Studies on the Schooling Behavior of Fish—I Spectral Analyses of Interaction between Two Individuals of Fish in Locomotion

Wataru SAKAMOTO*, Ichiro AOKI*, and Tosiro KUROKI*

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A method for the analysis of fish behavior applicable to laboratory study is presented. Power- and bi-spectral analyses of fluctuation of separation distances between two individuals of fish have been carried out to find the deterministic force to control their distance in visual recognition. Two pairs of *Gnathopogon elongatus elongatus* were used. The maximum period from approach to next approach was about 100 seconds, which was seemed to change according to the size of the water tank. Bi-spectra showed that this periodic component interfered widely to the other shorter periods.

The variance of distance between two non-living particulate matters on the sea surface is mainly related to the ocean turbulence, and the increase of separation distance is proportional to the rate of dissipation of kinetic energy and elapsed time.¹⁾ This fact suggests us that if the swimming motions of individuals in a fish school are quite random, the distances among them gradually increase with time and it becomes impossible to maintain a school. But practically, a fish school does not disperse for long time during their migration. Therefore the swimming motions of fish in a school are regarded to have some forces to control their distances, which are originated in the visual recognition. It can be defined as the deterministic force²⁾ whose power may be changed due to the rate of recognition of each individuals, that is, a power of mutual attraction when the individuals are at a sufficient distance from each other, and a repulsive force, when they come closer than a certain critical distance.

The fish movement in swimming will contain two factors; one of them is the deterministic force mentioned above, which is consisted of different periodic elements brought from the biological natures such as species or stage of development. Another is a random force. Usually spectral analysis has been used to distinguish the periodic component from random fluctuation, but it is very few example to apply to fish behavior analysis. In this experiment, two different of pairs which are considered to be the least unite of school have been used and attempted to analyze the fluctuation of separation distance between two individuals of fish by means of power- and bi-spectra.

* Ocean Research Institute, University of Tokyo, Nakano-ku, Tokyo (坂本 亘・青木一郎・黒木敏郎: 東京大学海洋研究所)

Apparatus and Method

The side view of the fish positions were taken on the cine-films by a 16 mm cine-camera (BOLEX 16) at a speed of 12 fr/sec through the side glass of water tank (60×30×30 cm). The roll of movie films were read with the aid of a film-motion analyzer (LW photo optical data analyzer) each three frame intervals (0.25 sec.intervals).

Four individuals of *Gnathopogon elongatus elongatus* (Japanese name, Tamoroko) were used. This species was chosen for the reason that behavior of individuals scarcely show territorial or aggressive movement in the tank but to form school. They were

about 50 mm in total length and all of them were male, and were divided into two experimental series called Pair 1 and Pair 2. These series were carried out on the different day. The distances were measured from the head of one fish to the head of the other. Fluctuation of separation distances measured from side view were recorded for 25minutes and water temperature was maintained 18°C through the experiments. Spectral analyses were carried out by FACOM-230. Fig. 1 shows the process of data analysis.

Fig. 1. Process of statistical analysis.

Results

Fig. 2 is the examples of separation distance of two individuals obtained during 150 seconds under the same condition. Patterns of fluctuation between two pairs were different.

Large and small dots in Figs. 3 and 4 show the position of two individuals respectively as the spatial distributions obtained on the cine-films without the consideration of time elapsed. Fig. 3 indicates random distributions and Fig. 4 shows the contagious type. Figs. 5 and 6 show the probability density histograms of separation distance, P_k , of Pair 1 and Pair 2. P_k is shown as,

$$P_k = \frac{m_k}{M \Delta h} \quad (k = 1, 2, \dots) \quad (1)$$

and Δh is given

$$\Delta h = \frac{(\xi_{\max} - \xi_{\min})}{K} \quad (2)$$

where m_k is the number of members of the series that fall into k -range of values and M is the total number of members of the series, Δh is the distance of variation of random

Fig. 2. Separation distances of Pair 1 (top, solid line) and Pair 2 (bottom, broken line).

Fig. 3. Spatial distributions of fish positions of Pair 1.

Fig. 4. Spatial distributions of fish positions of Pair 2.

Fig. 5. Probability density histogram of Pair 1. $\Delta h = 1.17$ cm, $M = 512$, mean = 17.5 cm.

Fig. 6. Probability density histogram of Pair 2. $\Delta h = 1.57$ cm, $M = 512$, mean = 15.6 cm.

variable. We chose $K=20$. $\xi_{\max}$ is the value of maximum difference from mean, which falls into 10th range and $\xi_{\min}$ is the minimum value, which falls into -10th range. Fig. 5 indicates that Pair 1 repeated two movements; one was to approach about 2 to 4 cm and another was swimming motion keeping about 20 cm distances. Pair 2 kept less than 2 cm distances during the most of experimental observations and sometimes they separated longer than 40 cm (Figs. 2 and 6). Figs. 5 and 6 do not show the Gaussian but bi-modal distributions.

