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14. ABSTRACT

The objective of this project was to numerically and experimentally evaluate the underwater precision maneuverability of a cylindrical body, in particular the STOP & HOVER motions, by using fore and aft pairs of pectoral fins, similar to their usage in a fish.
We examined the hydrodynamic characteristics of a mechanical pectoral fin through experimental and numerical analyses andthe optimal match of the fin motions to generate the maximum hydrodynamic forces.
We constructed an underwater vehicle equipped with two pairs of mechanical pectoral fins and pectoral fin controllers to examine the the swimming performance of the underwater vehicle in still water and its control performance both in still water and in waves. We developed automatic control algorithms for guidance and control of the test body in 3D underwater space. Fuzzy Algorithms were utilized as necessary to compensate for short-comings in mathematical descriptions of 3MDMPF performance. We demonstrated the high maneuverability of the cylindrical underwater vehicle equipped with 3MDMPFs following a prearranged trajectory around undersea obstacles.

15. SUBJECT TERMS

Mechanical pectoral fin, Optimization, CFD, Biomimetic underwater vehicle, Guidance and control, Water currents, Waves

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FINAL REPORT

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INSTITUTION: The Study Group of Aqua Bio-Mechanisms

GRANT TITLE: US-Japan Cooperative Research on Biology-Inspired Precision Maneuvering of Underwater Vehicles

AWARD PERIOD: 1 April 2001 – 31 December 2003

OBJECTIVE: To numerically and experimentally evaluate the precision maneuverability of an underwater cylindrical body, in particular the STOP & HOVER motions, by using fore and aft pairs of pectoral fins, similar to their usage in a fish.

APPROACH:

1)Experimentally assess three-motor-driven mechanical pectoral fin (3MDMPF) performance in a controlled laboratory environment.

2)Construct a test body utilizing fore and aft pairs of 3MDMPF for maneuvering control.

3)Develop automatic control algorithms for guidance and control of the test body in three dimensional underwater space.

4)Demonstrate the high maneuverability of the cylindrical underwater vehicle equipped with 3MDMPFs following a prearranged trajectory around undersea obstacles.

ACCOMPLISHMENTS:

US collaborators, Dr. J.A. Walker and Dr. M.W.Westneat, investigated the kinematics, dynamics, and energetics of pectoral fin motion for two types. One is paddle-shaped fins rowing back and forth in a plane that is parallel to fish motion(drag-based swimming mode), and the other is wing-shaped fins flapping up and down in a plane that is perpendicular to fish motion(lift-based swimming mode). They have concluded from the simulation based on a quasi-steady blade-element theory that a flapping fin is more mechanically efficient than a rowing fin a rowing fin across the entire range of biologically relevant swimming speeds, and that a rowing fin generates more thrust per stroke than a flapping fin at low swimming speeds but this trend is reversed at higher swimming speeds. They also discussed that rowing fins may allow fish to hover in still water better than flapping fins. They found that rowers hover very well by oscillating their pectoral fins with large attack angles on both recovery and power strokes while flappers can only hover for a few strokes.

US collaborator, Dr. T. J. Gieseke, developed an articulated fin drive mechanism producing motions with three degrees of freedom of rotation to validate and support the effort by the Japanese team. This device was shown to be capable of producing arbitrary three degree of freedom motions at rates of the order 1hz.

Upon the above mentioned results by US collaborators, the Japanese team developed a compact mechanical pectoral fin device with rigid fin independently generating a flapping motion, rowing motion, and feathering motion in a precise manner at rates of the order 3hz. The device is capable of producing both the drag-based swimming mode and the lift-based swimming mode. Optimization of the parameters of fin motion so as to generate maximum propulsive force in terms of flow condition and motion pattern revealed that the lift-based rather than the drag-based swimming mode is suitable for generation of propulsive force in uniform flow, whereas the drag-based rather than the lift-based swimming mode is suitable for generation of propulsive force in still water within the range of motion of the device. This result corresponds with the result by US collaborators.

The Japanese team constructed an underwater robot equipped with 2 pairs of mechanical pectoral fins. The fuselage has the principal particulars of 1.36 m in length, 0.12 m in diameter and 14.5 kg in mass. Each pectoral fin has the chord length of 0.1 m and the span of 0.08 m. It has tilt sensors for pitching and rolling, azimuth sensor, rate sensors for pitching rolling and yawing. depth sensor, acoustic positioning system, force sensors on fins and angular sensors on fin motion. The power is supplied from the ground through a cable and the data are transmitted through a cable between the computer on board and the computer on the ground. A laser range finder was attached at the head of the fuselage to measure the distance between the robot and the wall of an underwater structure within the range of 1 m.

The comparison of the forward swimming performance from rest with a constant frequency of fin motion of the robot between the optimized lift-based mode in uniform flow and the optimized drag-based mode in still water proved that the propulsive force using the optimized drag-based swimming mode in still water is larger at the beginning of the start than the optimized lift-based mode in uniform flow, and that vice versa after the robot has an advancing speed. This supports the result by the US collaborators that rowing fins may allow fish to hover in still water better than flapping fins. It was found that the robot has a high maneuverability in 3D space in hovering condition such as turning, descending and ascending in vertical direction and lateral swimming without advancing speed.

The task sharing by fore and aft pairs of mechanical pectoral fins enabled a precise Point To Point control in 3-D underwater space that needs simultaneous performance of azimuth control, position control in horizontal plane and depth control. We made the fore pair of mechanical pectoral fins take part of the depth control based on the motion parameters for descending and ascending without advancing speed, and the rear pair of mechanical pectoral fins take part of the azimuth control based on the motion parameters for lift-based mode. Because the motion of the vehicle is highly non-linear about the control variables and because it is not possible to express the equations of the motion explicitly in terms of the control variables, we used a fuzzy control algorithm that is applicable to such problems. The vehicle stops at the target point and reaches the target depth.

We found through the control experiment that the drag-based swimming mode of the mechanical pectoral fin rather than the lift-based swimming mode is suitable for the motion control of the underwater vehicle that needs a prompt response under disturbances such as waves. The response in rolling motion without control reaches its maximum state at 1.5 s where the rolling motion is synchronized with the incident wave. The control of the rolling motion was performed after 10 seconds. The effect of the control is remarkable.

We succeeded in performing guidance and control near wall in waves where the underwater vehicle was guided to a certain point from a start point using PTP control and the vehicle was guided to repeat the lateral swimming right and left keeping the distance between the vehicle and the wall in water. We also succeeded in performing rendezvous and docking with an underwater post in water currents and guidance and control near a circular cylinder in water currents keeping the distance to the wall and turning the head to the center of the cylinder.

CONCLUSIONS: A mechanical pectoral fin device with rigid fin independently generating a flapping motion, rowing motion, and feathering motion is useful for rapidly producing propulsive force in any direction. An underwater robot equipped with 2 pairs of the mechanical pectoral fins can be used for the practical inspection work in coastal region where disturbances like water currents and waves are significant.

SIGNIFICANCE: Our studies have provided information as to precision maneuverability of a cylindrical body, in particular the STOP & HOVER motions, by using fore and aft pairs of pectoral fins.

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