

## Fuzzy logic vorticity control of oscillating foil UUV

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**Abstract**—This paper describes the design of a biomimetic inspired fish swimming like UUV based on 2-D oscillating foil mechanism which plays guiding role in biomimetic propulsion research field, the relation between vorticity control and motion control parameters for 2-D oscillating foil has been built, a fuzzy logic vorticity controller is designed to achieve straight line maneuverable swimming and thrust efficiency can be ensured at the same time. Experimental result of field test shows that an obviously improved vehicle performance is obtained. Meanwhile, burst-and-coast maneuvering is found to be a more effective swimming mode for the vehicle while compared with steady swimming.

### I. INTRODUCTION

THE propulsive efficiency of fishes can reach as high as 80%. For lunate tail swimming fish as tuna, dolphin or whale, their maximum swimming speed can be 20 knots while its body keeps rigid, the flapping lunate tail forms an efficiency thruster, resembling an oscillating foil. The two-dimensional(2-D for simplified) oscillating foil theory played a wide guiding role in the domain of bionic fish-like swimming propulsion which had been studied according to a mount of hydrodynamic experiments by Predecessors[1]. The high-lift mechanism of bird, insect flight, caudal fin and pectoral fin were modelled by oscillating foil [2]. It was found that the St number (Strouhal number) has great impact on thrust coefficient and efficiency (or lift force in flight mechanism), Triantafyllou [3] applied St in describing the shedding vortex as fish flapping its tail fin and found in the experiment that the optimal area of combining both the thrust coefficient and efficiency was generated in the range of  $0.2 < St < 0.4$  (It should be noted that the optimal St number of insect and bird fly are also in this range.). But when the St number is too low (e.g.  $St=0.05$ ), the oscillating foil will be unable to provide sufficient thrust force and even generate negative value, while the St is too high, its thrust efficiency will be lower than that in the reasonable range although large thrust coefficient generated[4]. The maximum angle of attack  $\alpha_{max}$ , non dimensional heave amplitude  $h$  and phase

difference  $\psi$  other than St number are parameters that can influence the oscillating foil thrust performance, which are called the “vorticity control parameters” of oscillating foil. The maximum thrust efficiency acquired in the experiment reached as high as 87%. In the biology research field of fish maneuvering, the fish manifests multiple mode of straightline maneuvering as fast-start[5](C-shape and S-shape start), burst-and-coast[6], steady swimming, reverse swimming, brake etc, which also rendered approaches and inspiration for bionic engineering. Taking both biology researches and control theory into consideration, we can consider that: by adopting reasonable vorticity control mechanism, fishes completed all kinds of maneuver behavior thus achieved the control objectives of speed, angle or position.

In biomimetic engineering, the high efficiency as well as maneuverability of fishes were attempted to make up the defects as low efficiency, poor maneuverability in traditional UUV(Unmanned Underwater Vehicle). The study of robotic fish gained rapid development since the nineties of last century. By research of thrust mechanism, the bionic VCUUV of Draper obtained the maximum speed of 1.25m/s[6].Kato et al. made “Blackbass” to study the propulsive mechanism of pectoral fin[7]. T. Fukuda et al. developed a micro machine fish using Ionic Conducting Polymer Film (ICPF) as its driving system [8]. Liang et al. utilizing the biomimetic fish in archeological observation[9]. Wen Li et al. gained a long voyage by robot fish with 7 hours’ voyage duration, a distance of 22km, and average speed of 1.03m/s, with the body-length speed ratio 0.75[10]. While in robotic fish control algorithm, Kato[11] realized maneuverability and stability of pectoral fin propulsive robotic fish in 2-D planar motion by fuzzy control. Yu[12] realized the two dimensional planar maneuverability of carangiform swimming mode by intelligent algorithm. Le Zhang Le[13] realized depth control using pectoral fin by fuzzy logic algorithm. However, in present research, the robotic fish were all controlled by motion parameters like frequency, wave amplitude, et al. although the motion control can achieve control objectives, but the thrust efficiency during swimming cannot be ensured. Considering the flow physics, direct control based on motion parameter cannot achieve formation of optimal vortex wake patterns[14], thus, incapable to generate an efficient swimming.

