Experimental Design and Performance of Underwater Vehicle based on Capacity of Voyage

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***Abstract*—The SPC-3 UUV robofish prototype is an experimental vehicle especially designed to improve efficiency of thrust and capacity of voyage based on the SPC-2 UUV robofish by Beijing University of Aeronautics and Astronautics. According to the record of power acquisition computer and camera which is used to measure the power and velocity of SPC-3 UUV in the still water, the speed-frequency and power-frequency curve were bulit. According to the estimation of capacity of voyage, the voyage time and voyage on condition of different frequency of flapping foils were calculated, the propulsion frequency could be selected base on the cruising velocity as well as voyage capacity. Experimental result of the long voyage performance in Bei Daihe showed that SPC-3 UUV achieved 22.761 kilometers, and its voyage time was 6.25 h, and obtain a average cruising speed as 1.03 m/s using the optimal frequency ranging from 1.5~1.6Hz of the flapping foils.**

***Keywords*—bionics, propulsion, unmanned undersea vehicle**

I. INTRODUCTION

In the 20th century, underwater vehicle technologies had become a major way for human to explore in the oceans. Since 1950s， UUV (Unmanned Underwater Vehicle) started to develop, mainly used to surveillance the situation and explore underwater oil pipeline. In the 1970s and 1980s, to meet the demand of the United States' Navy, UUV was gradually used for surveillance,detection, mine exploitation,communications,and other missions. Now as a advanced underwater weapon, UUV drawed more attention.Many countries had increased investment into this field. In January, 2005, the United States navy issued a new program, which clearly pointed out the UUV need further research in technologies of power system, thrust system and automatization. The program classifies UUV into four types: portable, light, heavy and large. The portable UUV is clearly prescribed to be under the mass of 45.4 kg[1]. as well as the diameter range from 3 and 9 feets. The portable type should have 10-20 hours' continuous capacity of voyage.

In 2003,the Woods Hole Oceanographic Institute developed "REMUS" with airscrews as its thruster. It weighs 36.5 kg and possess of 22 hours' continuous work underwater at a speed of 3 kts(knots per hour). In the same year, Beijing University of Aeronautics and Astronautics developed a bionic robot SPC-2, which had got a mass of 45 kg. In still water test, the velocity of the vehicle could reach 1.15m/s(that means 2.3 kts) when its flapping foils waving at the frequency of 2.5 Hz, the power consumption reached 240w, during the Bei Daihe sea perforamance in 2004, it achieved 3.4 kilometers, and voyage time was 2.3 h[2].

Although the bionical flapping foils which imitates the caudal fin of fish have more potential advantages than airscrew thruster in propulsion efficiency as well as flexibility, SPC-2 experimental results show that a lot of work still needs to be done to enhance capacity of voyage and reduce power consumption of the vehicle as well.

II. CHARACTERISTICS OF VEHICLE

The SPC-3 UUV prototype is an experimental vehicle which is especially designed to improve efficiency of thrust and capacity of voyage based on the SPC-2 by Beijing University of Aeronautics and Astronautics. SPC-3 has perfect automatic control ability including attitude close-loop control and GPS navigation control. Compared with SPC-2, it could keep the attitude of yaw and roll as well as pitch for 3-axis gyro were assembled. In order to reduce the drag and obtain higher thrust efficiency and greater capacity of voyage, the optimal design of SPC-3 has the following characteristics:

1) Using a torpedoes-like droplets streamline. Its body length –diameter ratio is about 7.3 and the thrust carbin just take about 7% of the total displacement;
2) The energy cost of entire thrust system had been analyzed and an optimal mechanical framework has been taken, and the energy loss had been reduced to about 15 w, the whole power consumption of the elctronic part is only 3.5 w. Ultra-low power control and navigation systems based on the use of inertial MEMS devices are used to make the power consumption of the antopilot reducing to only 1.2 w;
3) SPC-3 chooses a titanium as its material for flapping actuator organ and a carbon-fiber caudal fin to minish power loss while the flapping foils were actuated.

III. VEHICLE DESIGN

The body parameters of SPC-3 UUV platform are shown in Table 1.

