吸引するので定速吸引ではなく、加速、定速、減速を繰返して変動することになる。コいの幼魚は吸引ホース内の流速が一定速度以下になると、すなわち約 0.29m/s 以下の流速では水流に抵抗して吸引できない場合が観察された (陳, 1992)。

## (3) 魚体の所要計数時間

吸引室 9 および同 10 の吸引開始から排出完了までは 1 行程とすると、吸引側バルブの開閉回数  $N$  は吸引口から排出口までの所要行程数と同じなので、開閉回数  $N$  における魚水の合計吸引距離  $L$  は式(10)で示される。

$$L = (2N - 1)L_1 \quad (10)$$

また、吸引側および排出側バルブの開放および閉鎖の所要回転時間は各 3.0s (回転当たりの時間 1.5s  $\times$  2) なので、式(10)より吸引側バルブの 1 行程に要する時間 (すなわち、同バルブの開閉時間)  $T$  は式(11)で示される。

$$T = \frac{12 + (1 - 2N)L_1}{N \cdot r} + 3 \quad (11)$$

後述するように排出側バルブの開閉時間は 4.5s 以下では魚体が排出側バルブに挟持されないで、開閉時間を 4.5s に設定すると、魚体の吸引・排出総所要時間  $\Sigma T$  は式(12)で示される。

$$\Sigma T = N \cdot T + 4.5 \quad (12)$$

本シーケンス制御システムのバルブ開閉の設定時間の最小間隔は 0.5s なので、式(11)および同(12)より、吸引速度および吸引側バルブの開閉時間における所要計数時間は、吸引速度が 1.5m/s 以下では、理論値と実測値はほぼ一致した (Fig. 3 参照)。しかし、同以上では真空圧が低いと、本真空ポンプの作動が不安定となり、吸引速度の変動が大きくなるため実測誤差の増大が推定される。これに対応するためには、安定した低真空圧が得られ、流量が多い真空ポンプを利用すると、実測誤差は減少するものと考えられる。

吸引側バルブが開閉する際、吸引魚体と開閉する篩との強い衝突は見受けられなかった。拡大鏡 (倍率 20) による観察でも魚体に損傷がないことが確認された。各排出側バルブの開閉時間を 4.5s 以下に設定すると、吸引室内の在留魚体には排出側バルブの挟持に起因する損傷が認められた。また、真空時間を 3.0s 以下に設定すると真空圧 90kPa 以上となり、真空圧が不足するため魚

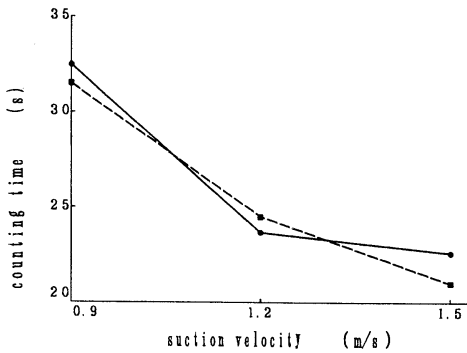


Fig. 3. Relationship between suction velocity and counting time (experimental values (●), theoretical values (■)).

水は吸引できなかった。真空時間を 3.0s 以上に設定しても、吸引速度は真空時間が 3.0s の場合とほぼ同程度であった。

以上より、本システムの排出側バルブの開閉時間を 4.5s、真空時間を 3.0s にする必要がある。

吸引速度が 0.9, 1.2 および 1.5m/s の場合、吸引側のバルブの開閉時間と、魚体と所要計数時間との関係を Fig. 4 示す。実線で示す吸引速度が 0.9, 1.2 および 1.5 m/s の場合、吸引側バルブの開閉時間をそれぞれ 4.5, 5.0 および 5.5s とすると、魚体の吸引側篩の通過待ち時間がほぼ零となるため、魚体の所要計数時間は最少 32.5, 23.9 および 22.5s にそれぞれなった。

