Effects of Cross Section and Flexibility of Pectoral Fins on the Swimming Performance of Biomimetic Underwater Vehicles

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Summary

This paper is aiming at investigating the effects of flexibility and chord-wise cross section of pectoral fins on the swimming performance of the biomimetic underwater vehicle PLATYPUS by designing and making new types of pectoral fins. Experiments using a mechanical pectoral fin device BIRDFIN fixed in uniform flow verify the advantage of fin flexibility in underwater robot control. Fundamental experiments using PLATYPUS investigate the roles of both fin flexibility and chord-wise cross section in propelling underwater vehicles and iterative computation of spanwise deformation between Finite Element software and wing theory analyze the hydrodynamic characteristics of these new pectoral fins. Finally PTP control tests in still water and water currents check the different performances of each fin in carrying out specific task, and at the meantime the fuzzy control rules are revised to find the most suitable one for each fin respectively. It is found that asymmetric flexible fin (harder) behaves best in PTP control in still water but symmetric rigid fin does best in PTP control in water currents.

1. Nomenclature

- $\Phi_R, \Phi_{FL}, \Phi_{FE}$ = the instant rowing angle, the instant flapping angle and the instant feathering angle of pectoral fin [degree]
- $\Phi_{R0}, \Phi_{FL0}, \Phi_{FE0}$ = the initial rowing angle, the initial flapping angle and the initial feathering angle of pectoral fin [degree]
- $\Phi_{RA}, \Phi_{FLA}, \Phi_{FEA}$ = the amplitude of rowing angle, the amplitude of flapping angle and the amplitude of feathering angle of pectoral fin [degree]
- $\Delta\Phi_{FL}$ = phase difference between flapping motion and rowing motion of pectoral fin [degree]
- $\Delta\Phi_{FE}$ = phase difference between feathering motion and rowing motion of pectoral fin [degree]
- ω_{fin} = circular frequency of fin motion [rad/s]
- K = reduced frequency of fin motion
- f_{fin} = frequency of fin motion [Hz]
- c = maximum chord length of pectoral fin [m]
- b = span of pectoral fin [m]
- U = uniform flow velocity [m/s]
- F_x, C_x = thrust force and nondimensional thrust force generated by pectoral fin movements
- ρ = water density [kg/m³]
- S = surface area of pectoral fin [m²]
- A = aspect ratio of pectoral fin
- Sym-rigid = symmetric rigid fin
- Asym-rigid = asymmetric rigid fin
- Asym-softer = asymmetric flexible fin (softer)
- Asym-harder = asymmetric flexible fin (harder)

- μ = the shear modulus of the material in the undeformed stress-free configuration [N/m²]
- φ = the azimuth of underwater vehicle [degree]
- $E\varphi, \Delta E\varphi$ = input variables in fuzzy rule of azimuth control
- $\delta E\varphi$ = output variable in fuzzy rule of azimuth control
- X = current distance of the underwater vehicle [m]
- $Ex, \Delta Ex$ = input variables in fuzzy rule of distance control
- δEx = output variable in fuzzy rule of distance control

2. Introduction

Kinematic studies of fish swimming indicate that pectoral fin propulsion can be utilized for underwater vehicles in the drag-based labriform swimming mode at low swimming speeds and in the lift-based labriform swimming mode at high swimming speeds¹⁾²⁾. The former is characterized by the rowing action of pectoral fins forming a large angle with the horizontal axis of the fish body. The latter is characterized by the flapping action of pectoral fins forming a small angle with the horizontal axis of the fish body.

Recent studies of fish locomotion have revealed that fish fins exhibit much greater flexibility and that there is considerable deformation of fin surface during locomotion. Many aquatic organisms exploit the flexibility of their fins/wings to achieve high maneuverability at low speeds. It is probable that flexible fin actuators should have an advantage over the rigid ones in both efficiency and maneuverability.

On the one hand, many researchers developed different kinds of flexible pectoral fins to investigate their performance or to propel underwater vehicles. Kato³⁾ group developed Active Pneumatic Actuator Fin and Passive Flexible Fin to investigate the performance of flexible fins. With the pectoral fins of the bird wrasse as the prototype, Palmisano⁴⁾ et al. constructed a pair of flapping fins with actively controlled curvature for an unmanned underwater vehicle, each of which is comprised of five independent compliant ribs connected by a flexible skin of thickness 0.4mm. By learning from the kinematics of bluegill

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sunfish, Tangorra⁵⁾ et al. developed a series of biorobotic fins, each of which uses five flexible fin rays attached to hinges mounted in a curved, rigid base and interconnected by webbings of thin polyester and elastane weaves. And the effects of fin stiffness and the shape of fin rays on hydrodynamics were investigated. Geder⁶⁾ et al. described the tradeoffs between performance and produceability during the bio-inspired design of an actively controlled curvature pectoral fin and the incorporation of it into both two-fin and four-fin swimming underwater flight vehicles.

On the other hand, the collaboration with experimentalists (biologists and engineers), through a multi-disciplinary effort, has enabled high-fidelity data to be used in the computational analysis, which is helpful in elucidating the role of flexibility in fin motions. Liu⁷⁾ et al. studied the effect of span-wise flexibility to the performance of oscillating propulsors. Bose⁸⁾ et al. and Prempraneerach⁹⁾ et al. investigated the effect of chord-wise flexibility on the performance of a flapping foil separately. Shoele and Zhu¹⁰⁾ carried out fluid-structural interaction analysis of skeleton-reinforced fins and concluded that structural flexibility of the fin rays leads to passive deformations of the fin, which could increase the thrust generation and the propulsion efficiency. Taft¹¹⁾ et al. proposed that the pectoral fin is divided into functional as well as morphological regions and that the fin rays in each functional region have distinct roles during steady swimming in sculpin. Ramakrishnan¹²⁾ et al. reinforced the notion that the dorsal leading edge of the bluegill's pectoral fin dominates the overall performance during steady swimming propulsion and further put forward the proposition that besides the dorsal region, the ventral region of the pectoral fin also plays an important role in modulating maneuvering forces. Tangorra¹³⁾ et al. studied how fins are regulated in response to external disturbances and concluded that the response of the pectoral fins to large deformations is not reflexible and that fin motions are regulated when it is necessary to correct for disturbances to the motion of the fish.