Table Ⅰ. SPC-3 body parameter

UUV	Length /m	Displacement /kg	Surface acreage $/m^2$	Total mass /kg
SPC-3	1.60	41	0.875	46

The mechanical structures of SPC-3 could be divided into three parts: head cabin, main cabin and thrust cabin. The cybernetic system framework of the vehicle can be divided into navigation and automatic control module, power and motor-amplifier module and thrust system module.

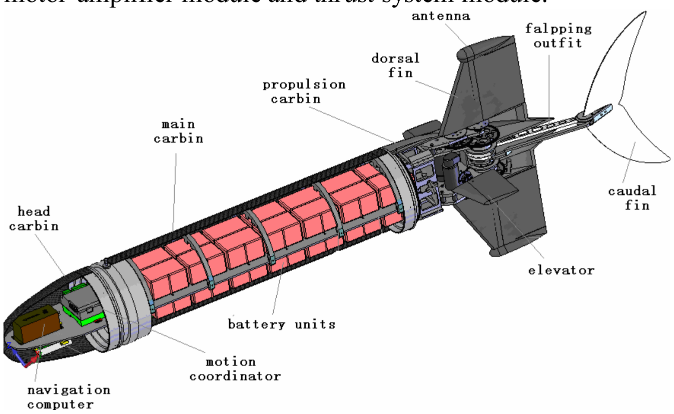

Figure 1. view of SPC-3 UUV layout

A. Navigation and automatic control system

An automatic control and navigation system was used in SPC-3, which integrates a GPS (Global Position System) and other inertial MEMS devices . A set of elevators were installed in order to maintain the fish swimming in the designated depth under the close-loop control of a press sensor. The main cybernetic control system of the vehicle consists of three units: communication and mission tasks control unit, bionic flapping actuator control unit as well as autopilot and navigation unit. With the cooperation of these 3 units, SPC-3 UUV can work in 3 modes: manual control by operators , cruising control by inertial MEMS devices, GPS location control.

B. Power system

Installed in the main cabin, the power battery consists of 26 pieces of lithium polymer batteries. Every two of them were combined as a group. At the same time an effective power management method was used, afterward, a printed board circuit was designed and electromagnetic compatibility issues were carefully solved as well to ensure power management system more reliable. In order to make sure of the battery discharging characteristics, the battery discharging experiment had been carried out through multiple discharge process during the work mode of vehicle, i.e. flapping foils were actuated. The discharging curve is shown in Figure 2.

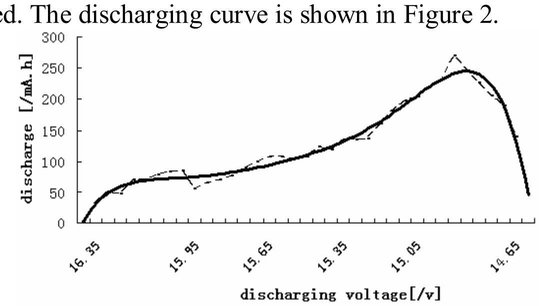

Figure 2. Discharge of lithium-polymer battery test

As shown in Figure 2, the maximum voltage of a single battery is 16.4 V. When the battery voltage is reduced to 14.65V, the discharging capacity dropped rapidly. For the entire vehicle system works under heavy load conditions, whether the thrust system works well depends on the discharge capability of the battery. A new set of batteries should be switched on while one piece of battery reduced to its cut-off discharge voltage as 14.65 V. It could be calculated that a single piece battery discharging capacity was about 4970 mAh. Therefore, when a group of batteries works, the cut-off discharge voltage should be around 29.2 V, with a discharge capacity of about 9940 mAh.

IV. VEHICLE-CRUISING EXPERIMENT

According to the experiments of the vehicle in a 25-meter-long swimming pool as a circumstance of still water, the flapping frequency of the foils(f)-vehicle cruising speed(v) as well as f-power consumption(w) curve of SPC3-UUV in still water had been founded.

A. f-v test of the vehicle

The experiment to test the speed of vehicle in the still water were carried out as follows: a digital camera is fixed on the side of the swimming pool which was paralle to the vehicle's cruising direction. There are two visible marks on the body of SPC-3 with a distance D between the two. When the vehicle travelled through the field view of the digital camera, the time difference ΔT between the two marks which entered the field of view successively had been recorded, thus,the instantaneous velocity was obtained: v = D / Δ T.

