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Submersible Unmanned Flying Boat: Design and Experiment

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***Abstract*—A real submersible flying boat which is both flight-capable and submersible has hardly been reported yet. In this paper, the Flying Fish created by Beihang University will be introduced to verify the feasibility of this kind of novel aircraft. The Flying Fish achieves its ability to transfer between the air and the water by imitating the flying fish and aquatic birds. The morphological characteristics of the flying fish and the variable density method of the aquatic birds are imitated in the design of this novel aircraft. Moreover, the technological deficiencies of this vehicle have also been concluded through the experiments, which can be referred to by the relative future studies.**

I. Introduction

A vehicle that is both flight-capable and submersible has aroused wide concern, for its advantages of maneuverability in the air and imperceptibility under the water [1]-[7]. There are lots of problems existing to design this kind of vehicle, for the properties of the air and the water differ from each other to a great extent [6], [7]. The most basic problem is how to make the vehicle transfer between the two media with high efficiency [8], [9].

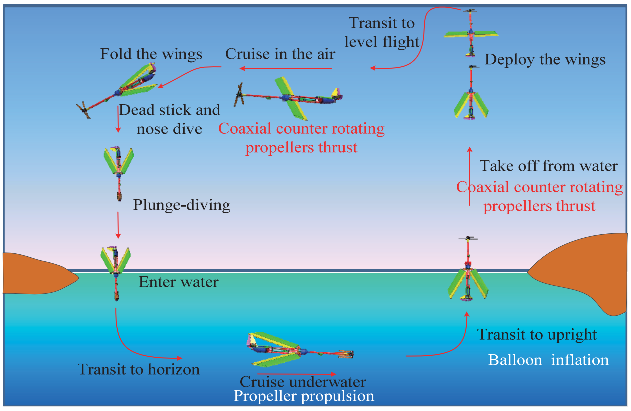

Fig. 1. Plunge-diving and vertical take-off mode [10]

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As to this problem, according to the previous studies, there are two main modes to realize it [11]. The first is plunge-diving and vertical take-off mode, as illustrated in Fig. 1. It is a bionic method inspired by the underwater prey process of aquatic birds, which was firstly public aroused by Hawkes on 2010 [6]. After that, Beihang University and MIT Lincoln Lab released their gannet inspired prototypes respectively [7], [12]. The researchers of Beihang University have also carried out many pioneering experiments to study the mechanism of gannet's plunge-diving process [8], [9], [13], [14].

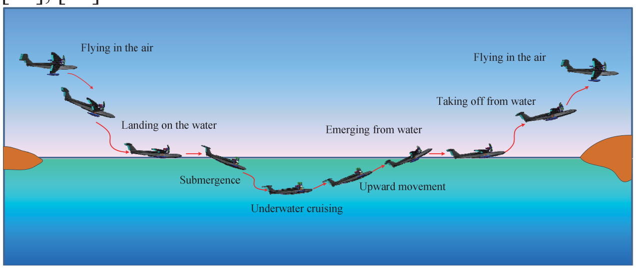

Fig. 2. Soft landing and taxiing take-off mode

The second is soft landing and taxiing take-off mode, as illustrated in Fig. 2. It is a combination vehicle of a flying boat and a submarine. During the operation process above the water, the vehicle is just like a flying boat. After absorbing enough water using the water pump and diving into the water, the vehicle is similar to a submarine. With the method of water volume adjustment, the vehicle can meet the density requirement both in the air and underwater. However, due to the large diversity of flying boat and submarine, it still remains numerous technological problems to be solved [6][9]. And many experiments on the aerodynamic shape, drive form, control strategy, structural efficiency and material strength should be carried out.

However, submersible flying boat with the ability of soft landing and taxiing take-off has hardly been reported yet. In this paper, a submersible unmanned flying boat named Flying Fish, which has being created by Beihang University from 2009, will be introduced to verify the feasibility of this kind of vehicle for the first time. And the technological problems about this kind of vehicle will also be concluded through the experiments, which can be referred to by the relative studies in the future.

This paper is organized as follows. Section II presents the operation concept of the Flying Fish. In Section III, we analyze the performance requirement. The development of the Flying Fish is described in Section IV, which includes the motion mode decomposition, airframe design, swept wing mechanism, propulsion system design, water volume regulation system and power supply system design. Section V presents the experimental results. Finally, conclusions and future work are drawn in Section VI.