Although many kinds of flexible fins were developed, most of the researches were concentrated on the hydrodynamics study of single fin, only a little work was done on how flexible fins apply to underwater vehicles propulsion, and even less work on the compatibility between underwater robots and flexible pectoral fins. Does any big difference exist when different flexible fins propel the same underwater vehicle? Do we need to adjust the controlling mechanism for different kinds of flexible fins? In real target mission carryout, what kind of flexible fins can achieve the best performance? Focusing on these questions, this paper shows a series of pectoral fin research specific to BIRDFIN and PLATYPUS, both of which were biomimetic underwater vehicles developed by Kato laboratory in Osaka University.

BIRDFIN, a fixed compact three-motor-driven mechanical pectoral fin device (3MDMPF) with high-speed capacity and precise movement, was developed to assess the hydrodynamic characteristics of pectoral fin motions¹⁴⁾. Following that, PLATYPUS, a free biomimetic underwater vehicle with two pairs of mechanical pectoral fins was developed to achieve dexterous hovering and low-speed maneuvering performance¹⁵⁾¹⁶⁾¹⁷⁾. The performance of PLATYPUS was limited as lift-based swimming mode was adopted to propel the vehicle but original fins were designed as drag-based rigid ones.

This research aims at improving the swimming performance of PLATYPUS by designing and making new types of pectoral fins from the viewpoints of fin flexibility and chord-wise cross section, which is comprised of three stages:

- 1) One rigid fin and one elastic fin with the same shape were made and installed on BIRDFIN to compare the effect of fin flexibility on hydrodynamics;
- 2) Four types of fins with different shapes and materials were made to propel PLATYPUS, fundamental experiments were carried out to obtain the optimal combination of fin motion parameters for each fin within the testing range and iterative computation was carried out to verify the fundamental experiments' results;
- 3) Point-to-Point control experiments of PLATYPUS with revised fuzzy control rules under still water and water currents conditions were investigated to compare the different performance of each fin and to verify the suitability of the corresponding fuzzy control scheme for each fin.

3. Effect of Fin Flexibility on Hydrodynamics Using BIRDFIN Fixed in Uniform Flow

3.1 Mechanical Pectoral Fin System (MPF)

There are three basic types of movements for pectoral fin of fish in real world: rowing motion (back-and-forth movement), feathering motion (twisting movement) and flapping motion (up-and-down movement), as shown in Fig.1.

Fig.1 Basic motions of pectoral fins

In Kato laboratory, BIRDFIN, a compact Three-Motor-Driven Mechanical Fin (3MDMPF) (0.66m in length, 0.12m in width and 0.12m in height) device was manufactured to generate combined pectoral fin motions. The coordinates system is shown in Fig.2 and the corresponding movement controlling equations are below.

$$\begin{aligned}
 \Phi_R &= \Phi_{R0} - \Phi_{RA} \cdot \cos(\omega_{fin} \cdot t) \\
 \Phi_{FL} &= \Phi_{FL0} - \Phi_{FLA} \cdot \cos(\omega_{fin} \cdot t + \Delta\Phi_{FL}) \\
 \Phi_{FE} &= \Phi_{FE0} - \Phi_{FEA} \cdot \cos(\omega_{fin} \cdot t + \Delta\Phi_{FE})
 \end{aligned} \tag{1}$$

Here, ω_{fin} and t denote the angular velocity of fin and time. The flapping angle Φ_{FL} is defined as the rotation angle around X axis in Fig.2 along the longitudinal axis of the fuselage, by which coordinate $X-Y-Z$ is transformed to coordinate $X'-Y'-Z'$. The rowing angle Φ_R is defined as the rotation angle around the Z' axis in Fig.2, by which coordinate $X'-Y'-Z'$ is transformed to coordinate $X''-Y''-Z''$. The feathering angle Φ_{FE} is defined as the rotation angle around the Y'' axis in Fig.2, by which coordinate $X''-Y''-Z''$ is transformed to $X'''-Y'''-Z'''$.

Fig.2 Coordinate system for fin motion

3.2 Two Types of Fins on BIRDFIN

One rigid fin and one elastic fin were made with the same shape (Fig.3). The rigid fin is made of chemical wood and the elastic fin is made of silicon gum. The cross-section of the fins is NACA0015. The aluminum shaft is located at one quarter of the chord to minimize the hydrodynamic moment acting around the shaft.

When the lift-based swimming mode is applied, rigid fin generates flapping movement and feathering movement. But as for elastic fin, deformation accompanies with the same motion as rigid one (Fig.4). The target of this stage is to investigate whether this passive deformation can assist the production of thrust force.

Side view of the fin model Upper view of the fin model

Fig.3 Specification of fins for BIRDFIN

Fig.4 Deformation of passive flexible fin

3.3 Experimental Setup and Results

The schematic view of experimental setup is given in Fig.5. In order to measure the thrust force, two pairs of waterproof strain

gauges were attached on both sides of the fin shaft. The hydrodynamic force of each fin can be calculated by subtracting the measured force of BIRDFIN with the fin and the shaft underwater by the measured force of BIRDFIN with the fin and the shaft in the air.

Fig.5 Experiment setup and strain gauge system

Table.1 Experimental conditions for BIRDFIN

No.	Flow velocity (m/s)	Flapping velocity (Hz)	Reduced frequency
1	0.269	0.5	0.7
2	0.314	0.5	0.6
3	0.377	0.5	0.5
4	0.471	0.5	0.4

Experiments for each fin were carried out in uniform flow for four different kinds of reduced frequencies (Table 1).

The definition of reduced frequency and non-dimensional thrust and lateral force are given below:

$$K = 2\pi \cdot f_{fin} \cdot c / U \quad (2)$$

$$C_x = F_x / (0.5 \cdot \rho \cdot U^2 \cdot S) \quad (3)$$

During the experiments, the fin motions are expressed as:

$$\begin{aligned} \Phi_{FE} &= -20 \cos(\omega_{fin} \cdot t) \\ \Phi_{FL} &= -20 \cos(\omega_{fin} + \Delta\Phi_{FL}) \end{aligned} \quad (4)$$

$$\Delta\Phi_{FL} = -180 \sim 150 \text{ with interval of } 30$$

Because the real data obtained in the experiment include high frequencies components, Fourier analysis was used to fit the original curves. An instant signal can be expressed by Fourier series as below:

$$f(t) = a_0 + a_1 \sin \omega t + \dots + a_n \sin n\omega t + b_1 \cos \omega t + \dots + b_n \cos n\omega t \quad (5)$$

The original data (flapping only motion: $\phi_{FL} = -20^\circ \cos(\pi t)$), fitted data up to the second harmonic components, those up to the third harmonic components and those up to the tenth harmonic components are shown in (Fig.6). It can be seen that the fitted data up to the third harmonic components are better than the other fitted data. So during the data process, the first three frequency components were chosen to fit the measurement data.