How to achieve high thrust efficiency while performing maneuverable motion is of great significance in biomimetic field. Predecessors has made detailed hydrodynamic researches of the relation between the vorticity control parameters and 2-D oscillating foil thrust performance according to various ways [15], and found it a multivariable,

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nonlinear connection, no quantitative model presently. But since a great deal of experiments offered a qualitative description between the thrust performance and related vorticity control parameters[16], experience obtained is of especially significance. This paper will discuss proper way to realize high thrust efficiency maneuverability swimming according to “fuzzy logic vorticity controller” based on the mechanism of 2-D oscillating foil. Experiments validation on the lunate-tail propelled UUV will be conducted to verify the control methods.

## II. CONFIGURATION OF OCILLATING FOIL PROPELLED UUV

We chose to conduct the experiment on the UUV "SPC" vehicle based on the lunate-tail propulsion which could be consider as a large aspect-ratio ocillating foil. The body diameter of "SPC" is 0.22m with a shape of cylinder, and its length is 1.6m, the oscillating foil thrust cabin is behind the cylinder-shape body (as shown in Fig.1).It should be notice that the proportion of thrust carbin displacement only takes 10% of the entire body. Battery and other electronics as well as sensors load in displacement came at a proportion of 70%. At present, 26 pieces of lithium polymer batteries were built in as power supply. Two 150w DC servo motors with reducer were installed symmetrically in the thrust carbin, two concentric output axis directly drive connecting rod to provide the motion of translational and rotational movement for ocillating foil. The carbon fiber is used as the foil's material, with a chord length of 10cm, and span of 50cm, the sweepback angle of the tail fin is 70°. The translational & rotational motion are coordinated according to motion controller Trio MC206. The maximal flapping frequency of the foil is 3Hz according to the mechanical system test, as fishes do. HMR3100 compass and ADXRS150 gyro were intalled in “SPC” and depth control could be realised by pressure sensor FMP200 and a pair of elevators.

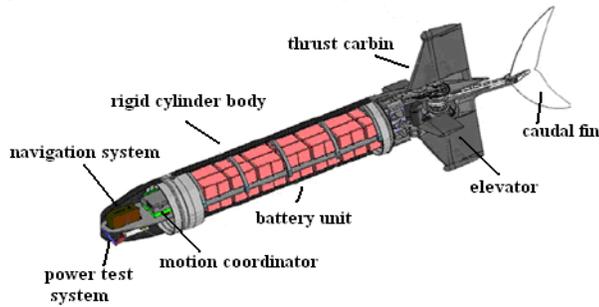


Fig. 1. view of SPC-3 UUV layout

The velocity feedback is obtained through a flow kinemometer fixed under the head of "SPC", the kinemometer is obtained by a modified instrument LS10 for measuring river flow velocity. When water current acts on the blade of kinemometer, it will produce a rotational motion and the rotational speed is get from the photoelectric encoder which is fixed to its root with seriuos waterproof. Static and dynamic calibration had been conducted to find the relation between flow velocity  $V$  and rotational speed  $n$ . By fixing the flow kinemometer to the guide rail and conducting

different uniform velocity for several times to complete static calibration, fitting data using least-squares procedure and got the linear relation:  $V = 0.0998n + 0.037$ , and mean square deviation is 1.64%. While conducting the dynamic calibration, an acceleration-deceleration movement was made due to a preset guide rail movement. The calibration result shows that the mean square deviation of the measurement result and the guide rail velocity preset is 2.2% in the range of 0.08m/s to 2.1m/s. The encoder signal processing will be taken in Trio MC206 after it is converted to analog signal through a frequency-voltage converting device inside "SPC". In order to get the power consumption, two honeywell current indicator CS050 was used to get the input current  $I_1, I_2$  of two servo motors, respectively. And the battery voltage  $V$  get from PC104, thus the power consumption of the vehicle could be calculated by  $W = (I_1 + I_2) \times V$ , where  $W$  represents power consumption.

