シミュレーションによる魚群行動の成群機構に関する考察*

モハメッド アリ ドウスタリ**・三 宮 信 夫***

A Simulation Study on Schooling Mechanism in Fish Behavior*

Mohammad Ali DOUSTARI** and Nobuo SANNOMIYA***

1. Introduction

In our earlier papers^{1),2)}, a mathematical model has been proposed for schooling behavior of fish using observation data from a water tank experiment. Each fish in a school regulates his movement based on the information which he receives from the members in school. However, the mechanism of school behavior and information exchange has not been clear yet.

It is well known that there exists no leader in a fish school^{3),4)}. In this paper, we consider school behavior of fish as an example of autonomous decentralized systems. The autonomous decentralized mechanism is considered to be constructed not by command of the supervisor, but by information exchange among fish. The mechanism is investigated by carrying out computer simulation.

2. Mathematical model

Let the position and the velocity of individual fish i be x_i and v_i , respectively, where $x_i, v_i \in R^2$. Then the motion of fish in a school can be described by

$$\begin{aligned} \dot{x}_i &= v_i \\ m\dot{v}_i &= F_i(t, x_1, v_1, x_2, v_2, \dots, x_{N_f}, v_{N_f}) \quad (1) \\ i &= 1, 2, \dots, N_f \end{aligned}$$

where N_f is the number of individuals in school and m is the mean mass of the individuals. F_i is the resultant of all forces which cause the motion of individual i . In our model, attention

is paid to the mechanism of schooling behavior. Then F_i consists of two components, i.e. $F_i = F_{i1} + F_{i2}$, which are given as follows.

2.1 Force due to his own swimming ability

An individual fish has a character of swimming forward with a constant speed (called the characteristic velocity) when any other causes do not exist for the motion of fish. The character is expressed by²⁾

$$F_{i1} = -a_i^1(\|v_i\| - a_i^2)(\|v_i\| - a_i^3)v_i \quad (2)$$

where $0 < a_i^2 < a_i^3$. As a result of phase plane analysis, in the case of $a_i^1 > 0$, the characteristic velocity of individual i is given by a_i^3 , and in the case of $a_i^1 < 0$, the characteristic velocity is a_i^2 .

2.2 Interaction among other individuals in school

An individual fish regulates his movement, i.e. speed and direction, with the positions and the velocities of other individuals in school. The character is given by²⁾

$$F_{i2} = \sum_{j \in N_b(i)} b_i(r_{ij}) \frac{x_j - x_i}{r_{ij}} + \sum_{j \in N_c(i)} c_i(r_{ij}) \frac{v_j - v_i}{M_c} \quad (3)$$

$$b_i(r_{ij}) = \begin{cases} \frac{(k_{bi}^2 - k_{bi}^1)r_{ij}}{\alpha_{i1} + k_{bi}^1}, & \text{for } 0 < r_{ij} \leq \alpha_{i1} \\ k_{bi}^2, & \text{for } \alpha_{i1} < r_{ij} \leq \alpha_{i2} \\ 0, & \text{for } r_{ij} > \alpha_{i2} \end{cases} \quad (4)$$

$$c_i(r_{ij}) = \begin{cases} k_{ci}, & \text{for } 0 < r_{ij} \leq \delta \\ 0, & \text{for } r_{ij} > \delta \end{cases} \quad (5)$$

where $r_{ij} = \|x_j - x_i\|$. The first term of (3) is an interactive force to keep a proper distance between neighboring individuals. The second term is a schooling force to make the velocity of each fish uniform. In (3), $N_b(i)$ and $N_c(i)$ are the subsets of $\{1, 2, \dots, N_f\}$ whose element consists of

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** 京都工芸繊維大学 大学院 Graduate School, Kyoto Institute of Technology, Faculty of Engineering and Design; Matsugasaki, Sakyo-ku, Kyoto 606, JAPAN