2) 複数尾吸引時におけるバルブ開閉時間と、吸引速度および吸引間隔の関係

複数尾の合計体長が内筒長より長いと、魚体の重複による魚体損傷が発生し易い。本システムの内筒長は 380mm であり、魚体長は約 60mm なので、魚体損傷の防止のためには内筒内の吸引魚数は 6 尾 (内筒長 ÷ 魚体長) 以下に限定する必要がある。すなわち、内筒内に 6 尾吸引後、吸引側バルブを直ちに閉鎖する必要がある。ここで、魚体の吸引間隔を  $L_s$ 、魚体長を  $L_f$  とすると、内筒内に  $N_f$  尾吸引するための所要時間  $t_s$  は式 (13) で示される。

$$t_s = \frac{N_f \cdot (L_f + L_s)}{V_0} \quad (13)$$

また、バルブの開放および閉鎖の所要回転時間は 3.0s なので、式 (13) より、魚体が損傷しない吸引側バルブの開閉時間  $T$  は式 (14) で示される。

$$T = 3 + \frac{N_f (L_f + L_s)}{V_0} \quad (14)$$

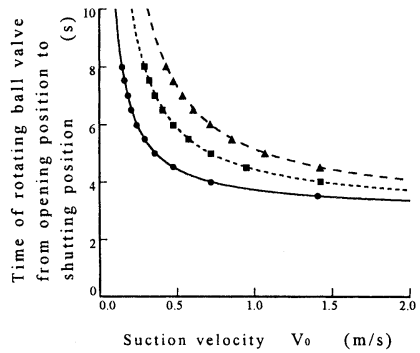


Fig. 4. Relationship between time of rotating ball valve from opening position to shutting position and suction velocity (● :  $L_s=L_f$ , ■ :  $L_s=3L_f$ , ▲ :  $L_s=5L_f$ ).  $L_s$  = intervening space of sucked fry,  $L_f$  : length of fry body.

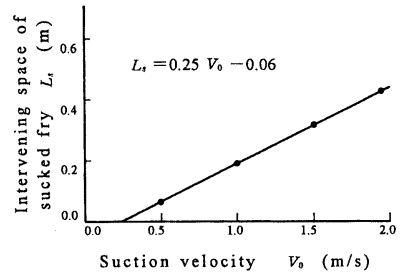


Fig. 5. Relationship between intervening space of sucked fry and suction velocity.

吸引魚数  $N_f$  を 6 尾とすると、魚体の吸引間隔が魚体長の 1, 3 および 5 倍の場合、式 (14) より吸引側バルブの開閉時間  $T$  とバルブ全開時の吸引速度  $V_0$  との関係を図 4 に示す。最高吸引速度 1.95m/s における吸引側バルブの開閉時間は 3.5s となる。しかし、排出側バルブの開閉には 4.5s が必要なので、吸引側バルブの開閉時間を 4.5s に設定する必要がある。この開閉時間 4.5s における吸引速度と吸引間隔との関係を Fig. 5 に示す。魚体の吸引間隔は最高吸引速度 1.95m/s の場合では 0.43m に、最低速度 0.24m/s では零に設定する必要がある。しかし、幼魚は 0.29m/s 以上の流速では水流に抵抗して吸引できないので、最低吸引速度を 0.29m/s 以上に設定する必要がある。

単尾の場合と同様に 2 尾以上を排出する場合には、排出側バルブの開閉時間を 4.5s、真空時間を 3.0s に設定する必要がある。

ここで、魚体長を 60mm、吸引速度を 1.0m/s とすると、便宜的に、2 尾が頭尾を接する場合における理論的

な所要吸引時間は、1尾増える毎に0.06s（魚体長÷吸引速度）多くかかることになる。また、吸引速度が1.0 m/sの場合、2および3尾が頭尾を接する場合における吸引バルブの開閉時間を4.5sに設定する必要がある、魚体の所要計数時間は、それぞれ24.5sおよび24.8sであった。

### 3) 本システムの計数能率

式(13)より、2室の吸引室が交互に作動して連続吸引する場合における $N_f$ 尾の行程当たり所要吸引時間は $t_s$ なので、本システムの単位時間当たりの吸引魚数 $P$ は式(15)で示される。

$$p = \frac{3600}{t_s} N_f \text{ (尾/h)} \quad (15)$$

吸引側バルブの設定開閉時間を4.5s、1吸引室の行程当たりの吸引魚数を6尾とすると、本システムでは単位時間当たり最大4,800尾を計数できることになる。

### 4) 本システムの実用方法

本報では、既報（矢田ら、1993）の間欠作動式システムを連続作動化するため、内筒長が380mmの吸引室を2つ設け、その作動限界について検討した。前述のように排出側バルブの開閉時間は4.5sなので、吸引側バルブの最少開閉時間を4.5sに設定する必要がある。単位時間当たり4,800尾以上を計数するためには、下記の3方法により、最高吸引速度における吸引間隔を短縮すると、本システムの計数能率の向上に寄与するものと考えられる。

