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Performance study on a novel variable area robotic fin

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ABSTRACT

Fish fin possesses large deformations in its motion cycle assisting fish's swimming, in which its geometric parameters such as surface area, aspect ratio change greatly, and the complex deformations and motions result in complicated hydrodynamic response. In this paper, the dynamic change of surface area is concentrated to improve the propulsion performance of underwater propeller. A novel variable area robotic fin is developed and the effect of surface area change on the hydrodynamic forces is investigated quantitatively. The robotic fin composes two parts: a base fin with hand shaped holes and a cover fin that fits the shape of the holes. The change of the surface area of the robotic fin is realized by rotating the cover fin to shield the holes in the base fin. A crank-rocker-cam composite mechanism is designed to realize the fin pitching motion and surface change motion synchronously with one driving motor. Four control modes of surface area change in a motion circle are investigated, namely, complete traditional invariable fin, traditional invariable fin with smaller surface, fin with larger surface during in-strokes and fin with larger surface during out-strokes. The thrust force and efficiency of the four control modes with various swimming speeds are detailed experimented and discussed. It is found that the variable area fin achieves a remarkable different hydrodynamic response and the corresponding control modes affect much. For the variable surface area fin, they generate average thrust force between the complete invariable fin and invariable fin with smaller surface, in which the fin with larger surface area during in-strokes follows closely the complete traditional invariable fin, while the fin with larger surface area during out-strokes performs more like the traditional invariable fin with smaller surface. It is interesting that fin with larger surface during in-strokes can generate much larger average thrust force than the fin with large surface during out-strokes. For the efficiency, the fin with larger surface during in-strokes behaves the best. And the effect of the surface area change ratio and time is closely connected with the control modes. Besides, the influences of pitching frequency and amplitude are also studied. The results demonstrate that the propulsive performance can be indeed improved by proper surface area change in a motion cycle, which will be an inspiration to the design of novel underwater robot propulsive system.

1. Introduction

Fish has fascinated researchers for their remarkable swimming talent with efficiency, speed, and agility for recent years, which has inspired a variety of research ranging from theoretical study on swimming features to robotic fish developing [1–5]. After the longtime of evolution to perfectly adapt to the underwater environment, the fins become vital in the swimming movement for most of the fish. The caudal fin acts as dominant propeller with the pectoral fin, dorsal fin and other fins assisting in the Body and/or Caudal Fin (BCF) modes, while the pectoral fin is the main propeller for the Median and/or Paired Fin (MPF) modes, the dorsal fin and anal fin may be used to assist the body position and stability in the motion [6,7]. Since their prominent and multiple roles in fish propulsion and maneuvering, abundant studies on the fins have been conducted including physiology, morphology and kinematic to study the fins' structure and swimming performance [8–12], to assist the development of robotic fins [13–15].

In recent years, the three-dimensional complex motions of fish fins have attracted researchers' attention and their hydrodynamic forces are intensively studied. Lauder *et al.* studied the highly deformable pectoral fin of bluegill sunfish during steady forward swimming [16,17], Flammang studied the caudal fin deformation of blue gill sunfish in maneuvering motions [18]. They found out that the fins exhibit complicated forms whether in cruising movement or maneuvering movement which may be caused by active control of the fin ray or the passive deformation because of the fin flexibility. To explore the three-dimensional motion, Bozkurttas *et al.* extracted

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several motion modes by proper orthogonal decomposition (POD) such as “cupping”, “expansion” which can describe the complex kinematics of pectoral fin of sunfish [19]. In the study on the pectoral fin of Koi Carp [20], the fin ray motions was extracted, and the highly deformable motions of the fin ray in a motion cycle were reconstructed. Based on these study, researchers have developed various robotic fins. Tangorra *et al.* designed bio-robotic fish fins with several moveable fin rays which can be controlled to generate complex conformations and studied their hydrodynamic response [21,22]. Their pectoral or caudal fin can closely mimic the three-dimensional motions and the fin’s flexibilities are evaluated. Zhang *et al.* also developed a robotic pectoral fin with shape memory alloy (SMA) in which the fin can realize some basic motions such as “cupping” and “expanding” [23].

Though many studies on the complex 3D motions and their comprehensive hydrodynamic forces of the fins have been conducted, little attention has been paid on the detailed surface shape change of fins and their effects on the hydrodynamic response quantitatively. For example, the fin conducts complex deformations in a motion cycle, the deformations lead to the change of effective flapping surface area, the equivalent aspect ratio, the sweepback and so on. How do these parameters change? What are these changes’ effects on the forces, especially in a dynamic motion cycle? A few studies have been conducted on these changes. The deformation is a complicated process, and it would be a tough work to analyze all the parameters together quantitatively. We first take the flapping surface area change into consideration since it possesses notable changes in either “cupping” motion, “waving” motion or “expanding” motion. In [20], we calculated the surface area change in hovering and retreating by digital image processing. The surface area shows a considerable change in a period and reaches up to 1.4 (with 560 /400 mm^2) which indicates that the surface area change may profit the propulsive performance. In this paper, we focus on the influence of variable surface area on propulsive performance and develop a variable area robotic fin, which can vary its area in a dynamic motion cycle. We then conduct plenty of experiments to explore its hydrodynamic response quantitatively.