## III. VORTICITY CONTROL PARAMETERS AND THRUST MODE

The transverse and rotational motions of the flapping tail are defined as follows:

$$h'(t) = h_f \times \sin(2\pi ft) \quad (1)$$

$$\theta(t) = \theta_f \times \sin(2\pi ft + \psi) \quad (2)$$

where  $h_f$  represents the amplitude of transverse motion,  $f$  represents the flapping frequency,  $\theta_f$  represents the amplitude of rotation, and  $\psi(t)$  is defined as the phase angle between transverse and rotational motion.

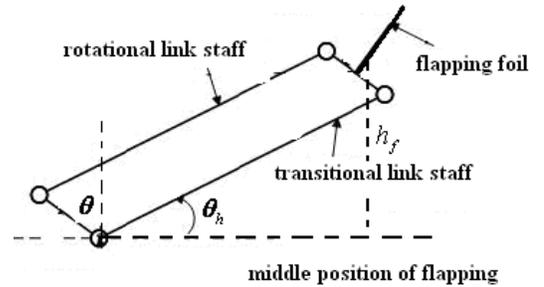


Fig. 2. Tail fin flapping mechanism

As shown in Fig.2, the transverse motion of the flapping tail is realized by mechanical links that make a circular arc. When the length of transitional link  $l$  is large and transitional angle  $\theta_f$  is relatively small, the circular arc is approximately equivalent to the displacement in the transverse direction. In this experiment,  $l = 0.36$  m and  $\theta_f \leq 15^\circ$ , which satisfies this approximation. If we suppose that  $A$  represents the angular amplitude (in radians) of the transverse motion, the transverse tail kinematic trajectory can be defined with the following equation:

$$h(t) = l \sin \theta_h \approx l \theta_h = l A \sin(2\pi ft) \quad (3)$$

Consider the relationship between the foil's kinematic and vorticity control parameters, firstly, the most important parameter in this study, the Strouhal number based on heave amplitude[3] is defined here:

$$St = \frac{2fh}{U} = \frac{2fAl}{U} \quad (4)$$

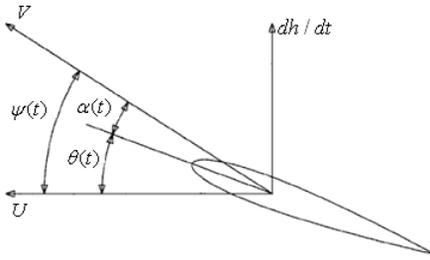


Fig. 3. Definition of relative velocity  $V$  and angle of attack  $\alpha(t)$  for an oscillating foil

It can be known from Fig. 3 that the direction of foil's motion is along the direction of  $dh/dt$  axis. The velocity of coming flow is perpendicular to the translational motion direction and equation can be get as follows:

$$tg(\alpha(t) + \theta(t)) = (dh/dt) / U \quad (5)$$

Taking the equation (3) and (5) into consideration, the oscillating foil angle of attack can be defined as:

$$\alpha(t) = \arctg\left(\frac{2\pi f l A \cos(2\pi f t)}{U}\right) - \theta_f \times \sin(2\pi f t + \psi) \quad (6)$$

The maximum value of  $\alpha(t)$  is  $\alpha_{max}$ , it has got great influence on the leading-edge vorticity thus making an obvious impact on the thrust efficiency[17]. Meanwhile, define the non-dimensional heave amplitude in (7), Where  $c$  is the chord length of oscillating foil(tail fin):

$$h = h_f / c \quad (7)$$

The motion control parameters of the 2-D oscillating foil are  $A, \theta_f, f, \psi$ , while  $St, \alpha_{max}, h, \psi$  represents the vorticity control parameters which determine thrust performance. The relation of vorticity control and motion control parameters is built in the equation (4)- (7).

