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Note: Dynamic analysis of a robotic fish motion with a caudal fin with vertical phase differences

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In this paper, a robotic fish with a caudal fin with vertical phase differences is studied, especially focusing on the energy consumption. Energies for thrusting a conventional robotic fish and one with caudal fin with vertical phase differences are obtained and compared each other. It is shown that a robotic fish with a caudal fin with vertical phase differences can save more energy, which implies the efficient thrusting via a vertically waving caudal fin. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4795550]

Recently, an attention has been paid for the biomimetic robots. Biomimetics set its sights on developing better man-made systems by copying the shape and motion of natural creatures for better performance, because the creatures in nature have their own unique features optimized for surviving in wild life.

For a similar reason, studies on mimicking fish have also been increased and conducted widely in the field of biology, robotics, marine engineering and oceanography for underwater missions.[1–3]

In nature, each fish has its own shape and motion underwater. This uniqueness is a product of long-time evolution according to its living habits and environments. Propulsion efficiency of fish was reported to reach out 91%.[4] Accordingly, various researches about a robotic fish have been conducted with various shape, motion, and functions for better efficient swimming. Previous studies on robotic fish mainly contain the mechanism, analysis, control, localization, and sensor fusion for a robotic fish. Triangulated space frames and cables were used to drive fish like robotic mechanism[5] and the flapping foil was also used to build an autonomous underwater vehicle.[6] Generally, a rigid plate actuated by a motor was usually used to drive a fish fin.[7] Also smart materials such as ionic conducting polymer film (ICPF) have been adopted to fish locomotion recently.[8,9] A Fuzzy logic and a Proportional-Integral-Derivative (PID) control algorithm were adopted to control the speed and orientation of a four-link robotic fish.[10] A robotic fish with a caudal fin and a pectoral fin was devised and a nonlinear control algorithm was used for locomotion and maneuver of it.[11]

Each fish can propel itself in different ways. Some use a caudal fin and other a pectoral fin and so on. Fish motion can be classified according to the body part used for propulsion. In this Note, we focus on the fish that uses a caudal fin for propulsion. Especially we will deal with the robotic fish with a caudal fin with vertical phase differences. In literature,[12] the concept for a caudal fin with phase difference was introduced as shown in Fig. 1, and some analysis and experiment for stability were demonstrated. The proposed caudal fin allows the robotic fish with more stable motion. Moreover, it was shown that the speed of a robotic fish with a caudal fin with vertical phase differences is faster than a conventional one with a plate type caudal fin through experiments. However, the detailed analyses have not been known in the literature.

In this Note, we discuss the dynamic energy of a robotic fish and aim at presenting the energy consumption of a caudal fin with vertical phase differences. And based on the analysis, we newly propose the fundamental reason for faster motion of a robotic fish with vertical phase differences.

A conventional robotic fish with a body and a rigid caudal fin may be simplified as shown in Fig. 2. Suppose that I_i and m_i(i = 1, 2) are the moment of inertia and the mass of body and the caudal fin, respectively. Also, the dimension of body is given. For simplicity, let us assume that $I_2 = 0$.

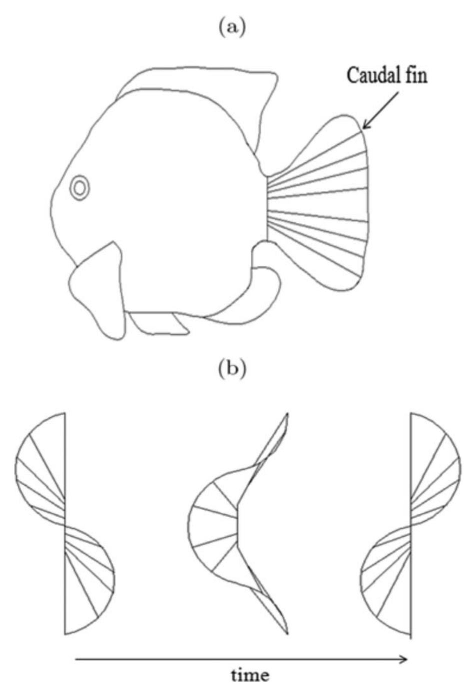

FIG. 1. The concept of a waving caudal fin with vertical phase differecnes. (a) Caudal fin. (b) Rear view of the caudal fin.

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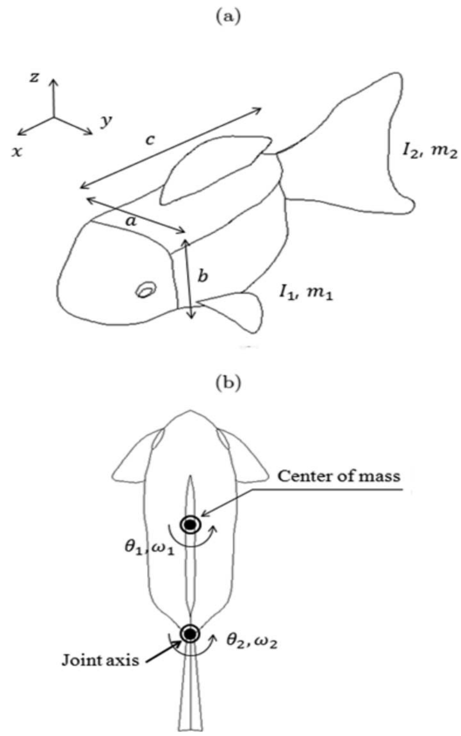

FIG. 2. Model for the robotic fish. (a) Simplified robotic fish. (b) Upper view of a robotic fish.