II. Concept of the Operation

Fig. 3. The Flying Fish and a biological one [15]

This submersible unmanned flying boat (Flying Fish) imitates the aquatic-aerial ability of flying fish, which specializes in the sea surface taxiing take-off and soft landing [16]-[18]. As presented in Fig. 3, the morphological characteristics of the aerodynamically designed vehicle are similar to a biological flying fish. The Flying Fish also absorbs the merits of flying boat, such as boat–type airframe and step-type hull. Besides, with the imbedded water pump, it can dive into the water by injecting water into the water tank, and climb up on top of the water by draining away the tanked water. Interestingly, aquatic birds also apply their biologic variable density method to transfer between the air and the water, which is also depending on the regulation of the water quantity attached [19]-[21]. The attitude adjustment of underwater can be obtained by controlling the surface of the T-type tail fin. Moreover, if the Flying Fish does not fold its wings, the lift force created by the interaction of the wings and the water may make it hard to submerge. As to the flying fish, no one attempts to swim in the water without folding its wings. Therefore, variable 90° sweptback-wing mechanism are designed. The sweptback wings can also reduce the resistance of moving in the water.

The Flying Fish can be used to assist a submarine to accomplish reconnaissance and attack task. After been released from a submarine at the depth of 10 m, it may navigate upstream to the waters where is 1-2 meters below the water surface. With the underwater propulsion system and attitude regulation system, the Flying Fish can cruise autonomously underwater. When it needs to transfer to the air, it would firstly climb up on top of the water by draining away the tanked water, and then take off from the water surface just like a flying boat. The Flying Fish can fly 50-100 meters high in the air with the speed of 65-85 km/h for about 20 minutes. After having completed the air mission, it would soft land on the water surface and then sweep back the wings and dive into the water by absorbing water into the tank. In the water, it can be retrieved by the submarine again or cruise to the secluded and secure place by itself.

The principal design parameters of the Flying Fish are listed in Table 1.

Table 1
The Principal Design Parameters of the Flying Fish

Parameter	Value	Parameter	Value
Gross weight	12.0kg	Body length	1.98m
Wing span	3.4m	Aspect ratio	15.0
Wing area	1.5m^2	Thrust-weight ratio	>0.6
Flight speed in the air	65-85km/h	Conventional flight altitude	50-500m
Cruising speed underwater	0.2-0.5m/s	Conventional cruising depth	1-2m

III. Performance Requirement Analysis

Since the physical properties of the air and the water differ from each other to a great extent, the characteristics of the flying boat and the submarine are significantly different. The flying boat that can float on the water and fly in the air must be designed to be light and possess good aerodynamic characteristics, while the submarine should be designed to be dense and possess good hydrodynamic characteristics. Therefore, the development of a high-performance submersible unmanned flying boat is concentrated on the efficient method of combining the characteristics of the flying boat and the submarine. That is to say, we must learn how to design an aquatic-aerial vehicle that is capable to transfer configuration between a flying boat and a submarine.

Some main differences between these two kinds of vehicle and the strategies we obtained in this article are presented in Table 2. It is observed that the airframe shape, propulsion mode, density, fluid characteristics are the key factors to design a high-performance submersible unmanned flying boat.

Table 2
The Main Differences Between the Flying Boat and the Submarine

Parameter	Flying boat	Submarine	Strategies
Kinematic velocity	Faster compared with the submarine	Slower compared with the flying boat	Dual drives; elongated shape
Density	Much smaller than the water	Close to the water	Water volume regulation system
Water discharge	Small, about 10%	Large, about 100%	Water volume regulation system
Configuration	Combination of airplane and boat	Streamline and water-drop shape	Sweptback-wing mechanism
Driving force	Aerodynamic force	Hydrodynamic force	Dual drives

IV. Development of the Flying Fish

A. Motion mode decomposition

Flying Fish is the combination of seaplane and submarine, as a result, its motion can be classified into flying boat mode and submarine mode. The functions of flying boat mode contain water surface movement, water surface taking-off, flying in the air, and water surface landing. The functions of submarine mode contain submerging, cruising underwater, floating, emerging from the water. Therefore, the motion can be classified into 6 statuses, as shown in Fig. 4

