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Submersible Unmanned Aerial Vehicle Concept Design Study

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A submersible UAV is a hybrid aerial-underwater vehicle which can fly in the air and navigate in the water. Survival in the two contradictory fluids needs particular shape, fuselage and wing structure, propulsion. In this paper, a concept of an amphibious UAV with the air-to-water transition of plunge-diving and the water-to-air transition of vertical take-off from the water surface is proposed. The structure characteristics that are adaptive to both of the air and the water, including the grider erection fuselage and the hollow and no-rib wings for the rapid water injection and drainage to adjust its average density, the foldable device for the wing to fold back to reduce drag in the water, are described and analyzed in detail. The estimation and design of the propulsions for the air and the water voyage and the balloon upright system are introduced. The impact accleration experienced by the whole structure of the UAV is calculated by the CFD method. Finally, the design and performance analysis of the wings are presented. The preliminary work carried out in this paper can provide some feasible proposals for the the ultimate realization of a submersible UAV.

Nomenclature

M	=	the total mass of the UAV
$V_{\text{displaced}}$	=	the total volume of the displaced water if the UAV is floodable
V_{space}	=	the volume of the water that submerges into the space among the griders of the fuselage and in the wings if the UAV is floodable.
W_{T}	=	the take-off weight
M	=	the total mass of the UAV without staining with water
g	=	the gravitational acceleration
C_{T_1}	=	the original thrust coefficient of the upper propeller
C_{T_2}	=	the original thrust coefficient of the lower propeller
R_{E}	=	the Reynolds number
ρ	=	the air density

I. Introduction

A vehicle that is flight-capable or submersible has been developed largely. An airplane or an unmanned aerial vehicle can fly freely in the air, which is provided with the characteristics of high-speed, high maneuverability and rapid deployment. A submarine or an unmanned underwater vehicle can navigate in the water freely, which is clandestine with the lower probability of detection. Thus, to devise a submersible aircraft with the speed and the maneuverability advantage of an airplane and the imperceptibility advantage of a submarine is an intriguing topic

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for the military scientists, aerospace and marine engineers. Inspired by this novel idea, some conceptual models and principle prototypes were proposed and developed to verify the feasibility of a combination vehicle of an airplane and a submarine.

In 1934, Dzerzhinskiy Ushakov proposed a "flying submarine" concept[1,2], which is a craft that could fly into enemy territory, submerge and then conduct surveillance and even torpedo attacks on enemy ships before flying to safety. As shown in Fig. 1, three aircraft engines were chosen to propulse the craft in the air, and a propulsion motor was used to power the whole craft underwater. The flying submarine posed many challenges to the builders, and the feasibility was questioned. So in 1937 the flying submarine project (LPL project) was refused.

Figure 1. The Russian flying submarine concept model.

In 1962, Convair studied a submarine that could fly. In a report, a proposal to study the feasibility of an aircraft designed to submerge underwater and operate submerged as an anti-submarine craft was presented[3]. As shown in Fig. 2, three jet engines were chosen to power the craft and the operation in the water was carried out by either a hydroski or hydrofoi. The submersion was accomplished by flooding sections of the wings, tail and hull. But due to some technical problems, the plan to create a prototype was cancelled.

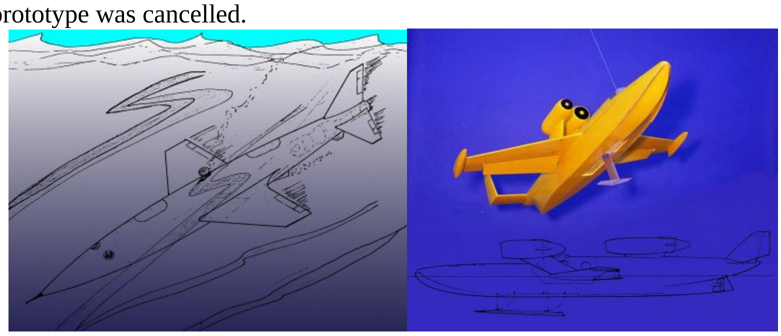

Figure 2. The Convair submersible aircraft concept model.

In recent years (2008), Defense Advanced Research Project Agency (DARPA) outlined a challenging set of requirements for a submersible aircraft that is capable of both flying in the air and submerging in the water[4]. From 2008 to 2011, DARPA was soliciting innovative research proposals on the topic all around the world[5-7]. However, because few feasible proposals were submitted, the project was cancelled in 2011. Fig. 3 shows the mission segments of this project.

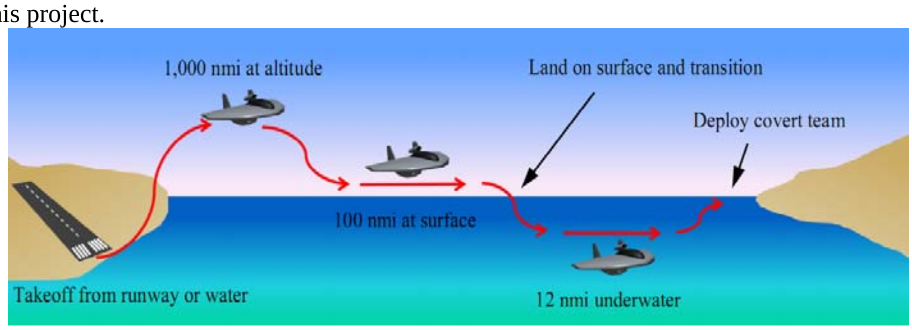

Figure 3. Mission segments.