The mean values of thrust coefficients below are all based on Fourier analysis.

The mean values of thrust coefficients of rigid fin and elastic fin versus phase differences are plotted in Fig.7 and Fig.8 respectively. From these figures, we can observe that elastic fin can generate larger average thrust coefficients than rigid fin. This

means that flexible fin is more adequate than rigid fin for the generation of thrust forces of underwater vehicles.

Fig.6 Original data and fitted data using Fourier analysis

Fig.7 Mean values of thrust coefficients of rigid fin

Fig.8 Mean values of thrust coefficients of elastic fin

4. Fundamental Experiments on Effect of Fin Flexibility Using PLATYPUS

Generating the maximum propulsive force is an important factor for an underwater vehicle in near-shore, high-energy environments to achieve stable and precise hovering. In this section, therefore, we focus on optimization of the motion parameters of mechanical pectoral fin to generate maximum thrust force within the testing range (in this paper the maximum speed of PLATYPUS is investigated to obtain the optimal combination of parameters within the testing range).

4.1 Why Are Fundamental Experiments Necessary?

Fish fins present great variability in shape, aspect ratio and structure, depending on the application they are intended for,

resulting in different movements expressions. Also the flexibility of the foils ranges greatly. Foils can flex along their span and/or along chord. Many studies show that a fin's oscillation parameters must be tuned to its stiffness for optimal performance¹⁸⁾⁹⁾. Kato et al. investigated the optimal parameters for original rigid fin installed on PLATYPUS¹⁴⁾. But original rigid fin for PLATYPUS was used to perform a drag-based swimming mode, and during this research we focused on lift-based swimming mode by devising new pectoral fins with different cross-sections and different shapes. Further more, flexibility was taken into consideration at the stage of designing the new fins to improve their performance. Therefore, the change of pectoral fin shapes and the use of flexibility of pectoral fins necessitate the investigation of those effects on the hydrodynamic characteristics of the new pectoral fins.

Besides, because PLATYPUS was designed to perform high maneuverability in low speed under disturbances such water currents and waves, the optimal combination of parameters of the new pectoral fins should be found from the aspect of maximizing the maneuverability in low speed under disturbances. Ideally speaking, it is better to enumerate all combinations of fin parameters to find the optimal one. But PLATYPUS has its own mechanical limitations. In this way we had no choice but only to find the optimal combination under the given conditions. For example, the fin installed on PLATYPUS can perform the maximum flapping amplitude of 30° , and we had to explore the optimal combination of fin parameters under these constraints.

4.2 PLATYPUS and Experiment System

The specifications of PLATYPUS are 1.36m in length, 0.12m in diameter and 14.5kg in mass. The fore pair of fins is arranged in horizontal plane and the rear pair in vertical plane (Fig.9). Each fin is controlled using the same mechanism as that of BIRDFIN.

Fig.9 Photograph of PLATYPUS

A cylindrical float is attached to the fuselage to adjust its buoyancy. The vehicle has tilt sensor for pitching and rolling, an azimuth sensor, rate sensors for pitching, rolling and yawing, a depth sensor, an acoustic position measurement system and angular sensors on fin motion. Each 3MDMPF has a maximum frequency of 3Hz with a rowing angle of $-50^\circ \sim 70^\circ$, flapping angle of $-30^\circ \sim 30^\circ$ and feathering angle of $-180^\circ \sim 180^\circ$. The power is supplied from the ground through a cable, and the data are transmitted through a cable between a computer on board and a computer on the ground. The computer on board has the functions of controlling the motions of two pairs of 3MDMPFs as expressed in the form of Eq.(1) every 10ms, sending the data from sensors to the computer on the ground, and receiving the data about the parameters of Eq.(1) from the computer on the

ground. The computer on the ground has the functions of receiving the data from acoustic position measurement system, receiving and sending the data between the two computers every 100ms, and computing the parameters by control program every 100ms. To measure the location of the vehicle, we set up three acoustic receivers on the wall of the water tank and one acoustic pinger at the bottom of the vehicle.

4.3 Four Types of Fins used on PLATYPUS

4.3.1 Fabrication of Four Kinds of Fins

In nature, the pectoral fins that employ drag-based mode usually have a short and round shape, for example largemouth bass (*Micropterus salmoides*); while those that use lift-based mode, usually have a narrow and long fin shape, Bluegill (*Lepomis macrochirus*) for example.

At present PLATYPUS employs lift-based swimming mode for propulsion but original fins were designed as drag-based ones. We try to make some lift-based fins for PLATYPUS to improve its swimming performance. The original rigid fin is made from a stainless-steel plate with a thickness of 0.7mm. Specifications of the original fin are listed in Fig.10.

Fig.10 Specifications of original fin

Two types of lift-based fin shapes were designed: symmetric and asymmetric. Symmetric fin has the elliptic cross-section, while the cross-section for asymmetric fins is NACA0015. They are given in Fig.11 and Fig.12, respectively.

Span: 0.13m
Chord: 0.055m
Aspect ratio: 3.0
Project area: 0.005595m²
Thickness: 0.00825m

Fig.11 Symmetric fin (plan view and chord-wise cross-section)

Span: 0.13m
Chord: 0.055m
Aspect ratio: 3.0
Project area: 0.005595m²
Thickness: 0.00825m

Fig.12 Asymmetric fin (plan view and chord-wise cross-section)

In total, four kinds of fins were made: Symmetric rigid fin, Asymmetric rigid fin, Asymmetric harder flexible fin, and Asymmetric softer flexible fin. The material of rigid fins is ABS resin (Young's modulus: 2.3×10^9 N/m²) and flexible fins are made of two types of silicon gums. As in nature most of pectoral

fins show asymmetric properties, we made only asymmetric flexible fins, but did not make any symmetric flexible fin. Hereafter, "asymmetric softer flexible fin" is abbreviated to "Asym-softer", "asymmetric harder flexible fin" to "Asym-harder", "asymmetric rigid fin" to "Asym-rigid", and "symmetric rigid fin" to "Sym-rigid".

4.3.2 Hyper Elastic Materials

The typical properties of silicone rubber include:

- The ability to remain elastic even given large deformation,
- A highly nonlinear relationship between load and extension,
- Nearly incompressibility.