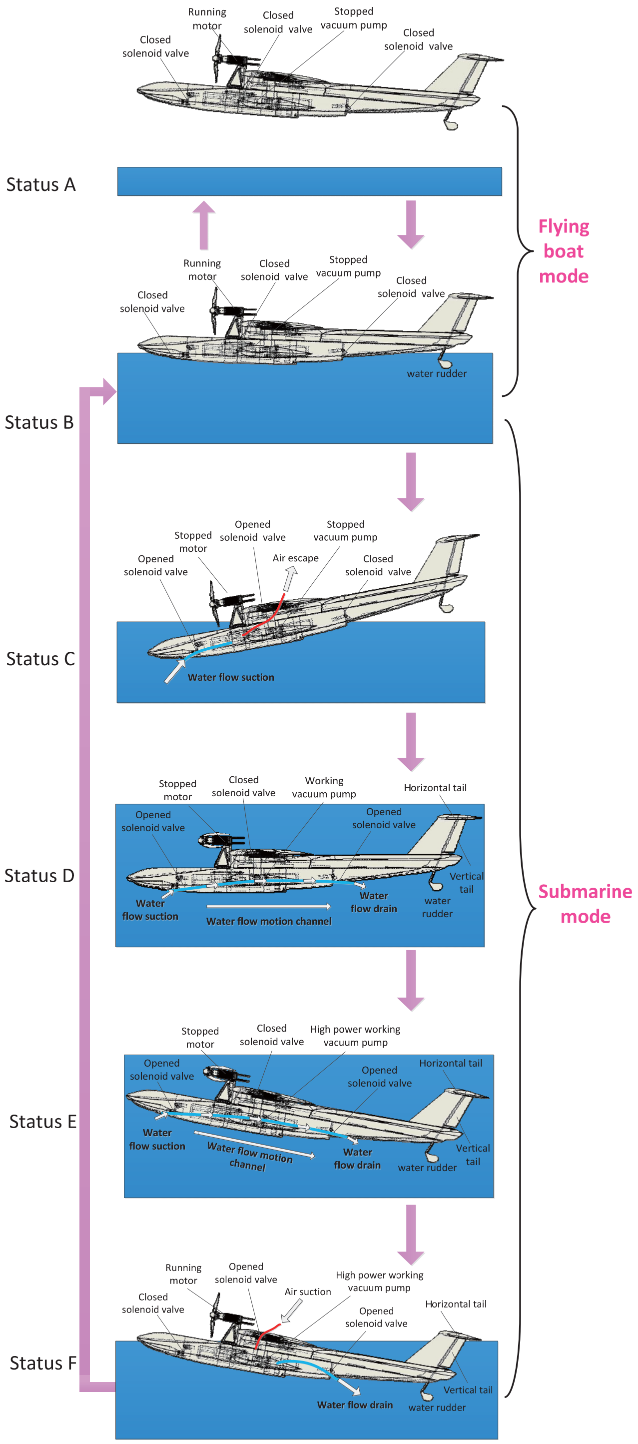

Fig. 4. Motion statuses of the Flying Fish

Status A: Flying in the air

This status is coincident with the status of seaplane flying in the air. The high-power brushless motor is used to drive the paddle propeller to generate aero propulsion, which can realize flying in the air with lift produced by the wings.

Status B: Floating on the water

This status is basically similar to the floating status of traditional flying boat. The main characteristic is low-draft floating. 10% of the fuselage is underwater, the water storage of the cabin is less than 1%, and the wings are expanded completely. In this status, the solenoid valves are closed, which can seal the entire watertight cabin, the centrifugal pump is stopped, and the whole water supply and drainage system is in the stand-by mode.

The high-power brushless motor drives the paddle propeller to generate aero propulsion to promote the fuselage gliding. The moving orientation is controlled by the water rudder which is linked with the vertical tail.

If the lifting-line of the propeller is slope upward, and the motor's working condition is under high-power condition, the water surface gliding can be realized.

Status C: Submergence

This status is the transforming progress from flying boat to submarine. The submergence is realized by increasing the integral density by inundating the watertight cabin. Firstly, Flying Fish sweeps back the wings for 90 degrees, so that they can cling to the fuselage. In this way, the layout which is suitable for flying in the air is transformed into the layout which is suitable for cruising underwater. Then open the solenoid valves locate at the front and the top of the fuselage. The water inlet and air exhaust port work respectively. Under the affection of the weight, water can infuse into the main cabin which has the largest fuselage proportion. Meanwhile, water starts to infuse into other permeable structures, like the wings. The integral density starts to increase and the vehicle submerges under water autonomously.

