Swimming behavior of small diving beetles

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This paper is concerned with the swimming characteristics and the structure dynamics of diving beetle legs. Diving beetles are highly adapted for aquatic life. When swimming, all of these insects use their flattened, paddle-shaped hind legs like oars. Their hind legs have a thick fringe of swimming hairs. Since diving beetles are excellent swimmers, the swimming behavior is studied with a high speed video camera system. The structural properties of legs are also studied by an optical microscope and scanning electron microscope. Some functional principles underlying leg design are revealed.

Keywords : Biokinetics, Diving beetle, Swimming characteristics, Hydrodynamics

I. INTRODUCTION

All living creatures are capable of movement. Most animals move about using legs, wings, or fins. In all living creatures are sensitive to certain changes in the environmental conditions. Their forms and modes of locomotion have been shaped by the evolutionary process. Body shape and size is a natural result of the adaptation of the manner of movement to environmental conditions.¹ Throughout nature, the adaptation of body shape, way of life, and locomotion to their surroundings seems to be ideal. Diving beetles and water bugs live in water. When swimming, all of these insects use their flattened, paddle-shaped hind legs like oars. Their hind legs have a thick fringe of swimming hairs. Diving beetles can swim skillfully by reciprocal motions consisting of a power stroke and a recovery stroke. The swimming motions of diving beetles are remarkable and fascinating. From the viewpoint of mechanical engineering, diving beetles are superior

micro machines propelling the water. The swimming analysis of small diving beetles may give us much information for the construction of the micro swimming machine system.

In this paper, the swimming behavior of some diving beetles is studied using a high speed video camera system. The structural properties of the diving beetle legs are also studied by an scanning electron microscope. The test diving beetle, *Guignotus japonicus* Sharp, is small insect with about 2 mm body length. Some functional principles underlying insect leg design are revealed by swimming analysis and morphological analysis.

II. FAMILY DYTISCIDAE

Insects are the most numerous and successful creatures on this planet. They belong to a group of invertebrates known as arthropods, which are characterized by their jointed limbs, segmented bodies, and tough outer skeletons. Arthropods play

an essential role in all of the world's major ecosystem. Dytiscidae is one of two large aquatic families with 177 species in 37 genera.² The hind coxae extend to the elytra on the sides and the antennae are filiform. They range from 1 to 40 mm in length, and are very smooth and mostly oval for rapid underwater movement. The hind legs are enlarged and the tarsi have a border of hairs acting as oars when the legs beat. Dytiscids breathe by coming to the surface backwards and exposing the tip of the abdomen which draws in air to store under the elytra. Both adults and larvae feed on dead or living animal material ranging from insects to fish.

Authors had reported the diving beetle robot developed according to the swimming analysis of *Gaurodytes japonicas* in the previous paper.³ The swimming analyses of smaller diving beetle are needed to develop micro diving beetle robot. In this paper, the swimming behavior and swimming organs of diving beetle, *Guignotus japonicus* Sharp, are analyzed experimentally.

III. EXPERIMENTAL APPARATUS AND PROCEDURES

A schematic diagram of the experimental apparatus used to analyze the swimming behavior of diving beetle is shown in Fig. 1. The experimental apparatus consists of optical measurement system and water container system. Water containers were used according to the experimental purposes, but the laboratory dishes with various sizes were mostly used. The high speed video camera, the microscope and the digital camera were used as optical measurement systems, but the high speed video camera was mostly used. In the experiment of swimming analysis, the container was partly filled with water, and the aquatic insect was released in water. The test aquatic insect was a diving beetle, *Guignotus japonicus* Sharp. The test insects were collected in the rice field in Honjo City, Japan. The body length was about 2 mm in most insects. A series of high speed video frames of insect free swimming were analyzed with the personal computer. The visualization photographs of swimming streak were obtained by the insect swimming in the boundary

between a under thin milk layer and upper water layer. Morphological observations of the insects were conducted with the optical microscope and the scanning electron microscope.