These characteristics can be generally defined as hyper elastic¹⁹⁾⁽²⁰⁾. Hyper-elasticity is defined as a material that has an elastic potential function W . A stress tensor is derived by differentiating W with respect to the conjugate strain tensor as

$$S_{ij} = \frac{\partial W}{\partial E_{ij}} \quad (6)$$

where the following definitions can be applied:

$$\mathbf{E} = (\mathbf{C} - \mathbf{I})/2 \quad (7)$$

Where $\mathbf{E}$ denotes the Green-Lagrange strain tensor, $\mathbf{C}$ the right Cauchy-Green deformation tensor, and $\mathbf{S}$ the second Piola-Kirchhoff stress tensor. The elastic potential function W is defined as the functions of the ratios of expansion and contraction, λ_1 , λ_2 and λ_3 , in three dimensions.

$$W = f(\lambda_1, \lambda_2, \lambda_3) \quad (8)$$

In this analysis we use the Ogden model²¹⁾ for W since this model can represent the behavior of slightly compressible rubber, and use Downhill-Simplex method to obtain the values of the corresponding parameters in Eq.(9).

$$W = \sum_{n=1}^N \frac{\mu_n}{\alpha_n} \left[J^{\frac{-\alpha_n}{3}} \left(\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} \right) - 3 \right] + 4.5K \left(J^{\frac{1}{3}} - 1 \right)^2 \quad (9)$$

μ_n, α_n : material constants; K : initial bulk modulus;
 $J = \lambda_1 \lambda_2 \lambda_3$: volumetric ratio; λ : principal stretch.

For practical purpose the sum in (9) is restricted to a finite number of terms, while, for consistency with the classical theory, the constants must satisfy the requirement²²⁾

$$\sum_{n=1}^N \mu_n \alpha_n = 2\mu \quad (10)$$

where μ is the shear modulus of the material in the undeformed stress-free (natural) configuration.

Tensile tests of two kinds of silicon gums give the stress-strain relationship (Fig.13). Table 2 and Table 3 show the values of corresponding parameters in Eq.(9). (Here we set $N=3$).

According to Eq.(10), Table 2 and Table 3, we can obtain

$$\mu (\text{Asym-softer}) = 1.05 \times 10^5$$

$$\mu (\text{Asym-harder}) = 4.25 \times 10^5$$

The shear modulus of the material of Asym-softer is smaller than that of Asym-harder, which validates that Asym-softer is more flexible than Asym-harder.

Fig.13 Relationship between stress and strain
(A: material of Asym-softer; B: material of Asym-harder)

Table.2 Ogden parameters of material of Asym-softer (N=3)

No.	Moduli μ_n	Exponents α_n	Initial modulus K
1	0.19e+02	0.228	0.67e+09
2	0.68e+02	0.17e+02	0.67e+09
3	0.11e+07	0.19	0.67e+09

Table.3 Ogden parameters of material of Asym-harder (N=3)

No.	Moduli μ_n	Exponents α_n	Initial modulus K
1	0.87e+07	0.14e-01	0.21e+10
2	0.15e+08	0.18e-01	0.21e+10
3	0.24e+08	0.19e-01	0.21e+10

4.4 Fundamental Experiment Results

4.4.1 Straight Forward Swimming

Straight forward swimming experiments using two pairs of fins were carried out to find the optimal forward combination of amplitudes for each type of fin within the testing range. Fin controlling parameters are listed in Table 4, where Φ_{FEA} was set as 20, 30, 40, 50 and 60, and Φ_{FLA} as 15, 20, 25 and 30. The frequency of the fin motion ω_{fin} was taken as 2.5 Hz. Results are given in Fig.14. With the increment of flapping amplitudes, the speed of the vehicle increases under each feathering amplitude. Under fixed flapping amplitude, the speed of the vehicle initially increases and then decreases with the increment of feathering amplitudes. It can be seen that the optimal parameters within testing range for four types of fins are: $\Phi_{FLA}=30^\circ$, $\Phi_{FEA}=40^\circ$.

Table.4 Fin parameters for straight forward swimming

Φ_{R0}	Φ_{RA}	$\Delta\Phi_R$	Φ_{FE0}	Φ_{FEA}	$\Delta\Phi_{FE}$	Φ_{FL0}	Φ_{FLA}	$\Delta\Phi_{FL}$
0	0	0	-90	Var1	0	0	Var2	90

(Unit: degrees)

4.4.2 Straight Backward Swimming

Straight backward swimming experiments under two pairs of fins were carried out to find the optimal backward combination of amplitudes for each type of fin. Fin controlling parameters are listed in Table 5, where Φ_{FEA} was set as 20, 30, 40, 50 and 60, and Φ_{FLA} as 15, 20, 25 and 30. The frequency of the fin motion

ω_{fin} was taken as 2.5 Hz. Results are given in Fig.15. With the increment of flapping amplitudes, the speed of the vehicle increases under each feathering amplitude. Under fixed flapping amplitude, the speed of the vehicle shows an almost decreasing tendency with the increment of feathering amplitudes (Except the point of Sym-rigid under $\Phi_{FLA}=30^\circ$, $\Phi_{FEA}=20^\circ$). It can be seen that the optimal parameters within the testing range for four types of fins are: $\Phi_{FLA}=30^\circ$, $\Phi_{FEA}=20^\circ$.

Table.5 Fin parameters for straight backward swimming

Φ_{R0}	Φ_{RA}	$\Delta\Phi_R$	Φ_{FE0}	Φ_{FEA}	$\Delta\Phi_{FE}$	Φ_{FL0}	Φ_{FLA}	$\Delta\Phi_{FL}$
0	0	0	90	Var1	0	0	Var2	-90

(Unit: degrees)

Fig.14 Results of straight forward swimming experiment

Fig.15 Results of straight backward swimming experiment

From the results in figures 14 and 15, the below items can be concluded:

- 1) Asymmetric rigid fin shows just a little superiority than that of symmetric rigid fin, although theoretically asymmetric rigid fin (NACA0015 cross-section) is supposed to have a great advantage than symmetric rigid fin (elliptic cross-section).
- 2) The performance of flexible fins is better than that of rigid ones, which verifies that flexibility takes a positive role in the generation of hydrodynamic forces.

3) Comparing two asymmetric elastic fins, the performance of harder one is almost the same as that of softer one in generating thrust force, although softer fin possesses much more flexibility than harder fin does.

4.5 Deformation Analysis for Flexible Fins

Up to now, we have to concentrate ourselves on the mechanism that lies behind the conclusions given just above.

First we used MSC.MARC software to calculate the natural frequency for the two kinds of elastic fins: $f(\text{Asym-soft}) = 21.25\text{Hz}$ and $f(\text{Asym-hard}) = 40\text{Hz}$. They are relatively much larger compared to the frequency of fin motion (2.5Hz). So it can be said that natural frequency has little influence on the performance of pectoral fins during our experiments.