Status D: Underwater Cruising

In this status, the integral density is similar with water. The main cabin and water supply and drainage system has been filled up with water, and almost all air is excluded. Other components like wings have also accomplished the internal dynamic permeability.

The working mode of the Flying Fish is similar to the submarine now. The underwater propeller will use water-inject propulsion to manage cruising. Firstly, the solenoid valves of water inlet and water outlet are opened, the top air valve is closed. Then activate the centrifugal pump, which shape the water flow at the head and the bottom into "water motion channel". Because the conservation of momentum between the aircraft and the water flow in the water supply and drainage system, the aircraft is able to move forward. In addition, the aircraft can adjust the integral underwater attitude by underwater control surface.

Because the whole aircraft submerges under water, the body structure and seal assembly will encounter tremendous water pressure. The Flying Fish cannot dive too deep and ordinarily cruises at 1-2 meters depth.

Step E: Upward movement

In this status, the water supply and drainage system continue to serve the function as propeller. Make the pump working at high-power condition and change the steerage of horizontal tail control surface, so that upward force moment is generated by the combination of gravity, buoyancy, and fluid pressure difference. In this way, the upright component of propulsion is increased, which makes the aircraft sailing to the water surface.

Step F: Emerging from water

When the aircraft sails to the water surface autonomously and the top ventilation pipe stick out of the water, open the top air seal valve, and close the water inlet solenoid valve which locates at the head of the fuselage. The seal space is formed in the front fuselage, and the air enters the fuselage through ventilation pipe, and fills the seal cabin naturally. Meanwhile, the water outlet solenoid valve is opened, and the centrifugal pump works in high-power condition. Most water in the cabin will be excluded from the bottom water outlet.

When the water capacity in the cabin is less than 5%, the system will close the water outlet solenoid valve and the top air seal valve, and unfold the wings. By that time, the underwater returning process is completed, and the aircraft will begin to float on the water. The rest water in the main cabin can be excluded when the Flying Fish starts to takes off from the water. As a result, the payload of the aircraft will be reduced, which can reduce the energy consume.

B. *Airframe design*

The total resistance of the taking-off process of the seaplane is constituted of aerodynamic resistance and hydrodynamic resistance. Thereinto, the hydrodynamic resistance can be divided into gliding resistance, fraction resistance, and wave resistance. And the hydrodynamic resistance mainly depends on the configuration of the aircraft's fuselage. Therefore, to realize the high-speed and efficient taking-off from water surface, the optimization design of the appearance of the fuselage is very necessary.

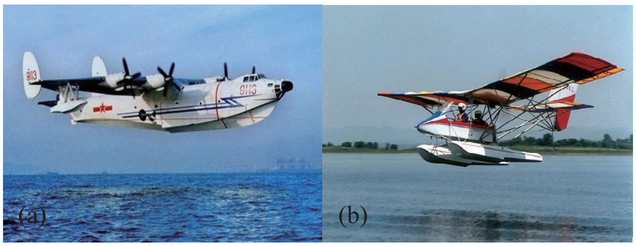

Fig. 5. Seaplane classifications. (a) Flying boat; (b) float plane.

The seaplane can be classified into flying boat and float plane according to the structure, as shown in Fig. 5. The buoyancy of the float plane is mainly provided by the buoy of the undercarriage. Because the sectional area is large and the shape is decentralized, the underwater motion of the float plane will generate large resistance. In addition, the main body of the aircraft will not contact the water, and possess high center of gravity, which means it is difficult to enter water. Meanwhile, the buoyance of the flying boat is provided by the belly of the fuselage. The buoys of the wings function as an auxiliary balance equipment. This kind of seaplane possesses the characteristics of deep-draft, and compact structure, which makes it suitable for the design of entering water. As a result, the Flying Fish adopts the configuration of flying boat.