Using the experimentation above, we tested the velocity of the vehicle with flapping frequency of caudal fin ranges from 0.6 to 2.0 Hz, sampling every 0.2 Hz and record. According to the analysis of the data, the velocity is proportion to flapping frequency. fitting data using least-squares procedure in Matlab, the f - v curve was obtained as shown in Figure 3:

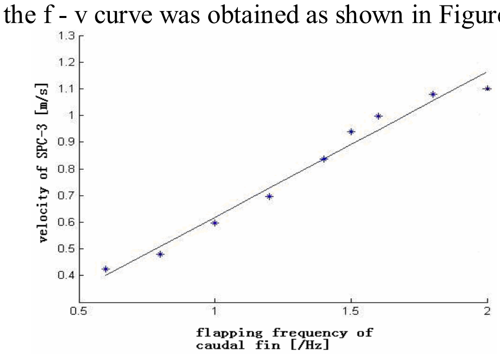

Figure 3. v-f curve of the vehicle

The f-v fitting- formula was considered:

$$v(f) = 0.5917 \times f + 0.007667 \qquad (1)$$

B. frequency-power test of vehicle

In the same experimental environment, the procedure to find out the relationship between the flapping frequency of caudal fin(f) and power consumption(w) in the still water was as follows: the voltage(V) and electronic current(I) of the thrust system were sampled 500 times per second according to a 12-bit PC104 data acquisition computer built inside. The calculated and power(which can be caculated as $W = U \times I$) had been record per second and transfered to the computer of the operator immediately.

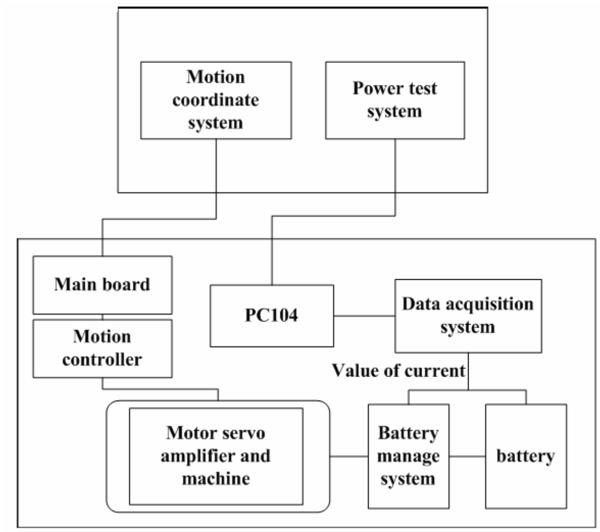

Figure 4 Data acquisition of power system framework

Fluid resistance R_T was calculated as:

$$R_T = 0.5 \times \rho \times V^2 \times C_d \times \Omega \quad (2)$$

Where ρ is fluid density, v is velocity of vehicle, C_d is Flat resistance coefficient, Ω is platform surface.

Meanwhile, the power consumption were considered as follows, a calculation relationship with vehicle velocity.

$$W = R_T \times v = 0.5 \times \rho \times V^3 \times C_d \times \Omega \quad (3)$$

As the velocity (v) is proportion to flapping frequency of the foils(f), i.e. the power consumption(W) and flapping frequency of caudal fin (f) character curve could be fitted using least-squares procedure as shown in fig.4, the fitting-formula was considered as follows:

$$W = -48.41 \times f^3 + 201 f^2 - 182.6 f + 57.27 \quad (4)$$

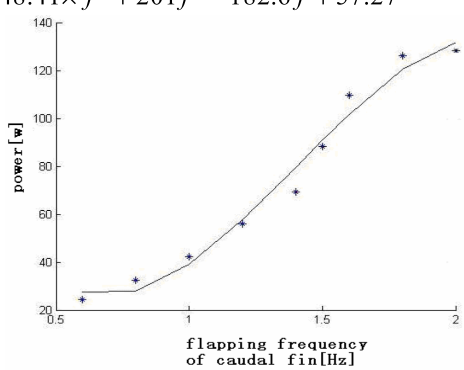

Figure 4. w-f curve of vehicle

Ⅴ Voyage estimation and frequency selection

Voyage of single battery unit as well as the voyage time distance could be estimated as follows:

$$S = (Q / W) \times V \quad (4)$$

$$T = Q / W \quad (5)$$

Where Q is battery discharge capacity as tested above in section Ⅲ, S for the voyage distance, W for the power consumption of the vehicle, V for the velocity of the vehicle.