Considering the torque balance between the body motion(i.e., $I_1\dot{\omega}_1$) and the reaction torque by the water,[12] one may have

$$I_1\dot{\omega}_1 = \tau_m \cos(2\pi f t), \tag{1}$$

where $\tau_m = 2C_D\rho r S_A(\pi r f A)^2$, and, C_D, ρ, S_A, f, r and A are the drag coefficient, the water density, the largest section area of the fin, the oscillating frequency, the distance from the rotation hinge to the mass center of added water, and the amplitude of oscillating angle, respectively. Thus, this leads to

$$\omega_1 = \frac{\tau_m}{2I_1\pi f}\sin(2\pi f t). \tag{2}$$

Therefore, we can get the energy as follows:

$$E_p = \frac{1}{2}I_1\omega_1^2 + \frac{1}{2}(m_1 + m_2)v^2 + \frac{1}{2}C_{Dp}\rho S_f v^2 \cdot vt + \frac{1}{2}C_{Dr}\rho S_s(r_b\omega_1)^2 \cdot r_b|\omega_1|t, \tag{3}$$

where θ_m, v, C_{Dp}, C_{Dr}, S_f, S_s, r_b are the amplitude of a caudal fin, forward speed of the robot, the drag coefficient in the propulsion direction, the drag coefficient in the rotational direction, the front surface area, the side surface area of the body and the distance to centroid of the sweep area of the oscillating body from the joint axis, respectively. And the kinetic energy from the inertia of the caudal fin itself, I_2, can be ignored compared to the body inertia, I_1.

Note that Eq. (3) provides explicitly the relationship between the energy and the swimming speed. In other words, given the energy, one may compute the corresponding swimming speed, v, by a numerical analysis.

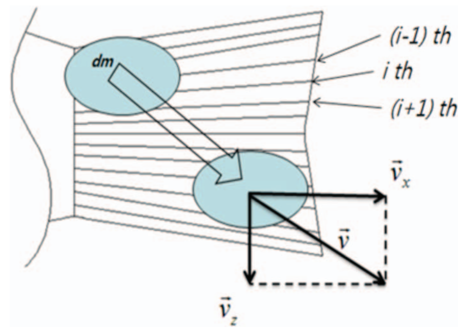

FIG. 3. Movement of water mass.

Now, the motion of a robotic fish with a caudal fin with vertical phase differences[12,13] is considered. In this case, we consider the divided caudal fin. In literature,[13] in the case of a waving caudal fin, not only backward water flow but also vertical flow is generated as shown in Fig. 3. Based on the principle of the literature,[13] the energy of water moving vertically can be obtained as

$$E_{wm} = \frac{1}{2}m_a v_z^2, \tag{4}$$

where v_z, m_a are a water velocity in the downward direction and added mass of water.[8]

Then, considering that the waving caudal fin is the sum of the divided fins, one may have the energy, from Eq. (1) to Eq. (4), as follows:

$$E_w = \frac{1}{2}I_1 \times \left(\frac{\sum_{i=1}^{N} 2C_D\rho r(\pi r f A\cos(2\pi f t + \frac{p}{N}i))^2 L\frac{h}{N}}{2I_1\pi f}\right)^2 + \frac{1}{2}(m_1 + m_2)v^2 + E_{wm} + \frac{1}{2}C_{Dp}\rho S_f v^2 \cdot vt + \frac{1}{2}C_{Dr}\rho S_s(r_b\omega_1)^2 \cdot r_b|\omega_1|t, \tag{5}$$

where p is the shape factor and N is the number of sub-fins.[12]

Note that Eq. (5) also provides explicitly the relationship between the energy and the swimming speed in the case of waving caudal fin. If the energy is given, one may compute the corresponding swimming speed, v, by a numerical analysis.

For comparison, suppose that a robotic fish has the design parameters as $a = 66$ mm, $b = 108$ mm, $c = 135$ mm, $m_1 = 1.255$ kg, $m_2 = 0.025$ kg, $C_D = 2.5$, $C_{Dp} = 0.7$, $C_{Dr} = 0.5$, $r_b = 90$ mm and $f = 2$ Hz, 3 Hz.