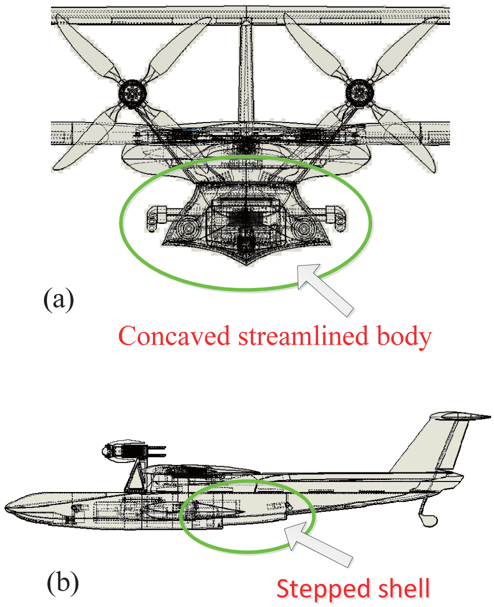

Fig. 6. Airframe characteristics of the Flying Fish

As shown in Fig. 6 (a), to overcome the large fraction resistance and viscous drag during the water surface taking-off process, the shell of the bottom of Flying Fish, which contacts the water surface, is designed to be concave streamline bottom shell. When the shell slips on the water surface, this kind of design will generate large upward differential pressure lift, which can make the aircraft to take off from the water.

As shown in Fig. 6 (b), two stepped shell structures are designed at the belly of the fuselage, which is adjoin with the water surface. When the head of the fuselage rises above the water, great acceleration will generated by the slip between the stepped part and the water surface. This is the key point for deep-draft aircraft to take-off from water surface.

In addition, in order to reduce the hydrodynamic resistance, large slenderness ratio was introduced to the design of the fuselage. Wing buoys are also designed to balance the aircraft floating on the water. The streamlined morphology of the wing buoys is similar to the fuselage. The wing buoys can also do fixed-axis rotation to make their axes consistent with the movement direction of the aircraft, when the wings are swept back.

C. *Swept wing mechanism*

F-14 fighters, MiG-23 fighter, B-1 bomber, Tu-160 bomber all utilize backswept wing structure to realize variable structure aerodynamic layout. They stretch wings to increase the taking-off lift, and sweep back wings to reduce the resistance of high speed flying. Referring to this, large lift can be generated when the Flying Fish stretches its wings, which is benefit for the taking-off process. Meanwhile, when the wings are swept back, it possesses streamline fuselage, which is suitable for cruising underwater.

As shown in Fig. 7, the guide screw-slider device is adopted to the design of the swept wing mechanism. The modified high torque metal gear servo (FUTABA S9206, 9.5 kg • cm at 4.8 V) drives the screw, the screw makes the slider move straight reciprocating, and the slider drives the parallel motion of two linkage groups. It will make the wings stretch and fold synchronously, and acquire the ability of self-lock.

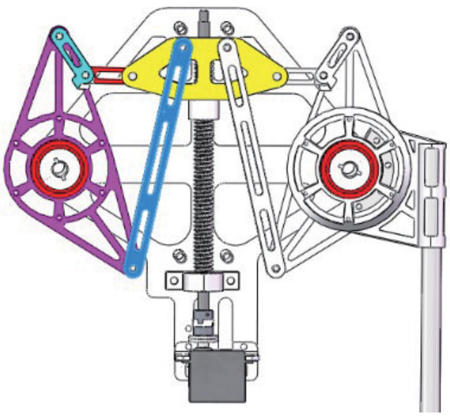

Fig. 7. Swept wing mechanism

In addition, ZAGI 12 standard wing with the aspect ratio of 15 is adopted, which is thick enough and possesses idea intensity, bending resistance, and vibration resistance. The appearance of wings is elliptic, that is the front of wings is swept back as curve, and the back of the wings is in a straight line shape. The purpose of this design is to make the wings form into streamline shape when swept back. This can decrease the vorticity of the tail-edge shedding vortex and the induction resistance. Meanwhile, the wings with 90 degrees backswept angle can weaken the differential pressure lift effect of wing structure. As a result, the aerodynamic structure interference to the underwater cruising can be excluded

D. *Propulsion System Design*

As a result of the great difference between the properties of the water and the air, the seaplane mode and submarine mode should adopt different propulsion style.

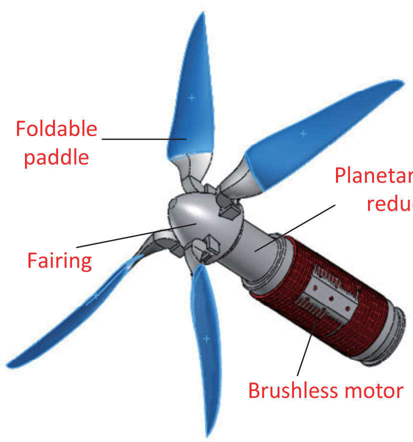

Fig. 8. Foldable screw propeller

In seaplane mode, double propeller propulsion is adopted. The thrust-weight ratio is 0.5-0.7.The high-power inner rotor brushless motor matched with planetary gear reducer, can drive the propeller to realize propulsion. As shown in Fig. 8, each propeller hub can drive four-leaf foldable sabre type carbon paddle, and the fairing is also equipped.