Then it comes to the deformation of flexible fins. It is very difficult to investigate the whole deformation of the fin surface during fin movements, as spanwise and chordwise deformation would couple together, which causes a big problem during the calculation of hydrodynamics. To simplify the problem, firstly we just observe the deformation along the spanwise direction.

4.5.1 Method of Spanwise Deformation Calculation

The calculation of spanwise deformation is an iterative process between MSC.MARC (Finite Element Method software) for structural computation and unsteady 2-D wing element theory for hydrodynamic computation. We divide the elastic fin into 18 segments along the spanwise direction (Fig.16). Inside each time step firstly theory of wing section is adopted to calculate the hydrodynamic force, which will be applied onto the one-quarter chordwise position of each segment (Fig.17). And then MSC.MARC software is utilized for structural analysis, from which we can observe the spanwise deformation of elastic fins under each working condition.

Fig.16 Segments of fin along spanwise direction

Fig.17 Point load applied on the one-quarter chordwise position for each segment

4.5.2 Hydrodynamic Force in One Segment

We divide the fin into eighteen segments. For each segment the 2-point hinge oscillating wing theory²³⁾ is adopted to simulate the motion of the cross-section, which is coupled with heaving and pitching movements (Fig.18).

Fig.18 Compositions of velocities in one cross-section

In Fig.18, the ordinate is along the linear velocity direction of flapping movement and the abscissa is along the chordwise direction assuming no feathering motion exists. Then we have following relations:

$$\begin{aligned} v &= -d(R\phi_{FL})/dt \\ \beta &= \phi_{FE} \end{aligned} \quad (11)$$

where R is the distance from the root of shaft to that segment. The value of U_∞ is set as 0.45 m/s during this calculation for three kinds of fins. Then we can obtain

$$\begin{aligned} U &= \sqrt{U_\infty^2 + v^2} \\ \alpha_v &= \tan^{-1} \frac{v}{U_\infty} \end{aligned} \quad (12)$$

The angle of attack is calculated as

$$\alpha = \alpha_v - \beta \quad (13)$$

Lift force, drag force and added mass force are obtained as follows:

$$\begin{aligned} L &= 0.5C_L\rho U^2 S \\ D &= 0.5C_D\rho U^2 S \\ F_n &= (\pi/4)\rho b c^2 (d(U \sin \alpha)/dt) \end{aligned} \quad (14)$$

Here, C_L and C_D are lift and drag coefficients separately, the value of which can refer to the relationship curve between angle of attack and C_L (or C_D)²⁴⁾, which is shown in Fig.19. S is the projecting area of each segment. b and c are the span and chord length of each segment separately.

Finally the hydrodynamic force along the x and y directions can be given:

$$\begin{aligned} T &= L \sin \alpha_v - D \cos \alpha_v + F_n \sin \beta \\ Z &= L \cos \alpha_v + D \sin \alpha_v + F_n \cos \beta \end{aligned} \quad (15)$$

T is the force along the abscissa and Z is the force along the ordinate for each segment. Sequentially we can calculate the hydrodynamic force applied onto each segment, which will be utilized during structural calculation on each time step. During the following hydrodynamic analysis, all forces are undimensioned by $0.5\rho U_\infty^2 S$ except Fig.26.

Fig.19 Relationship between Cl (Cd) and angles of attack

4.5.3 Results of Spanwise Deformation Calculation

Fig.20 shows that the non-dimensional average thrust force generated by each asymmetric fin first increases and then decreases with the increment of feathering amplitude under constant flapping amplitude, reaching maximum at FEA=30. The thrust coefficient when FEA=30 is a little larger than that when FEA=40, which is different from the experiment results. (But in the following PTP control test we still adopt FEA=40 based on the experiments' results). Another result is that the thrust forces produced by Asym-softer and Asym-harder are larger than that produced by Asym-rigid. Therefore, the forward speeds of PLATYPUS propelled by Asym-harder and Asym-softer are larger than that propelled by Asym-rigid, as shown in Fig.14. Comparing two elastic fins, we can see Asym-softer has a little advantage over Asym-harder.

Fig.20 thrust coefficient generated by asymmetric fins under different feathering amplitude with flapping amplitude 30°

In order to find the reason why Asym-softer has an advantage over the other two asymmetric fins, we analyzed the spanwise distribution of mean thrust coefficient per segment for three asymmetric fins when FLA=30 and FEA=40 (Fig.21). It can be seen that for the segments nearer to the tip the average thrust coefficient of Asym-softer is larger than that of Asym-harder and Asym-rigid. This result can be explained by the tip spanwise flexibility. Because the stiff shaft reaches up to the 12th segment, since the 13th segment flexibility can bring into effect along

spanwise. Further more, we analyzed the spanwise distribution of the component of mean lift coefficient along x direction, the component of mean drag coefficient along x direction and the component of mean added mass force coefficient, which are shown in Fig.22, Fig.23 and Fig.24. From three figures we can see lift force component plays a big role in the generation of thrust force. The value of the component of added mass force coefficient along x direction can be negligible compared to that of lift coefficient and drag coefficient.

Fig.21 Spanwise distribution of mean thrust coefficient per segment for three asymmetric fins (FLA=30 and FEA=40)

Fig.22 Spanwise distribution of mean lift coefficient component along x direction per segment for three asymmetric fins (FLA=30 and FEA=40)

Fig.23 Spanwise distribution of mean drag coefficient component along x direction per segment for three asymmetric fins (FLA=30 and FEA=40)

Fig.24 Spanwise distribution of mean added mass force coefficient component along x direction per segment for three asymmetric fins (FLA=30 and FEA=40)

Fig.25 Variation of attack angles of No.17 segment in one period. (FLA=30, FEA=40)

Fig.26 Variation of lift coefficients of No.17 segment in one period (FLA=30, FEA=40)

Further more, we investigated the variation of angles of attack and lift coefficients of No.17 segment in one period for three kinds of pectoral fins (Fig.25 and Fig.26). It can be clearly seen that the angles of attack of Asym-softer vibrate between 30° and 50° during one period, which provides some advantage to the generation of lift force.

In order to clarify why thrust force reaches the maximum when FEA=30, we investigated the time variation of thrust force during one period in different feathering amplitudes for Asym-harder when FLA=30 (Fig.27). From these three figures we can see the time variation of thrust force when FEA=30 has an advantage over those of other feathering amplitudes.