In Fig. 4, the simulation results on the consumed energy are summarized. The robotic fish with a vertically waving caudal fin consumes less energy for two different oscillatory frequencies. And the swimming speed of the robotic fish with a plate type caudal fin and of the robotic fish with a waving type caudal fin is calculated when energy of the plate type shown in Fig. 4 is applied. With the same prototype proposed in literature,[12,13] we performed the experiments to measure the swimming speeds and acceleration of the robotic fish and the results about the steady state speed are summarized in

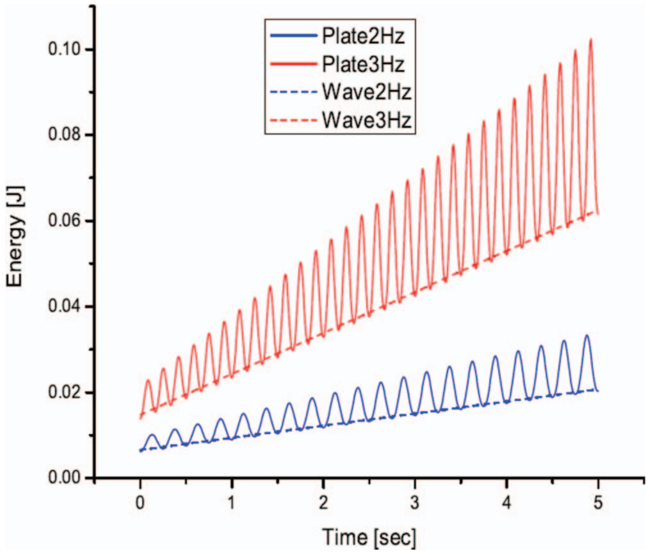

FIG. 4. Energy calculation results.

Table I. In this table, it is found that a robotic fish with a waving caudal fin swims faster than a conventional robotic fish with a plate type caudal fin by 1.1 times in the case of theoretical analysis and by 1.15–1.78 times in the case of experiments. There are gaps in measuring results of speed between analysis and experiments. These differences arise from the weight of cables which are used for carrying control signal and power to motor as the cables hinder the robotic fish from going forward.

TABLE I. Comparison of swimming speeds.

Waving frequency	Measured speed (cm/s)			Calculated speed (cm/s)		
(Hz)	$p = 0$	$p = 2\pi$	Ratio	$p = 0$	$p = 2\pi$	Ratio
2	6.3	11.2	1.78	10.43	11.37	1.10
3	11.0	12.7	1.15	15.64	17.05	1.10

Although there are some differences in absolute values of the obtained speed between experiments and analysis, the ratio between a plate type and a waving type is nearly accordance with each other. From the above comparison, we could conclude with certainty that a robotic fish with a caudal fin with vertical phase differences goes faster than a robotic fish with a plate type caudal fin underwater by about 1.2 times.

This Note describes the dynamic analysis for a robotic fish. Especially, we dealt with two kinds of robotic fish—one with a caudal fin with vertical phase differences and the other with a conventional plate type caudal fin. We derived equations for energy and speed of each robot. It was shown that the robotic fish with vertical phase differences can save energy compared to the conventional robotic fish. And this can also be explained that the robotic fish with a caudal fin with vertical phase differences can swim faster than the conventional one given the same amount of energy.

[1] G. V. Lauder and P. G. A. Madden, Int. J. Autom. Comput. **3**(4), 325–335 (2006).
[2] G. V. Lauder and P. G. A. Madden, Exp. Fluids **43**(5), 641–653 (2007).
[3] K. Low, Mech. Mach. Theory **44**(3), 615–632 (2009).
[4] M. Sfakiotakis, D. M. Lane, and J. B. C. Davies, IEEE J. Ocean. Eng. **24**(2), 237–252 (1999).
[5] D. S. Barrett, M. S. Triantaftllou, D. K. P. Yue, M. A. Grosenbaugh, and M. J. Wolfgang, J. Fluid Mech. **392**, 183–212 (1999).
[6] S. Licht, F. Hover, and M. S. Triantafyllou, in *2004 International Symposium on Underwater Technology* (IEEE, Taipei, Taiwan, 2004), pp. 311–316.
[7] J. Yu, S. Wang, and M. Tan, Robotica **23**, 101 (2005).
[8] S. Guo, K. Wakabayashi, N. Kato, T. Fukuda, T. Nakamura, and K. Oguro, in *International Symposium on Micromechatronics and Human Science* (IEEE, Nagoya, Japan, 1997), pp. 205–210.
[9] Zheng Chen, Stephan Shatara, and Xiaobo Tan, IEEE/ASME Trans. Mechantron. **15**(3), 448–459 (2010).
[10] J. Yu, M. Tan, S. Wang, and E. Chen, IEEE Trans. Syst., Man, Cybern., Part B: Cybern. **34**(4), 1798–1810 (2004).
[11] K. A. Morgansen, B. I. Triplett, and D. J. Klein, IEEE Trans. Rob. **23**(6), 1184–1199 (2007).
[12] Dongwon Yun, Kyung-Soo Kim, Soohyun Kim, Jinho Kyung, and Sunghee Lee, Rev. Sci. Instrum. **82**, 075114 (2011).
[13] Dongwon Yun, Kyung-Soo Kim, Soohyun Kim, and Jinho Kyung, in *11th International Conference on Control, Automation and Systems* (ICROS, Gyeonggi-do, Korea, 2011), pp. 445–447.