Fig.1. A schematic diagram of the experimental setup.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

IV-A. Swimming analysis of diving beetle

The diving beetles are oval and streamlined with smooth, shiny bodies. Most species are black or dark brown. The hind legs are flat and fringed with hairs to provide propulsion. The diving beetles are highly adapted for aquatic life. Hydrodynamical characteristics of diving beetle are useful for the development of micro swimming robots. In this paper, free swimming behavior of smaller diving beetle, *Guignotus japonicus* Sharp, is examined with high speed video camera system.

Fig. 2 shows a sequence of photographs of swimming behavior of the diving beetle, *Guignotus japonicus* Sharp. A black stick in the frames is a sign with 2 mm length and 0.5 mm diameter. Therefore, the body length of the diving beetle is $L = 2.16$ mm. It can be seen from Fig. 2 that the right and left hind legs move alternately. Such movement of hind legs is quite different from bigger diving beetles. The leg tip movement in diving beetle swimming was plotted to time progress. To analyze the swimming behavior, we define the symbols as shown in Fig. 3. Fig. 4 shows the analyzed result of beetle swimming behavior. The orbit of left leg shows a repetition movement that draws character "e". The dotted lines

Fig.2.Sequence of photographs of swimming behavior of the diving beetle, *Guignotus japonicus* Sharp.

in Fig. 4 show invisible legs, that is, the legs are under the body of diving beetle. The phase between

Fig.3.Measuring points on the diving beetle.

Fig.4.An example of analyzed results of beetle swimming behavior.

motion L3 and R3 is inverse, but the phase between motion L3 and R1 is almost corresponding. The head and tail show synchronizing waves with the hind leg motion. Such vibrational motion of diving beetle is convenient for hiding in mud and escape from predators. The mean swimming velocity of the diving beetle is $v_{\text{mean}} = 46.4$ mm/s. The paddling frequency of diving beetle legs is $f_p = 25.6$ Hz. Then the Reynolds number Re and swimming number S_w are as follows;

$$Re = \frac{v_{\text{mean}} L}{\nu} = 100 \quad (1)$$

$$S_w = \frac{v_{\text{mean}}}{f_p L} = 2.15 \quad (2)$$

where ν is the kinematic viscosity. These numbers show the efficient swimming of the diving beetle in low Reynolds number region. Fig.5 shows the visualization photograph of general swimming orbit. The orbit visualization was obtained by the mixture of milk and water layers. The mixture of milk and water layers is generated by the motion of diving beetle legs. The backward flow is induced by the motion of diving beetle legs. The reaction on the backward flow becomes diving beetle propulsion.

IV-B. Microscopic observations of swimming organ

Diving beetles are excellent swimmers. They use their flattened, paddle-shaped hind legs like oars. As before, paddling of the beetle, *Guignotus japonicus* Sharp, is reciprocal motion consisting of a power stroke and a recovery stroke. *Guignotus japonicus*

Fig.5.Footprints of the diving beetle swimming in the boundary between milk and water layers.

Sharp moves the hind legs alternately when swimming. In this paragraph, we observe microscopically the diving beetle legs as swimming organ.

Fig. 6 shows a micro photograph of *Guignotus japonicus*. It can be seen from Fig. 6 that the all legs are enlarged and the tarsi have a border of hairs acting as oars when the legs beat. However, the detailed observation of minute hairs with the optical microscope is difficult. Fig. 7 shows an electron micrograph of left middle leg of beetle, *Guignotus japonicus*. The diameter of a lot of minute hairs is about 1.33×10^{-6} m. There are thorn hairs on the legs. These hairs induce higher fluid dynamic drag as the paddle.

Fig.6.Photograph of the diving beetle.

Fig.7.Scanning electron microscope photograph of diving beetle leg.

V. CONCLUSIONS

The diving beetle, *Guignotus japonicus* Sharp, moves alternately right and left hind legs, and swims in a zigzag line. The legs have a lot of minute hairs of diameter about $1.3 \mu\text{m}$. The minute hairs play the role of a pressure drag increase. The dynamic pressure generates forward thrust of the diving beetle.

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