Predecessors' abundant work on force measurement and flow visualization provide sufficient evidence that the thrust performance is optimal while  $h = 1, \psi = 90^\circ$  within the range of fish-swimming  $Re$  (Reynolds number).[4] It should be notice that we got similar conclusion while doing the hydrodynamic experiment on 2-D oscillating foil in water tunnel before conducting "SPC" free swimming field test. Thus, vorticity control parameters variables are reduced to  $St, \alpha_{max}$ . Taking predecessors' work into account, fig.4 showed the foil wake patterns as well as the thrust mode distribution as function of  $St$  and  $\alpha_{max}$ , among all the vorticity control parameters,  $St$  number, which plays a similar role of reduced frequency mentioned by Ohim et al[17] will be the governing parameter,  $\alpha_{max}$  should change to its proper

value while  $St$  appears in different region, if not, poor wake patterns will be generated and bad thrust performance become evident. Obviously, the thrust mode will have impact on the propulsion performance of the vehicle, both on speed and thrust efficiency.

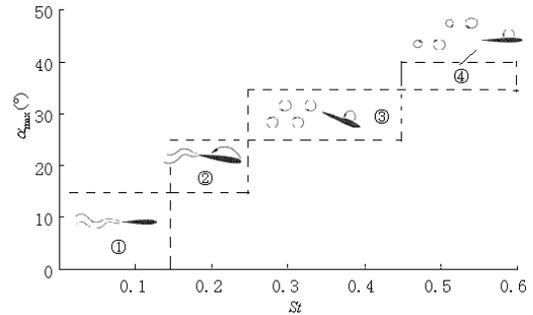


Fig. 4. Foil wake patterns and thrust mode distribution as function of vorticity control parameters

Thrust mode was classified to the following 4 sorts as follows:

①:  $0 < St < 0.15, 0 < \alpha_{max} < 15^\circ$ , no flow separation and no leading edge vortex, basically, no thrust generated in this region, the UUV will surely deceleration but with little power consumption.

②:  $0.15 < St < 0.25, 15 < \alpha_{max} < 25^\circ$ , a weak leading edge vortex generated, and less-organized separated vortex in the region, thrust force is small but high thrust-efficiency generated, the UUV maybe deceleration or hold regularity speed.

③:  $0.25 < St < 0.45, 25 < \alpha_{max} < 35^\circ$ , obvious leading-edge vortex generated periodically and forms vortex pair with the trailing-edge vortex, this is an optimal region for the combination of thrust force and efficiency, in most cases, UUV may acceleration gently or hold regularity speed also with high efficiency.

④:  $0.45 < St < 0.6, 35 < \alpha_{max} < 40^\circ$ , obvious leading edge vortex structure then combined with trailing edge vortex, form a vortex pair in reverse direction which is different with mode ③, large thrust force but relatively low efficiency, the vehicle will of course accelerate but power consumption will be bigger.

Except these four thrust modes, other mode of thrust will have poor thrust performance. Trantyllyou et al. [3] found from the result of observation to multiple sorts of fish that their  $St$  numbers for swimming range within 0.2~0.3. But for inherent difference between biomimetic vehicle and biological live fishes, the range of  $St$  for optimal thrust efficiency of the vehicle can be ascertained only after field test is conducted.

As mentioned in the introduction, we defined several straight line maneuvering swimming as follows:

#### A. Steady swimming

The UUV will employ an acceleration or deceleration to target velocity from initial velocity, whole process will adopt thrust mode ② or ③, thus the range of vorticity control parameters can be ensured as shown in fig.3.

### B. Burst and coast

A Burst-and-Coast swimming style which consists a burst phase and a coast phase is employed here in order to obtained agile vehicle speed and potential power consumption saving[6]. The Burst phase is defined as in thrust mode ④ and play a role of fast acceleration process, then slide to target velocity by coast phase (tail will stop flapping). Obviously there is no power consumption in Coast phase.

### C. Fast start

Typical fast start includes C and S start. The rigid body UUV cannot imitate its biological shape apparently, however, as mentioned in Domenici's research[5], fish will adopt large amplitude and high frequency flapping to conduct instantaneous behavior like prey or escape. So the vehicle can employ maximum amplitude and frequency (here,  $h=2, f=2.6\text{Hz}$ ) that the mechanical structure could endure to perform a fast-start motion. Fast start will be used to accelerate from rest state to a certain initial velocity by the vehicle. Here, fast-start is a simple motion control process, not vorticity control, further researches will be taken to explore its vorticity control method.