#### (1) 内筒長の長大化

魚体の頭尾を交互に接して1.95m/sで連続吸引する場合、吸引側バルブの開口時間は1.5s（開閉時間4.5s－所要回転時間1.5s×2）なので、魚体損傷の防止の観点から内筒長を2.93m（吸引速度×開口時間）に設定する必要がある。その場合には、内筒に魚体長0.06mの48尾（内筒長÷魚体長）を吸引することが可能となり、式(15)より、本システムでは単位時間当たり最大38,400尾の計数が可能となる。また、単位時間当たり1、2および3万尾を計数する場合には、それぞれ0.78、1.5および2.28mの内筒長が必要と試算される。

#### (2) 吸引室の増設

前項による方法では、内筒が長いと、運搬・設置などに支障を生じる場合が危惧される。そこで、吸引室を新

たに1室を増設して3室とし、吸引を1室で排出を2室で行うように設定すると、吸引側バルブの開口時間が短縮でき、高速吸引時においても魚体の頭尾を交互に接した場合にも、吸引が可能と考えられる。ここで、A、BおよびCの3吸引室の吸引・排出順を次のように設定すると、計数能率は大幅に向上するものと推定される。すなわち、吸引室Aは吸引開始から3.5s後に排出を開始し、同Bは吸引室Aの排出開始と同時に吸引開始3.5s後に排出を開始する。各吸引室の所要排出時間は4.5sなので、吸引室Aおよび同Bの排出には1s間重複しており、同Bが排出を開始してから同Cは吸引を開始する。吸引室Cが吸引開始1s後に同Aは排出を完了し、次行程の吸引態勢に入る方式である。

例えば、最高吸引速度を1.95m/s、内筒長を1.0m、吸引側バルブの開閉時間を3.5sとすると、式(15)より、3つの吸引室を有するシステムでは、時間当たり最大16,500尾が計数可能となる。吸引計数速度は1.95m/sが最高であり、吸引側篩の手前における魚体の待ち時間がなくなるため、3室以上に吸引室を増設しても、単位時間当たりの計数増大は期待できないことになる。

#### (3) バルブの所要回転時間の短縮

バルブを交換して同回転時間を現行の1.5sから0.5sに高性能化すると、同バルブの開閉時間は1.5s、排出側のバルブの開閉時間は2.5sになり、式(15)より、前項の3つの吸引室を有するシステムでは、単位時間当たり最大38,400尾の計数が可能となる。

前項により内筒を長大化するか、または3つの吸引室システムを3、6および8系列化すると、単位時間当たり10、20および30万尾の計数が可能になるものと推定される。

## 4. 要 約

幼魚計数の高能率化を目的として吸引・排出行程を間欠作動式から連続作動式にするため、並列配置する2つの吸引室が交互に作動する連続計数システムを試作し、計数能率と各バルブの開閉時間、吸引速度および内筒長等の関係について検討した。結果の概要は次のとおりである。

1. 吸引速度が0.9、1.2および1.5m/sの場合、単尾吸引時における吸引側バルブの開閉時間はそれぞれ4.5、5.0および5.5sが、また所要計数時間はそれぞれ32.5、23.9および22.5sに設定する必要がある。

2. 吸引速度が1.0m/sの場合、2および3尾が頭尾

を接する場合における吸引側バルブの開閉時間は4.5sにする必要があり、所要計数時間はそれぞれ24.5および24.8sであった。

3. 2つの吸引室システムでは、単位時間当たり4,800尾の計数ができる。内筒長を2.93mに長大化するか、または吸引室の3室化および所要回転時間0.5sのバルブと交換すると、単位時間当たり38,400尾の計数が可能になるものと推定される。

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1995年4月7日 受領

1966年4月4日 受理

## 学 会 記 事

1. 1996年4月22日(月)東京水産大学において平成8年度第1回幹事会が開かれた。主要な議事は下記の通り。

- 1) 平成8・9年度評議員選挙結果報告
- 2) 平成8・9年度会長選挙結果報告
- 3) 平成8・9年度副会長、幹事、監事の選出  
原案どおり承認した。
- 4) 平成7年度事業報告
- 5) 平成8年度日仏海洋学会賞受賞候補者選考経過報告
- 6) 平成7年度収支決算報告および監査報告
- 7) 平成8年度事業計画案審議  
原案どおり承認した。
- 8) 平成8年度予算案審議  
原案どおり承認した。
- 9) 平成8年度学会賞受賞候補者推薦委員会委員選出委員候補者を選出した。