During the result analysis, we use tip deformation to describe the spanwise deformation in different feathering angle amplitudes for two flexible fins. Tip deformation is defined as the maximum distance difference of fin tip between the elastic fin and rigid fin during fin motions. Fig.28 shows that the tip deformation of Asym-softer become larger when the value of feathering amplitude increases, but the tip deformation of Asym-harder shows almost constant value. So it can be probably said that for our two kinds of elastic fins, spanwise deformation has positive influence on the thrust force generation.

Because during this calculation we used simple wing theory to obtain the hydrodynamic force, it is better to validate this result in the future by adopting computational fluid dynamics method to get the pressure distribution around the fin surface. Besides in order to clarify the mechanism more clearly, it is advisable to investigate what happens to the chordwise deformation. The validation of the effect of spanwise deformation on hydrodynamics and the effect of chordwise deformation of the flexible fins on hydrodynamics will be discussed in the subsequent paper in details.

Fig.27 Time variation of thrust coefficients during one period in different feathering amplitudes for Asym-harder (FLA=30)

Fig.28 Relationship between tip deformation and feathering amplitude under flapping amplitude 30°

5. Point-to-Point Control Test of PLATYPUS

PTP control was employed to verify the performance of four kinds of fins in carrying out specific task. In PTP control, the vehicle is guided from a far point to a target point and finally hovers around the target point. The PTP control in this study includes azimuth control and distance control during the guidance of the vehicle.

5.1 Control Laws

Because the motion of vehicle is highly non-linear about the control variables and also because it is difficult to express the equations of the motion explicitly in terms of control variables, fuzzy control algorithm is adopted here.

Then one problem comes up—how can we define the range of control variables. From the point of carrying out specific task of underwater vehicles, sometimes the vehicle has to swim fast and turn quickly in order to reach prescribed location, and in this case large velocity is required. But sometimes the vehicle has to finely adjust its gesture to hover or track certain trajectory, and here it means the vehicle can slow down itself by offsetting initial motions or achieve zero velocity freely.

So it is better to investigate the direct relationship between control variables and task achievements. Then we can choose the range of control variables within which the vehicle can achieve from low to high velocities.

5.1.1 Azimuth Control

Azimuth control is performed by controlling the upper and below rowing angles of the 3MDMPFs on the basis of motion parameters shown in Table 6, where $\Delta\Phi_{FE}$ was set as a control variable for the azimuth control.

Table.6 Basic parameters for azimuth control

Φ_{R0}	Φ_{RA}	$\Delta\Phi_R$	Φ_{FE0}	Φ_{FEA}	$\Delta\Phi_{FE}$	Φ_{FL0}	Φ_{FLA}	$\Delta\Phi_{FL}$
0	30	0	0	40	Var	0	0	0

(Unit: degrees)

Two input variables $E\varphi$ and $\Delta E\varphi$ are defined from the azimuth φ of the vehicle and the target azimuth φ_0 as follows:

$$E\varphi = \varphi_0 - \varphi \quad \Delta E\varphi = -\dot{\varphi} \quad (16)$$

where $\dot{\varphi}$ denotes the yaw rate. Each value is transformed into five fuzzy variables of Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB) using triangular continuous membership functions. The output variable $\delta E\varphi$ is also represented by five fuzzy variables. Here we assume that the i -th fuzzy rule is expressed as below:

$$\text{If } \Delta E\varphi = A_i, E\varphi = B_i \text{ then } \delta E\varphi = C_i \quad (17)$$

Where A_i , B_i and C_i denote the corresponding variables to the i -th fuzzy rule. The membership function $\mu(\delta E\varphi)$ is obtained:

$$\mu(\delta E\varphi) = \max_{1 \leq i \leq 25} \left\{ \min \left\{ \mu A_i(\Delta E\varphi), \mu B_i(E\varphi) \right\} \cdot \mu C_i(\delta E\varphi) \right\} \quad (18)$$

The definite value of the output variable $\delta E\varphi$, denoted by $\delta E\varphi_0$ is given by:

$$\delta E\varphi_0 = \int \mu(\delta E\varphi) \cdot \delta E\varphi \cdot d\delta E\varphi / \int \mu(\delta E\varphi) \cdot d\delta E\varphi \quad (19)$$

We obtain the phase angle $\Delta\Phi_{FE_ur}(t)$ and $\Delta\Phi_{FE_lr}(t)$ for the rear-upper feathering phase angle and the rear-lower feathering phase angle, respectively as follows:

$$\begin{aligned} \Delta\Phi_{FE_ur}(t) &= \Delta\Phi_{FE_ur}(t) - \delta E\varphi_0 \\ \Delta\Phi_{FE_lr}(t) &= \Delta\Phi_{FE_lr}(t) - \delta E\varphi_0 \end{aligned} \quad (20)$$

In order to confirm the control range of $\Delta\Phi_{FE}$, basic experiments were carried out to test the turning ability using only rear fins by changing $\Delta\Phi_{FE}$ from -110° to 110° for four types of

fins. During the turning ability test, both fore fins were set into no motion. The results are given in Fig.29. From the graph, it can be seen that the control range of $\Delta\Phi_{FE}$ can be chosen in the range from -90° to 90° for symmetric rigid fin, in the range from -70° to 90° for asymmetric rigid and Asym-harder. Asym-softer could not be used in fuzzy control because it could not turn in counterclockwise direction.

Due to a mechanical limitation of PLATYPUS, asymmetric fins have to employ their trailing edge as leading edge to generate the force to rotate the vehicle. We can see that among three asymmetric fins, asymmetric harder flexible fin shows the best performance in turning. As for Asym-softer, it cannot turn in counterclockwise direction. From experiment videos, it was observed that the thin and soft trailing edge of Asym-softer fin swings freely underwater, which does not act in harmony with the motion of fins and therefore impairs the generation of thrust force. Therefore, fin flexibility can improve hydrodynamic performance, however, too much softness may have a negative effect.

(sign of angular speed: + clockwise; - counterclockwise)

Fig.29 Turning ability test of PLATYPUS using only rear fins

5.1.2 Distance Control

Distance control is performed by controlling the right and left fore flapping angles of the 3MDMPFs on the basis of motion parameters in Table 7.