It is easy to infer that  $St$  number in Mode A and B can act as controlled variable as well as observed variable which can reflects thrust efficiency because clear relationship between thrust mode and vorticity parameters was defined in fig.4. While the  $St$  number in the mode C can only serve as observed variable for it employs motion control parameters.

## IV. FUZZY LOGIC VORTICITY CONTROLLER DESIGN

The introduction mentioned that the thrust efficiency cannot be ensured just using simple motion control, The key issue then becomes how to choose suitable vorticity parameters in response to vehicle speed changes, which is clearly a hard nut to crack owing to un-modeled uncertainty in fish's motion. Luckily, there is an increasing tendency to use fuzzy logic controllers (FLC) to resolve an issue of un-modeled uncertainty. so vorticity parameters will be directly controlled here so as to achieve different thrust mode given in fig.4, thus, a fuzzy logic vorticity controller (FLVC for simplified) based on hydrodynamical experiment experience was built as shown in fig.5:

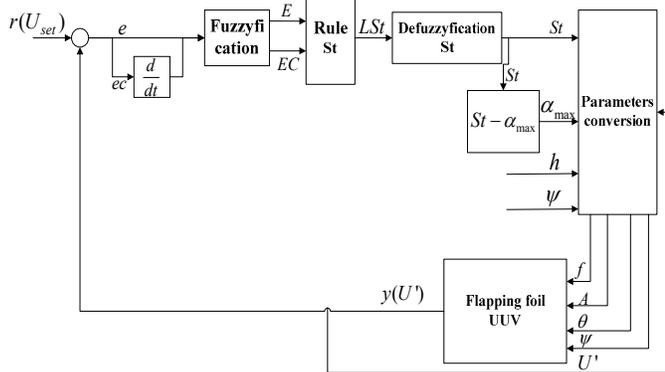


Fig. 5. Fuzzy logic vorticity controller for efficient swimming

The purpose of the FLVC is to build a fuzzy logic controller which determines the thrust mode according to the

vorticity parameters when the vehicle move from its initial speed to final speed using straight-line maneuvering. As shown in Fig.9, the fuzzy logic controller contains two inputs( $e, ec$ ) and one output:  $St$ , the desired speed is  $U_{set}$ ,  $U'$  represents UUV speed feedback by kinemometer, Suppose that in a certain instant, the values for error and its change are  $e$  and  $ec$ , respectively. The inputs are depicted by  $e_t = r_t - y_t, ec_t = e_t - e_{t-1}$ , the output of the FLVC is  $St$ , through another rule evaluation which export  $\alpha_{max}$ , thus, thrust mode is determined. According to a kinematic model which switch vorticity control parameters  $St, \alpha_{max}, \psi, h$  to motion control parameters  $f, A, \theta, \psi$ , the relationship of which has already been defined above, it should be noted that  $\psi, h$  is selected to be constant:  $\psi = 90^\circ, h = 1$  according to the hydrodynamical experience on oscillating foil. Hence there are two inputs and one output in the controller, the range of input and output variable are as follows:  $-2(\text{m/s}) \leq e \leq 2(\text{m/s}), -0.2(\text{m/s}) \leq ec \leq 0.2(\text{m/s})$  and  $0 \leq St \leq 0.6$ , the discourse universe of the variables are expressed as  $E, EC$  and  $LSt$ , here the scaling factors which (not shown in Fig.5) are determined by experiments and their value are  $k_e = 1.5, k_{ec} = 15, k_{st} = 10$ .

