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Propulsion Mechanism in Fluid Using Variable-Stiffness Fin with Torsional Rectangular Elastic Plates

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A propulsion mechanism using a bio-inspired oscillating elastic fin has advantages for resolving problems regarding environmental and safety issues on the use of the screw propeller, namely, the entanglement of fishing nets or algae, the disturbance of mud that pollutes the water, and the danger to aquatic animals from the high-speed rotation and intense churning of the propeller. However, the optimum elasticity of the fin is not constant and changes with propulsion speed and task. Moreover, it is very difficult to replace fins of different stiffnesses while they are moving. Thus, we have developed a propulsion mechanism using a variable stiffness fin with torsional rectangular elastic plates. The stiffness of the fin could be changed by adjusting the rotational angle of two rectangular elastic plates. We discuss the behavior and thrust force characteristics of the fin and the flow field surrounding the fin in still water and under uniform water flow. The stiffness required to generate maximum thrust force and thrust efficiency could be adjusted in various oscillation cycles and angles.

INTRODUCTION

The conventional screw propeller is widely used for propulsion in ships and underwater vehicles. However, screw propellers have environmental and safety issues, namely, the entanglement of fishing nets or algae, the disturbance of mud that pollutes the water, and the danger to aquatic animals from their high-speed rotation. As an alternative propulsion mechanism that compensates for these demerits of screw propellers, there has been significant research on underwater propulsion methods based on studies of aquatic animals. Recently, the use of a bio-inspired oscillating elastic fin has been proposed as an alternative propulsion mechanism. The proposed system resembles the caudal or pectoral fin of a fish. A number of studies have documented the development of this system for use in ships or underwater vehicles/robots: e.g., the tuna robot (Triantafyllou and Triantafyllou, 2000), dolphin robot (Nakashima et al., 2000), robotic research for pectoral fins (Kato et al., 2006; Lauder et al., 2007), manta ray robot (Moored et al., 2011; Low, 2006), fish robot (Liu and Hu, 2010), bioinspired elastic fin (Watanabe et al., 2002), bioinspired robots for research on the stiffness of fish (Long et al., 2011), and fin boat (Morikawa and Isshiki, 1980). The optimum elasticity of a fin modeled on the caudal fin for propulsion is not constant and changes with swimming speed and task. However, it is very difficult to replace fins of different stiffnesses while they are moving. To address this problem, we proposed the concept of the variable-stiffness fin. Although applying the variable stiffness mechanism is a novel approach, any research activities that attempt to control such constructions use many different robots or mechanical control devices: e.g., a variable-stiffness spring for which the stiffness is changed by varying the spring coefficient and controlling the displacement of the spring (Oda et al., 1993), a mechanism in which the stiffness could be changed by moving air in and out of a thin tube filled with polystyrene foam beads, which showed the kinesthetic application of the device (Mitsuda et al., 2001), and a mechanical element with variable stiffness enabled by changing the inside pressure of a laminate structure consisting of polypropylene sheets folded over a vinyl frame, whose ability to change the stiffness was discussed by Kawamura et al. (2003). However, the application of the variable stiffness mechanism in a fin is the novel approach and very useful for aquatic propulsion. We started with the investigation of the repetition of ciliary motion using a variable-stiffness fin using electrical magnets for the development of a propulsion mechanism in a paramecium-like robot (Kobayashi at al., 2003). As the first study of the oscillating elastic fin of the propulsion mechanism, we developed a variable-stiffness fin with a variable-effective-length spring for the propulsion of aquatic vehicles (Kobayashi et al., 2006; Nakabayashi et al., 2009, 2010). The apparent stiffness of the spring can be changed dynamically. However, this mechanism was simplified to two rigid fins with the use of a variable-stiffness joint, and thus a more flexible variable-stiffness fin was needed. In this study, we developed a new variable-stiffness fin with torsional rectangular elastic plates that provide more flexible bending of the fin. The stiffness of the fin was changed by adjusting the torsional angle of two rectangular elastic plates. We evaluated the behavior and thrust force characteristics of the fin and the flow field surrounding the fin in still water. This will provide data for the start-up of the mechanism and the conditions when the mechanism is fixed in still water.

STRUCTURE OF PROPULSION MECHANISM

Figure 1 shows the structure of the fin with torsional rectangular elastic plates. The total length and height of the fin are 192 mm and 60 mm, respectively. The system consists of an aluminum

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