2. 1996年4月22日(月)東京水産大学において平成8年度評議員会が開かれた。主要な議事は下記の通り。

- 1) 平成8・9年度評議員選挙結果報告
- 2) 平成8・9年度会長選挙結果報告  
評議員による投票の結果、有賀祐勝会員が選出された。
- 3) 平成8・9年度副会長、幹事、監事の選出  
下記のとおり選出した。  
副会長 高木和徳 岡市友利  
幹 事  
(庶務) 森永 勤 前田 勝  
(会計) 松山優治 岸野元彰  
(編集) 佐藤博雅 落合正宏  
(研究発表) 関 文威 小池勲夫  
(渉外) 佐伯和昭 隆島史夫  
監 事 久保田穰 辻田時美  
編集委員長 山口征矢
- 4) 平成7年度事業報告
- 5) 平成8年度日仏海洋学会賞受賞候補者選考経過報告
- 6) 平成7年度収支決算報告および監査報告
- 7) 平成8年度事業計画案審議  
原案どおり承認した。

8) 平成8年度予算案審議

原案どおり承認した。

9) 平成8年度学会賞受賞候補者推薦委員会委員選出  
下記の通り選出した。

青木三郎 今脇資郎 落合正宏 鎌谷明善  
岸野元彰 小池 隆 小池勲夫 関根義彦  
竹松 伸 谷口 旭 中村重久 村野正昭  
門谷 茂 柳 哲雄 山口征矢

3. 新入会員(正会員・\*印学生会員)

氏 名	所属・住所	紹介者
Saowapa Angsupanich	Department of Aquatic Science, Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand	山口征矢
才田春夫*	筑波大学生物科学系 〒305 茨城県つくば市天王台1-1-1	関 文威
佐久間日良*	筑波大学生物科学系 〒305 茨城県つくば市天王台1-1-1	関 文威
鄭 洪彬*	筑波大学生物科学系 〒305 茨城県つくば市天王台1-1-1	関 文威

4. 所属・住所等の変更(正会員)

矢内秋生	武蔵野女子大学短期大学部 生活科学科 〒202 東京都保谷市新町1-1-20
奥村 裕	水産庁中央水産研究所 環境保全部 〒238-03 神奈川県横須賀市長井6-31-1
前田昌調	水産庁南海海区水産研究所 赤潮環境部 〒739-04 広島県佐伯郡大野町丸石2-17-5
市川 香	愛媛大学工学部 環境建設工学科 〒790-77 愛媛県松山市文京町3
松生弥生(旧姓 池田)	〒752 山口県下関市長府侍町1-2-16
徳田拓士	〒232 横浜市南区大岡1-47-31

サンテラス 蒔田103

崔 鎔奎 大韓民国国立水産振興院郡山分所  
大韓民国全北群山市蔵米洞49-37

## 5. 退 会

(正会員) 原田英司

## 6. 受贈図書

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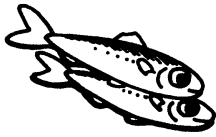


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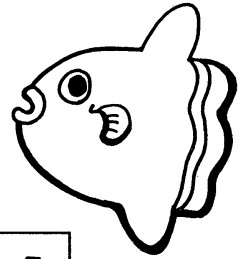
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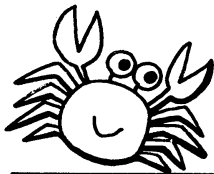


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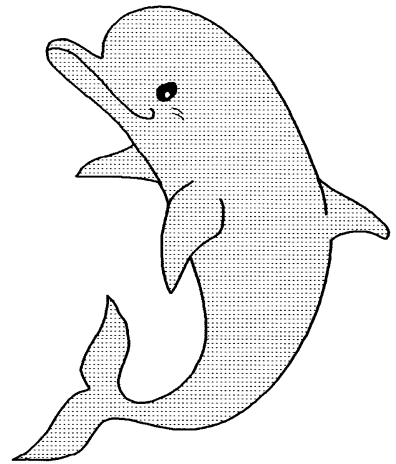
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