The following step is to represent the variables by linguistic terms. Let  $E, EC$  denote the fuzzy sets of  $e, ec$  respectively, We represent  $E, EC$  by linguistic fuzzy set  $\{PB, PM, PS, Z, NS, NM, NB\}$ , abbreviated from positive big, positive medium, positive small, zero, negative small, negative medium, negative big, respectively, it is known that fuzzy variable sets are set of overlapping values represented by fuzzy membership functions. The membership functions of the variable  $E$  and  $EC$  was fixed and a triangular shaped membership function was adopted. Based on the theoretical and experimental result of flapping foil, a fuzzy associative memory matrix which involves the fuzzy rules of the inference engine is designed. (As shown in TABLE.I) If-Then rule is adopted and a  $7 \times 7$  fuzzy associative memory matrix is built. The fuzzy rules are given as: if  $e$  is  $E_i$  and  $ec$  is  $EC_j$  then  $St$  is  $b_{ij}$ . Where  $E_i$  is the  $i$ th member of the fuzzy set  $E$ ,  $EC_j$  is the  $j$ th member of the fuzzy set  $EC$  and  $b_{ij}$  denotes one of the members of the fuzzy set  $LSt$ , it should be noted that, while vehicle travels in a certain speed, acceleration & deceleration can be adjusted by thruster, predecessors used to adjust motion parameters like frequency or wave amplitude respectively. Here, we achieve speed control by adjusting thrust mode which depend on  $St$  number, that is the principle of the fuzzy rule.

TABLE I  
RULE TABLE FOR VORTICITY PARAMETER CONTROL

$LSt$		Charge-in-error $EC$						
		$NB$	$NM$	$NS$	$Z$	$PS$	$PM$	$PB$
$E$	$NB$	$NS$	$NS$	$PS$	$PB$	$PB$	$PB$	$PB$
	$NM$	$NS$	$NS$	$PS$	$PM$	$PB$	$PB$	$PB$
	$NS$	$NM$	$NS$	$PS$	$PM$	$PM$	$PB$	$PB$
	$Z$	$NM$	$NS$	$NS$	$Z$	$PS$	$PM$	$PB$
	$PS$	$NM$	$NS$	$NS$	$Z$	$PS$	$PM$	$PM$
	$PM$	$NM$	$NM$	$NS$	$NS$	$PS$	$PS$	$PM$
	$PB$	$NB$	$NM$	$NS$	$NS$	$PS$	$PS$	$PM$

In the inference mechanism, Mamdani-type inference is adopted. In the step of defuzzification, as in equation (8), the method of center of gravity (COG) is used to calculate the output:  $u_{crisp}$ .

$$u_{crisp} = \frac{\sum u_{ij} b_{ij}}{\sum u_{ij}} \quad (8)$$

Where  $u_{ij}$  is the conjunction degree of  $i \times j$ th fuzzy rule, which is obtained by Mamdani-type, after  $u_{crisp}$  multiply the scaling factor  $k_{st}$ ,  $St$  number used to control the flapping can be achieved,  $St - \alpha_{max}$  rules described in fig.5 will be piecewise in terms of the distribution function given by:

$$\alpha_{max} = \begin{cases} 10St(0 \leq St \leq 0.15) \\ 10St(0.15 \leq St \leq 0.25) \\ 50St + 12.5(0.25 \leq St \leq 0.45) \\ 33.3St + 15(0.45 \leq St \leq 0.6) \end{cases} \quad (9)$$

Since all vorticity parameters have been decided, parameter conversion will convert the vorticity parameters into motion control parameters  $f, A, \psi, h$  which can be programmed in Trio MC206, as described in equation (4)-(7), the vehicle speed value is needed, so  $f, A, \psi, h$  could only be solved when  $St, \alpha_{max}, h, \psi, U'$  are assured.

Using such a method, combine FLVC and straight line maneuvering motions description mentioned above, oscillating foil motion with confirmable thrust mode is obtained.

## V. EXPERIMENTAL RESULT

A field test of the UUV is conducted in a swimming pool with size of  $25 \times 15m$ . In order to verify the validity of FLVC algorithm in straight-line maneuverable swimming control, after calibration check for vehicle system and sensors, the field test is conducted as follows: first, accelerate to initial velocity by fast-start mode and then achieve the target velocity by three swim modes respectively: Burst-and-coast(BC for simplified), Steady swimming(SS for simplified) and 2.0Hz flapping frequency with 1.2c oscillating amplitude swimming without FLVC algorithm (using this mode we use to conducted a long voyage of 22km in Beidaihe) The experiment set the target velocity as 1.65m/s

while power consumption is recorded according to PC104 simultaneously, including the output of the compass.