Based on the caculation above, according to formula(1) and (4), the voyage distance of single battery unit(S)-flapping frequency(f) was considered and the charceter curve was shown in Figure 8:

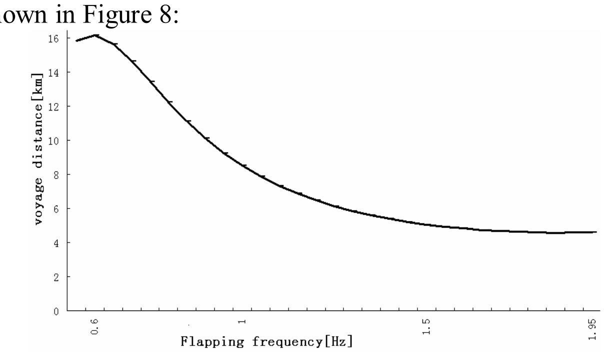

Figure.5. S-v estimate character curve

And the voyage time(T)-flapping frequency(f) character curve was shown in Figure 6:

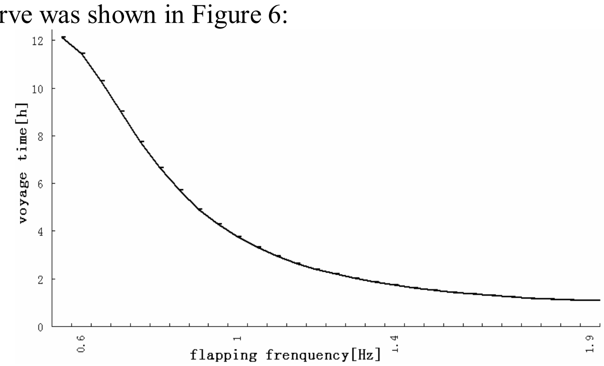

Figure.6. T-v estimate character curve

According to fig. 3, fig.5 and fig.6, it is concluded that:

the vehicle could keep a cruising speed of more than 2 kts with a flapping frequency of 1.5Hz of the foils. Voyage capacity estimates is almost the same range from 1.5 to 2.0Hz , but the weakest among the range of 0Hz~2.0 Hz. The voyage time estimates of single battery unit varies around 15min range from 1.5 Hz to 2.0Hz.

Thus, a long voyage performance should consider the following criterion:

Taking into account that the minimum cruising speed should be maintained at least 2 kts.Voyage distance and time should be the main criterion while chosing its working mode for thrust, i.e.,the flapping frequency of the foils should follow the criterion.

Too many unknown factors should be taken into account while the vehicle doing its first performance, heavy-load working mode on condition that high frequency of flapping foils (2.0Hz and above)will make the vehicle unstable, according to the analysis, the cruising speed and capacity of the voyage obtained a relationship of inverse proportion. The final choice of working mode was ranging from 1.5 to 1.6Hz as the flapping frequency actuating of caudal fin for Bei Daihe long voyage performance.

V. VOYAGE PERFORMANCE OF VEHICLE

A. *Analysis of long voyage performance*

On October 11th, 10:29 am, in Beidaihe, after final testing and data communications check, the SPC-3 UUV cruising in east-southeast direction of 19 ° on the navigation working mode. Operators on the boats followed and observed the performance. The experiment ended on the same day at 17:20pm. GPS track graph of the whole process of long voyage experiment (with flapping frequency at 1.5 ~ 1.8 HZ) was shown in Figure 8:

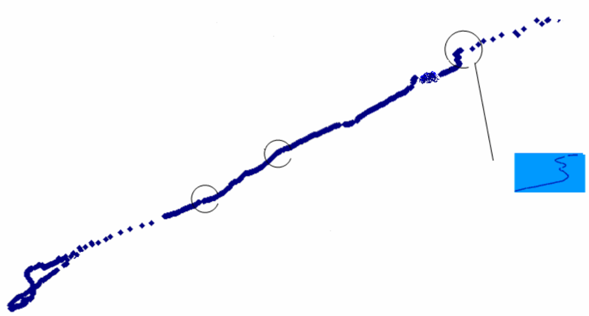

Figure 7. GPS track of long voyage performance in Bei Daihe

During the experimental process, total breakdown time for vehicle system is 50 min. The main cause of the malfunction was that motor of the thrust suferring overheating problems and then stopped working. According to the information feed back from GPS, among all the batteries, No. 3 lasted for 5.441 km and 81 min. The average cruising speed reached 1.12 m/s. Since there are totally 13 sets of batteries units inside the vehicle, the following conclusions are presumed:

Assume that there is no failure for the thruster, with the flapping frequency at 1.5-1.6 Hz, the cruising time of SPC-3 UUV would be 17.5 h, as well as the voyage achieved 70.733 km, with an average speed of 1.12 m / s.

B. Comparison with the estimated results

Table Ⅱ Contrast between estimate and experiment conclusion of voyage

value	Voyage /km	Voyage time /h	Cruising speed m/s
Eatimate result	5.144	1.57	1.57
Experiment result	5.441	1.37	1.12

Compared with the voyage capability estimation of single set of battery in Section Ⅴ, the experimental result was 297m shorter than the estimation with the voyage time 12 minutes longer than the estimation as well as cruising speed 0.12m/s higher than the estimation, as shown in table Ⅱ . Because of the oceanic fuction, the difference between the experimental data and the estimation was accessible.Anyway, the comparation still showed the accuracy of the voyage estimation, and useable.

C. Comparison with the domestic and international UUV

Table III Contrast between SPC-3 UUV and other UUV

UUV	Body length/m	Diameter /m	Voyage /km	Voyage time /h
REMUS ,Woods Hole 2003-2004	1.60	0.19	118	22
Bass JAPAN	1.6	0.2	26.4	8
SPC-2 UUV Beihang unvercity	1.4	/	5	2.5
SPC-3 UUV Beihang unvercity	1.6	0.21	70.7	16.7

According to the standard of United States "Unmanned Undersea Vehicle overall plan", SPC-3 UUV should be in small portable UUV series. As shown in Table 4, the voyage capacity of SPC-3 UUV has little difference with the other UUV propellers of most other countries, but remains a certain distance with REMUS UUV of United States, which has been used to remove coastal mine in Iraq war.

VI. CONCLUSIONS

SPC-3 UUV uses a torpedoes-like droplets streamline and designed to have a new exterior and structure as well as material, the energy cost of entire thrust system had been analyzed and an optimal mechanical framework has been taken. These series of optimal design were in principle of the vehicle reliability and keeping the total mass still, the vehicle performance during the Bei Daihe experiment showed that the voyage capability had been improved distinctly, meanwhile, the following summary had been made:

1) Bionic flapping foils thrust vihicle could also take a long voyage mission, and it has potential advantage in aspect of mobility, low-noise compared with the airscew thruster.

2) The reliability of thrust system should be enhanced in an other step, while Bionic flapping foils thrust vihicle should take into account that optimize the design of the framework to make the vihicle low-noise, low-power consumption,as well as heavy-load.

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REFERENCES

[1] Anderson J,M , Kerrebrock PA.The vorticity control unmanned undersea vehicle(VCUUV) -an autonomous vehicle employing fish swimming propulsion and maneuvering . In: Proc.10th Int. Symp. Unmanned Untethered Submersible Technology, NH. 1997, 9: 189～195

[2] Liang Jianhong Zou Dan Wang Song Wang Ye. Trial voyage of SPC-2 fish robot [J]. Journal of Beijing University of Aeronautics and Astronautics. 2005,31(7):709-713

[3] M.S. Triantafyllou, M.S. Barrett, D.S. Yue, etal. New paradigm of propulsion and maneuvering for marine vehicles [J]. Trans Soc Naval Architects Marine Eng, 1996, 104: 81-100

[4] D.S. Barrett, M.S. Triantafyllou., etal. Drag reduction in fishlikelocomotion [J]. Journal of Fluids Mechanics. 1999, 392: 183-212

[5] Liang Jianhong,Wang Tianmiao,Wei Hongxing, ecal. Research and development of underwater robofish I- development of a small experimental robofish[J]. ROBOT,2002, 24(3): 234-238

[6] Liang Jianhong, Propulsive Mechanism of Bionic Undersea vehicle[D]. Beijing: Beijing University of Aeronautics and Astronautics,2006