Table.7 Basic parameters for distance control

Φ_{R0}	Φ_{RA}	$\Delta\Phi_R$	Φ_{FE0}	Φ_{FEA}	$\Delta\Phi_{FE}$	Φ_{FL0}	Φ_{FLA}	$\Delta\Phi_{FL}$
0	0	0	-90	40	0	0	30	Var

(Unit: degrees)

We define X_0 and X as the target distance and the current distance respectively. Then two input variables are defined:

$$Ex = X_0 - X \quad \Delta Ex = -(Ex(t) - Ex(t - \Delta t)) / \Delta t \quad (21)$$

where t and Δt denote time and time step. We obtain the definite value of output variable δEx , denoted by δEx_0 , using the same fuzzy rules as that above. Then the flapping phase $\Delta\Phi_{FL_lf}$ and $\Delta\Phi_{FL_rf}$ can be given as follows:

$$\begin{aligned} \Delta\Phi_{FL_lf}(t) &= \Delta\Phi_{FL_lf}(t - \Delta t) - \delta Ex_0 \\ \Delta\Phi_{FL_rf}(t) &= \Delta\Phi_{FL_rf}(t - \Delta t) - \delta Ex_0 \end{aligned} \quad (22)$$

In order to confirm the control range of $\Delta\Phi_{FL}$, basic experiments were carried out to test the straight swimming ability using only fore fins for four types of fins. During swimming ability test, both rear fins were set into no motion. The results are given in Fig.30. From the graph, it can be seen that the control

range of $\Delta\Phi_{FL}$ can be chosen in the range from -130° to 60° for four types of fins.

From the graph, we can also see that Asym-harder fin can achieve larger working range compared to the other three fins, which is a very important property in precise control of underwater vehicles.

Fig.30 Swimming ability test of PLATYPUS using only fore fins

5.2 Control Strategy

The PTP control strategy consists of two modes:

- Mode1: The center of the vehicle is located outside of the circle with the radius R_0 . The fore pair of MPFs play a role in distance control about Dist and the rear pair of MPFs play a role in azimuth control about $E\phi$ defined in Fig.31.
- Mode2: The center of the vehicle is located inside the circle with the radius R_0 . The fore pair of MPFs play a role in distance control about Dist and the rear pair of MPFs play a role in azimuth control about $E\phi$ defined in Fig.32.

The switch between two modes in PTP control test is given in Fig.33 (Here $R_0=0.3m$).

Fig.31 Notation for Mode1

Fig.32 Notations for Mode2

Fig.33 Switch of two modes in PTP control

5.3 PTP Control in Still Water

Experiments were carried out at the towing tank of Osaka University (100m long, 7.8 wide and 4.35m deep).

During this stage we tried to find out the most appropriate fuzzy control rule for each fin, namely the control rule that can minimize the distance and the change of azimuth to the target point. The reason lies in that original fuzzy rule was developed based on symmetric fin but during PTP experiments Asym-rigid fin and Asym-harder are employed to propel the vehicle. So we tested different kinds of fuzzy rules to find out the most appropriate one for each fin.

		$\Delta E\phi$						Azimuth			$\Delta E\phi$					
		NB	NS	ZO	PS	PB	NB				NS	ZO	PS	PB		
$E\phi$	NB	NB	NB	NB	NB	NS	ZO	$E\phi$	NB	NB	NB	NB	NS	ZO		
	NS	NB	NB	NB	NS	ZO	PS		NS	NB	NB	NB	NS	<i>PS</i>	<i>PB</i>	
	ZO	NB	NS	ZO	PS	PB	ZO		NB	NS	ZO	PS	PB			
	PS	NS	ZO	PS	PB	PB	PS		NS	ZO	PS	PB	PB			
	PB	ZO	PS	PB	PB	PB	PB		ZO	PS	PB	PB	PB			

Fig.34 Original and modified fuzzy rules for azimuth control of Asym-rigid

		ΔEx						Distance			ΔEx					
		NB	NS	ZO	PS	PB	NB				NS	ZO	PS	PB		
Ex	NB	NB	NB	NB	NB	NS	ZO	Ex	NB	NB	NB	NB	NS	ZO		
	NS	NB	NB	NB	NS	ZO	PS		NS	NB	NB	NB	NS	<i>PS</i>	PS	
	ZO	NB	NS	ZO	PS	PB	ZO		NB	NS	ZO	PS	PB	PB		
	PS	NS	ZO	PS	PB	PB	PS		NS	<i>NS</i>	PS	PB	PB	PB		
	PB	ZO	PS	PB	PB	PB	PB		ZO	PS	PB	PB	PB	PB		

Fig.35 Original and modified fuzzy rules for distance control of Asym-rigid

5.3.1 Fuzzy Rule for asymmetric rigid fin

The original and modified fuzzy control rules in azimuth control for Asym-rigid fin are given in Fig.34. Because Asym-rigid is not good at counterclockwise turning, we modified the azimuth control rules to strengthen its turning ability in the counterclockwise direction. For example, $E\phi=NS$ and $\Delta E\phi=PS$ mean that the vehicle is now a little over the target direction and turning slowly in the counterclockwise direction to the target

azimuth from the definition in Eq.(11). According to the original azimuth control rule in Fig.34, the output is $\delta E\phi_0=ZO$ at this stage, which means the vehicle will keep the previous state from the definition of Eq.(20). But during the modified azimuth control rule, the output is $\delta E\phi_0=PS$ at this stage, which means the vehicle will strengthen its counterclockwise rotation from the definition of Eq.(20).

The original and modified fuzzy control rules in distance control for Asym-rigid fin are given in Fig.35. Because the vehicle swims fast when inside the target circle, we modified the distance control rules to slow down the speed when the vehicle is near around the target point.

The corresponding real-time azimuth and distance comparisons are given in Fig.36 and Fig.37. It can be seen that modified rule can improve the performance of PTP control.

Fig.36 Comparison of azimuth in PTP control in still water for Asym-rigid under original and modified rules

Fig.37 Comparison of distance in PTP control in still water for Asym-rigid under original and modified rules

5.3.2 Fuzzy Rule for Asymmetric Flexible Fin Harder

The original and modified fuzzy control rules in azimuth control and distance control for Asym-harder fin are given in Fig.38 and Fig.39. Because Asym-harder is not good at turning counterclockwise, we modified the azimuth control rules to strength its turning ability in the counterclockwise direction. And also because the vehicle swims fast when inside the target circle, we modified the distance control rules to slow down the speed when the vehicle is near around the target point.

The corresponding real-time azimuth and distance comparisons are shown in Fig.40 and Fig.41. It can be seen that modified rule can improve the performance of PTP control.