As shown in Fig.7A, it can be seen that UUV spent 2.19s employ fast-start and accelerated to 0.5m/s ( $t_1$  marked in Fig.6 A). The fast-start process was followed by large yaw amplitude(as shown in Table II), the average power consumption came to 95w. The BC swimming under the control of FLVC accelerated from 0.5m/s to the maximum speed 1.85m/s using 7.3s during its burst phase( $t_2$  marked in Fig.6), then decelerated to target velocity(final speed) 1.65m/s by its coast phase, the average speed of BC swimming is 1.31m/s. The burst phase was attended by larger yaw amplitude, which hardly occurred during the coast stage. The accelerating process in SS mode is relatively slow, taking 8.03s, the average velocity is 1.21s. Taking Fig.6 and Table I into consideration, it is obviously that the power consumption, average vehicle speed of both BC and SS are superior to the case of 2.0Hz. By comparison, there is little difference between BC and SS mode on power consumption, while BC is larger in terms of average velocity, which tallies with the conclusion of the biological observation estimation[6]. The experiment result shows that burst-and-coast is indeed an effective swimming style for the vehicle.

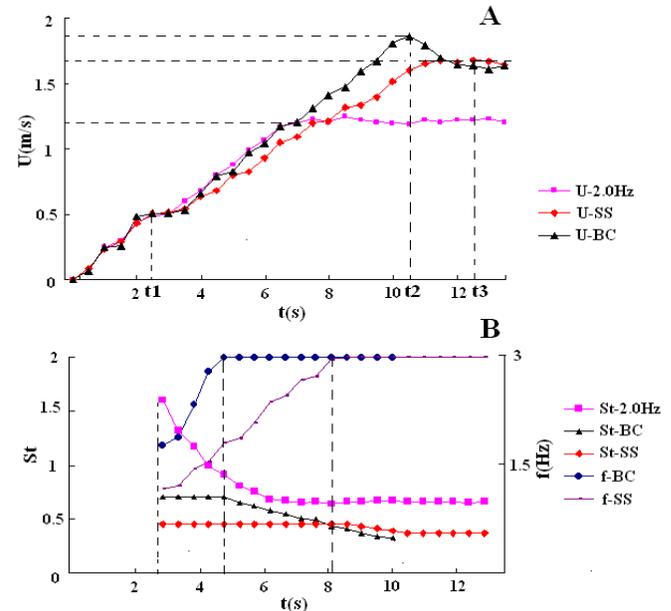


Fig. 7. Straightline maneuverability experiment result (U indicates the speed, St was strouhal number, f indicates flapping frequency)

TABLE II  
PERFORMANCE OF FLAPPING FOIL UUV

Value	FLVC BC	FLVC SS	2.0Hz
Power(w)	61	57	75
Yaw	7	5	8
Amplitude ( $^{\circ}$ )			
Average Speed (m/s)	1.31	1.21	1.07

For  $St$  numbers in these three swimming modes as shown in Fig. 7B above, the  $St$  numbers for 2.0Hz swimming located between 0.68~1.65 and it is uncontrollable here, while the  $St$

numbers of BC and SS are controlled within 0.32~0.6 and 0.35~0.45 respectively, good thrust performance was achieved. It shows that:

1. St number can reflect the swimming performance indeed;
2. Adopting FLVC controller with proper maneuverable motion can realize speed control at the same time thrust efficiency of vehicle can be improved.

By carrying a water quality testing instrument, "SPC" made a 50.79km voyage and achieved an endurance of 11.7h during the water quality testing experiment in Taihu Lake and made its own contributions to the environmental protection.



Fig.8. SPC swimming in Taihu lake

## VI. Conclusion

This article introduced the idea that setting up fuzzy logic vorticity controllers according to speed feedback can give ideal vehicle maneuver performance both on speed and power consumption. Since the 2-D oscillating foil mechanism is seen as the basic model for biomimetic thrust kinematics&dynamics modelling, this control method can also provide effective way of high-efficiency thrust mechanism for pectoral fin swimming as well as flapping&hovering flight et al, further researches will focus on the self-learning for vorticity control so as to get a better vehicle performance and make the high-efficiency swimming of UUV more adaptive to different circumstance.

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