In submarine mode, the water-injection style is adopted. Utilizing "water motion channel" from the front of aircraft to the bottom of the aircraft generated by centrifugal pump, the water-injection propulsion can be realized. It should be noted that the prototype in this mode possesses very low velocity, and the performance should be improved by optimizing the relative design parameters, for instance, using centrifugal pump with higher power.

E. *Water volume regulation system*

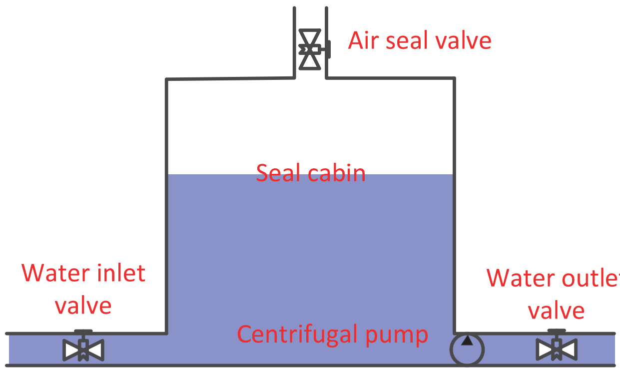

Fig. 9. Water supply and drainage system

As shown in Fig. 9, the water supply and drainage system of this aircraft is constituted of seal cabin, water inlet valve, water outlet valve, air seal valve, and centrifugal pump. The adjustment of the water volume in the seal cabin is realized by the collaboration of the logic relationship between the valves, working status of centrifugal pump, and the motion status of aircraft. In this way, the integral density of the aircraft is changed.

In addition, wings, empennage and the mechanical cabin at the back of the aircraft, are all permeable shells, which can increase the density autonomously after the aircraft entering the water.

F. *Power supply system*

To meet the request of high power density and large current of inner rotor brushless motor, lithium polymer battery with the characteristic of high power, large capacity, little volume, lightness, and the ability of large current discharging is used.

The ultimate parameters of the lithium polymer battery are shown as the following: The single voltage is 3.7-4.2V. 6 cores are combined in series, and 2 groups are combined in parallel. The total voltage is 22.2V-25.2V, the total capacity is 4400mAh, and the total weight is 750g. The standard discharging current rate is 18C (79.2A), and the instant extreme discharging current is 25C (110A). According to the experiment, these indexes can meet the technical requirement of experiment prototype.

V. EXPERIMENT AND RESULTS

To investigate the application performance of the submersible flying boat, and find out the shortcomings that need to be improved, some experiments have been carried out in the Huairou Reservoir of Beijing, as shown in Fig. 10.

Fig. 10. Field tests of the Flying Fish

The experiments having been performed include the floating and taxiing, the takeoff and landing, submerging and emerging and underwater cruise experiments. The experimental results on the main parameters of the Flying Fish are presented in Table 3.

TABLE 3
RESULTS OF THE EXPERIMENTS

Parameter	Value
Takeoff distance	More than 30 meters
Landing distance	More than 40 meters
Transition time from flight to submerging	About 15 minutes
Transition time from submerging to flight	About 20 minutes
Cruising speed underwater	0.2-0.5 m/s

The results indicate that the Flying Fish has basically achieved the functions of both operating in the air and underwater, but it is in poor performance. The transition time between the flying boat and submarine is too long, and the cruising speed underwater is rather slow. In addition, the taxiing trajectory is hard to stay straight when the surface of the water has been stirred violently.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, the Flying Fish designed by Beihang University was introduced to verify the feasibility of the novel aircraft: submersible flying boat. The design concept was confirmed by the field experiments. According to the experiments, it indicates that this kind of aircraft is capable of both flying in the air and swimming underwater, but with poor transition performance underwater propulsion capability. Many problems are to be studied and solved before making a practical submersible flying boat. Meanwhile, some design criteria should also be made to evaluate the design concept.

Further studies should be carried out to improve the rate of water volume adjustment, and the cruising speed underwater. Maybe centrifugal pump with higher power should be employed. In addition, other problems also deserve attention. Such as the structural strength of the wings, the pressure resistance and corrosion resistance of the underwater mechanism, and the environment effects on the working performance of the aircraft.

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