Discussions

The data obtained through such system is a kind of Lagrangian type, because the position of fishes were varied with time and the change of distances showed relative value. For example, the data of fluctuations of Pair 1 included the form that one swam after the other around the water tank keeping equal distances though it can not be indicated by Figs. 2 and 3. Then the power-spectrum shows the relation between characteristic frequency and Fourier transformation of auto-correlation function.⁸⁾ Usually the spectral analysis is carried out on the assumption that the fluctuation is stationary and ergodic random process and variance is shown as the Gaussian distribution. Figs. 5 and 6 do not show the Gaussian but bi-modal. These distributions will not be changed even if the experiment would have been continued for longer series. The phenomena that these histograms do not show the Gaussian suggest the existence of interference of periodic component.

The periodic components of fluctuations which were caused by the attractive or re-

pulsive force of two fishes are shown as peaks at each frequencies. The process of response or reaction has two different types, one is a linear response and the other is a non-linear. The former means the fish responds directly to the other's movement; applicable to "following reaction", in this case, the periodic component can obtain to calculate the power-spectrum of fluctuation of separation distance, that is,

$$P(N) = \int_0^{\infty} R(\tau) \cos 2\pi N \tau d\tau \quad (3),$$

where $P(N)$ is power-spectrum, N is frequency, τ is lag time in calculation, π is the circular constant and $R(\tau)$ is auto-correlation function of fluctuation of distance, which is shown as follows,

$$R(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-T/2}^{T/2} f(t) f(t+\tau) dt \quad (4),$$

where $f(t)$ is the function of fluctuation, T is a measuring period.

The latter type will be observed when one individual of fish receives the effect of the other's action and may be repeated the restraints each other. Then the interferences are occurred with respect to their periodical components of behavior. In this case, it is impossible to analyze the phenomena by means of power-spectrum. For the calculation of the interference component and its intensity, it is needed to compute bi-spectrum, which is given,⁴⁾

Fig. 7. Power-spectra of Pair 1 and 2. ○: Pair 1, ▲: Pair 2.

$$B(N_1, N_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} Q(\tau_1, \tau_2) e^{-2\pi i (N_1 \tau_1 + N_2 \tau_2)} d\tau_1 d\tau_2 \quad (5),$$

and $Q(\tau_1, \tau_2)$ is shown

$$Q(\tau_1, \tau_2) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-T/2}^{T/2} f(t) f(t + \tau_1) f(t + \tau_2) dt \quad (6),$$

where τ_1 and τ_2 are time lags and Q is correlation function, i is imaginary number. Fig. 7 shows power-spectra of Pair 1 and 2. Pair 1 does not indicate significant peak, but shows gentle slope at 1.2×10^{-1} Hz and plateau at 4.0×10^{-2} Hz. Fig. 8 points out 4.0×10^{-2} Hz interfered with a vast range. It may be brought from the movement of a very long period of fishes from approach to next approach and its movement would have been effected by the size of water tank. Since the longest separation distance is defined by the width of tank, the maximum period has a limitation. This limitation will affect to the other smaller periodical movements. The dominate frequency 1.2×10^{-1} Hz which may be brought from an usual periodical movement interfered to the other lower frequencies (Fig. 8).

Fig. 8. Bi-spectrum of Pair 1.

Figs. 7 and 9 are the power- and bi-spectra of Pair 2, eminence peaks are seen at 2.5×10^{-2} , 1×10^{-2} , 1.8×10^{-1} and 2.2×10^{-1} Hz respectively. Frequencies of 2.5×10^{-2} and 1×10^{-1} Hz which interfered to the other higher frequencies were brought from the periodical movement of Pair 2 from closing to separation. The other peaks of 1.8×10^{-1} and 2.2×10^{-1} Hz would be caused by the movements such as picking or dangling with each other whose observed always during they were closing nearer than 2 cm distances, which does not mean minimum normal swimming distance. These were independent to the other frequencies since the rate of interference were not so strong (Fig. 9).

The difference of spectral pattern between two pairs is caused by the fact that the experimental series was too short to determine the behavior of this species. Both spectral

Fig. 9. Bi-spectrum of Pair 2.

analyses, however, seemed to be useful methods to determine the fish behavior though the analyses were carried out by the data of very limited conditions. There is no reason that this approach could not be used to analyze horizontal fluctuation of fish movement. It is needed moreover to compare school structure among different size classes of fish varying from larvae to adults.

References

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