The reminder of the paper is organized as follows: in Section 2, the design concept of the robotic fin and driving module are introduced, the control strategy of the surface area change is also presented. In Section 3, the detailed manufacturing and realization of the fin and experimental system are exhibited. Then in Section 4, experiments of various control modes and kinematic parameters are conducted, their thrust forces and efficiency are detailed presented and discussed. Section 5 concludes the paper.

2. Variable area robotic fin system

As presented in [16,17,19,20], the fish fin possesses great deformations in a motion cycle, its geometric parameters vary dynamically. Its contours, the aspect ratio (which is defined as span-wise length versus chord-wise length) and the flapping surface area vary much in such a transient cycle because of the three-dimensional motions such as “cupping” and “undulation”. These changes affect the hydrodynamic forces and assist fish cruising or maneuvering. In this paper, the change of flapping surface area is taken into consideration.

2.1. Variable area robotic fin

To realize the change of surface area with other geometric parameters such as aspect ratio, appearance contours fixed, we design a robotic fin as shown in Fig. 1. The robotic fin composes two parts: a base fin with holes and a cover fin that fits the shape of the holes. The base fin is simplified into a fan shaped model, on which several holes are punched. These holes are arranged similar to hand shape, and they occupy the same size with the ridges. The cover fin also possesses the same size with the holes. When the cover fin is driven to

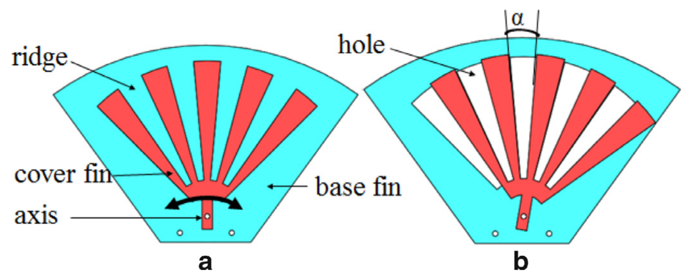

Fig. 1. Variable area robotic fin: base fin (sky blue colour) and cover fin (red colour): (a) cover fin covers the holes in the fin model; (b) cover fin is driven to rotate around the axis to cover the ridges, so the holes in the base fin is uncovered. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

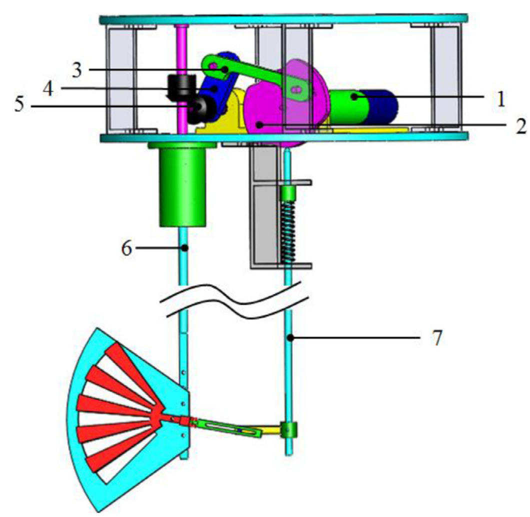

Fig. 2. Sketch of the driving module. 1. motor, 2. crank-cam, 3. middle rod, 4. rocker, 5. bevel gear, 6. pitching rod, 7. slide rod.

rotate around the axis on the base fin, it can cover or uncover the holes exactly. In this way, the robotic fin’s surface area is changed.

Hand shaped separate holes rather than a big square hole are adopted because the former one can realize a larger changing ratio of the surface area with a relatively smaller rotation angle.

2.2. Driving module of the robotic fin

We apply a pitching motion on the robotic fin during propulsion, so there are two motions for the robotic fin to achieve synchronously, namely, pitching motion and surface area change motion. We propose a crank-rocker-cam composite mechanism to realize the two motions synchronously with one driving motor as shown in Fig. 2, in which the crank and the cam are integrated into component (2).

For the pitching motion, the motor (1) drives the crank-rocker system (2-3-4) to move, the rotation motion of the motor (1) is transferred into a swinging motion of the crank (4). By the bevel gear set (5), the swinging motion changes direction, then through the pitching rod (6), the robotic fin realize the pitching motion. For the surface area change motion, the motor (1) drives the cam-slide rod (2–7) to move, the designed cam drives the slide rod (7) ups and downs, which then drives the cover fin rotates around its axis through several connecting rod. The cover fin’s rotating angle and time reflect the surface area change ratio and time, and it is directly actuated by the slide rod, but is determined by the profile of the cam. By designing different cam profiles, we can achieve different surface area change ratios and time.