		$\Delta E\phi$						Azimuth	$\Delta E\phi$					
		NB	NS	ZO	PS	PB	NB		NS	ZO	PS	PB		
$E\phi$	NB	NB	NB	NB	NB	NS	ZO	E	NB	NB	NB	NB	NS	ZO
	NS	NB	NB	NB	NS	ZO	PS		NS	NB	NB	NS	PS	PS
	ZO	NB	NS	ZO	PS	PB	PB		ZO	NB	NS	ZO	PS	PB
	PS	NS	ZO	PS	PB	PB	PB		PS	NS	NS	PS	PB	PB
	PB	ZO	PS	PB	PB	PB	PB		PB	ZO	PS	PB	PB	PB

Fig.38 Original and modified fuzzy rules for azimuth control of Asym-harder

		ΔE_x						Distance			ΔE_x					
		NB	NS	ZO	PS	PB	NB				NS	ZO	PS	PB		
E_x	NB	NB	NB	NB	NB	NS	ZO		E_x	NB	NB	NB	NB	NS	ZO	
	NS	NB	NB	NB	NS	ZO	PS			NS	NB	NB	NS	PS	PB	
	ZO	NB	NS	ZO	PS	PB	PB			ZO	NB	NS	ZO	PS	PB	
	PS	NS	ZO	PS	PB	PB	PB			PS	NS	PS	PS	PB	PB	
	PB	ZO	PS	PB	PB	PB	PB			PB	ZO	PS	PB	PB	PB	

Fig.39 Original and modified fuzzy rules for distance control of Asym-harder

Fig.40 Comparison of azimuth in PTP control in still water for Asym-harder under original and modified rules

Fig.41 Comparison of distance in PTP control in still water for Asym-harder under original and modified rules

5.3.3 Comparisons Between Three Types of Fins

Comparisons between the results of three kinds of fins under modified control rules are shown in Fig.42 and Fig.43. Statistical comparison is given in Table 8 (The statistics sample was taken

from $t=30$ to the end moment). It can be seen that in still water the performances of the distance control are almost the same for three kinds of fins. But from the viewpoint of the performance of the azimuth control, Asym-harder exerts the best control performance in terms of standard deviation of offset azimuth from target azimuth, because fluctuation of azimuth decreases workability of the robot like observation by camera.

Fig.42 Comparison of azimuth in PTP control in still water for three fins under modified control rules

Fig.43 Comparison of distance in PTP control in still water for three fins under modified control rules

Table.8 Statistical comparison of PTP control in still water

Category	Azimuth (degree)		Distance (m)	
	Ave	Standard-deviation	Ave	Standard-deviation
Sym-rigid	-10.76	27.68	0.15	0.108
Asym-rigid	18.99	22.47	0.17	0.069
Asym-harder	10.18	8.01	0.21	0.065

5.4 PTP Control in Water Currents

Three thrusters were set up at the water depth of 0.55m to generate water currents in the lateral direction of the towing tank. Fig.44 gives the positions of the thrusters, start point and target point within experimental area and Fig.45 shows the distribution of water currents at the water depth of 0.55m. The mean value of water currents is 0.095 m/s.

Comparisons between the results of three kinds of fins in water currents are shown in Fig.46 and Fig.47. Statistical comparison is shown in Table 9 (The statistics sample was taken from $t=30$ to the end moment). Generally speaking, the performance of three fins in water currents is worse than that in still water. From Fig.44 we can see the target point is located very near to one thruster and

from Fig.45 we can also know that the water currents along the axes of thrusters are stronger than those in other areas. Both reasons above cause the underwater vehicle difficult to hover stably around the target point.

It is found that there is not so much difference in distance control among three types of fins, but “Sym-rigid” is superior to other two types in fluctuation of azimuth. Asymmetric fins cannot produce enough force to turn against water currents, especially for flexible one. Sometimes the robot can turn to the target azimuth only when it is pushed away from the thrusters. The reason lies in that due to the mechanical limitation of PLATYPUS, symmetric fin can use both edges of the fin effectively during both clockwise and counterclockwise rotation, but asymmetric fins can use their leading edges for production of lift forces more effectively in clockwise rotation than in counterclockwise rotation.

Fig.44 Allocation of thrusters, target point and start point

Fig.45 Distribution of water currents

Fig.46 Comparison of azimuth in PTP control in water currents

Fig.47 Comparison of distance in PTP control in water currents

Table.9 Statistical comparison of PTP control in water currents

Category	Azimuth (degree)		Distance (m)	
	Ave	Standard-deviation	Ave	Standard-deviation
Sym-rigid	28.25	23.31	0.31	0.17
Asym-rigid	58.91	46.58	0.29	0.16
Asym-harder	60.78	33.21	0.32	0.11

6. Conclusion

Aiming at investigating the effects of flexibility and chord-wise cross section of pectoral fins on the swimming performance of PLATYPUS, a series of researches were carried out:

- 1) Experiments using a mechanical pectoral fin device BIRDFIN fixed in uniform flow verify that flexible fin is more effective than rigid fin for the generation of thrust forces of underwater vehicles;
- 2) Fundamental experiments on swimming performance of a biomimetic underwater vehicle PLATYPUS verify that asymmetric flexible fin has an advantage in propelling underwater robots over symmetric rigid fin and asymmetric rigid fin. The optimal combination of amplitudes for each fin to propel PLATYPUS is obtained. Iterative computation of spanwise deformation between Finite Element software and wing theory shows that Asym-softer fin can generate larger thrust force compared to Asym-harder and Asym-rigid. Lift force plays an important role in generating this thrust force. The investigation of time variation of thrust force for three asymmetric fins in one period shows that the thrust force when the feathering amplitude is 30 degree has an advantage over those of other feathering amplitudes. Finally the investigation of spanwise deformation clarifies that spanwise deformation has positive influence on the generation of thrust force for our two kinds of elastic pectoral fins.
- 3) PTP control using PLATYPUS in still water and in water currents were carried out to test the different performances of each fin in carrying out specific task. During this stage, fuzzy control rules for asymmetric fins were improved to find the most suitable one for each fin. Asymmetric flexible fin (harder) behaves best in PTP control in still water but symmetric rigid fin does best in PTP control in water currents. Asymmetric flexible fin does not behave well during PTP control in water currents. This is due to the feathering motion limitation of PLATYPUS, leading to

asymmetric fins have to employ its trailing edge as leading edge to generate force to rotate the vehicle.

Fin design process is a series of try-and-trial stages, and during this process different factors may dominate the performance in different working conditions. For instance, flexibility plays an important role during forward swimming and backward swimming test, but during rotation test of PLATYPUS flexibility instead becomes a disadvantage factor because of the mechanic limitation of the vehicle.

The performance of the fin is limited to the mechanical workout and depends on the working conditions of the vehicle. During fin design, we have to take into account the matching among many factors: fin shape, fin flexibility, mechanical workout probability, working conditions and so on. Then according to the specific characteristics of each fin, the designers have to find out the suitable controlling methods for each one to achieve certain prescribed mission.

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