*** 京都工芸繊維大学 工学部 Kyoto Institute of Technology, Faculty of Engineering and Design; ditto.

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Table 1 Parameter estimates ($N_f = 5$)

i	a_i^1	a_i^2	a_i^3	k_{bi}^1	k_{bi}^2	k_{ci}	a_{i1}
1	-0.00366	11.9	35.0	-6.20	4.20	1.570	8.47
2	-0.00275	11.0	38.4	-6.40	4.38	1.310	8.44
3	-0.00330	10.9	37.9	-4.40	3.11	1.490	8.35
4	-0.00180	10.6	46.4	-5.60	2.57	1.300	9.64
5	-0.00122	10.4	52.9	-6.90	4.02	1.460	8.88

The other parameters are given as follows :
 $m = 2.58 \text{ g}$, $\delta = \alpha_2 = 50 \text{ cm}$

the individual number existing near individual i . Let M_b and M_c be the numbers of the elements in $N_b(i)$ and $N_c(i)$, respectively.

The model given by (1)–(5) includes several parameters. These parameters were estimated by using an observation data from a water tank experiment. Table 1 shows the parameter estimates obtained by applying the least squares algorithm to an experimental data for a school of five fish.

3. Simulation results and discussion

Fish school is defined by Breder⁵⁾ as a group of individuals in a state of swimming at a uniform speed in a fixed configuration. We investigate a schooling behavior of twenty fish swimming in the two-dimensional free space (i.e., $N_f = 20$). The school is assumed to consist of five groups of individuals, and each group has four individuals with identical parameter values. The values of parameters for each group are given by Table 1.

In a fish school, it is difficult to know how each individual exchanges information among other individuals around him. For investigating this matter, simulation was carried out by changing the values of M_b and M_c , and some important characteristics of fish school were calculated. The characteristics are the school size d , the average speed v of individuals, the average distance d_1 of the nearest fish to each individual, the average distance d_2 of the second nearest fish to each individual, and the average ratio $r = d_2/d_1$. Of these characteristics, r is considered as the degree of the structure of a school. If the school is in complete order, i.e., the school makes a crystal type configuration, then $d_1 = d_2$ and $r = 1$ holds. On the other hand, if the schooling configuration is quite random, then we have $r = 1.6^{(3)}$. It is reported that real data shows $1 < r < 1.6^{(3)}$.

Fig. 1 shows the variation of the school size d with time for various values of M_b and M_c . It is observed from Fig. 1 that d becomes constant as

Fig. 1 Time variation of school size for various values of M_b and M_c

$t \rightarrow \infty$. As M_b increases, any individual obtains much information and the total information exchange becomes active within the school. Consequently, the school behavior for large M_b becomes a steady state faster than that for small M_b . Simulation results show that, for $M_b < 4$, the school is divided into several small schools.

Simulation results also show that the value of M_c , for $M_c \geq 1$, does not give any significant difference on the characteristics of the school. Fig. 2 shows the variation of the school size d with M_b . Fig. 3 shows the variation of the average speed v with M_b . The average distances d_1 and d_2 , and the ratio r are shown in Fig. 4. These values are the average values of twenty fish, obtained when the school is in stationary condition. It is found that the values of d , d_1 and d_2 vary with M_b .

When a fish school swims in a free water, the shape, the size and other characteristics of the

Fig. 2 Variation of school size with M_b

Fig. 3 Variation of average speed with M_b

Fig. 4 Variation of d_1 , d_2 and r with M_b

school vary in some moment. These variations are considered to be due to a certain stimulus given by an environmental field. It is interesting to conjecture that these variations are also due to variations in the values of M_b and M_c . This conjecture is based on Balchen's idea of fish movement⁶⁾. According to his idea, an environmental state gives an influence on the biological state of fish, and the biological state decides fish movement. Further, it is assumed that the values of M_b and M_c depend on the biological state of fish. The biological state of fish can not be observed. However, we can observe the school size, from which the biological state and the values of M_b and M_c are expected to be estimated.

4. Conclusion

The behavior of a fish school in a free water

has been simulated. A special attention has been paid to an autonomous decentralized mechanism of fish school. It is shown that some characteristics of fish school such as the school size and the average distance between two individuals vary with M_b . However, the average speed of individuals and the degree of school structure given by r do not vary with M_b significantly.

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