The above three submersible aircrafts are manned. In order to maintain the life and safety of passengers, more design demands, such as the crew compartment, the life-support system and payload are needed in addition to the structure and propulsion demands that are compatible in both the air and the water. The manned submersible aircraft adds more complexity and difficulty to the whole system, which makes this air-water amphibious concept more difficult to achieve. Thus a concept of a submersible unmanned aerial vehicle (UAV) may be more feasible and easier to be put into practice.

In this paper, a concept of a submersible UAV is proposed. The goal of the study is to seek a solution for a submersible UAV that can transit successfully between aerial and submerged operations. A variety of technologies are considered, including the materials, the structures, and the propulsions. The concept of operation (CONOP) and the characteristics of the structure are described in detail. The selection and the arrangement of the propulsion system in the air and water are presented respectively. The wing design and aerodynamical analysis are implemented.

The work carried out suggests that the concept is feasible within the current state of the art. The structure and the propulsion can be designed to meet the demand of the density in different fluid media, and the analysis of the wing performance can provide effective data for the design of the wing and the tail.

II. Concept of Operation (CONOP)

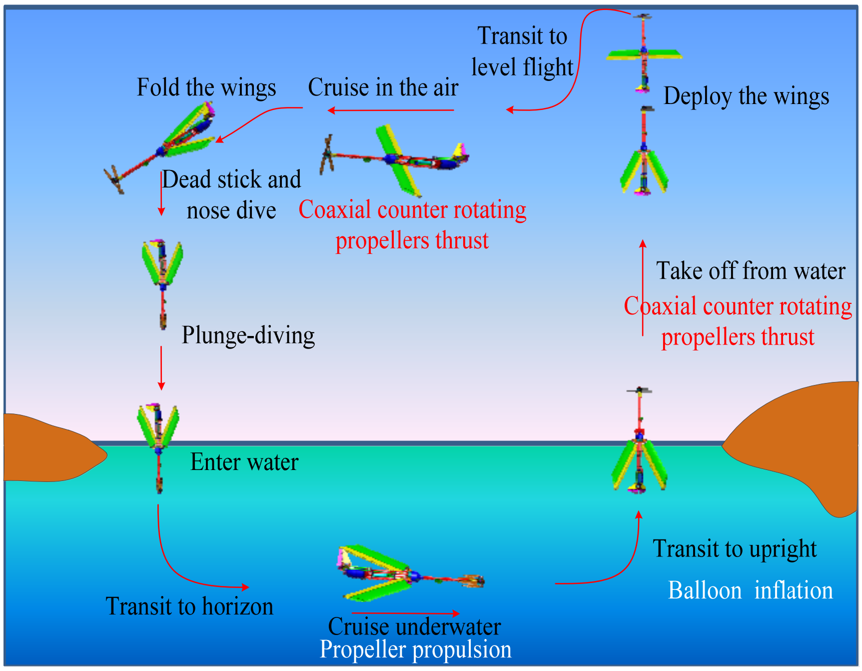

Figure 4. The concept of operation of the submersible UAV.

This submersible UAV system is developed to assist a submarine to accomplish reconnaissance and attack task. The UAV can be released from a submarine at the depth of 10 m, and navigate upstream to the waters where is 1-2 m from the surface. The UAV does not require the submarine to provide the power to navigate underwater or take off. Fig. 4 presents the concept of operation of the UAV. The UAV itself has the underwater propulsion system, and can cruise autonomously with the speed of 0.5 m/s underwater for about 20 minutes. When the UAV begins to take off, the air pump will inflate the balloons, and then the buoyancy makes the whole craft upright. Thus the coaxial counter rotating propellers are stretched out of the water, and then thrust the UAV to take off from the water surface. The takeoff weight should be more than 12.5 kg, and the transition time is within 30 s. When the UAV ascends to a proper height, it will hover overhead and the wings will be deployed preparing for the flight in the air. Subsequently the UAV will push over and transit to level flight. The cruise speed is about 20 m/s in the air, and the loitering time is over 30 minutes. Before the transition back to the water from the air, the wings will be folded firstly and the coaxial counter rotating propellers will be set to dead stick. Here a bionic plunge-diving transition is adopted as a gannet enters water in nature[8], as shown in Fig. 5, which demands more strengthened structure. This transition strategy is timesaving, and the transition time is shortened within 10 s. In addition to the strengthened structure, the average density of the whole craft must also change quickly. Here a girder erection fuselage and hollow and no-rib wings are used. After the wings and fuselage are flooded and full of water, the specific gravity of the whole UAV approximates to that of water, which is

Figure 5. The plunge-diving segments of a gannet.

beneficial for the underwater navigation. Then the underwater propeller starts to work. The UAV can navigate autonomously to the submarine and be retrieved.

III. The Characteristics of the Structure

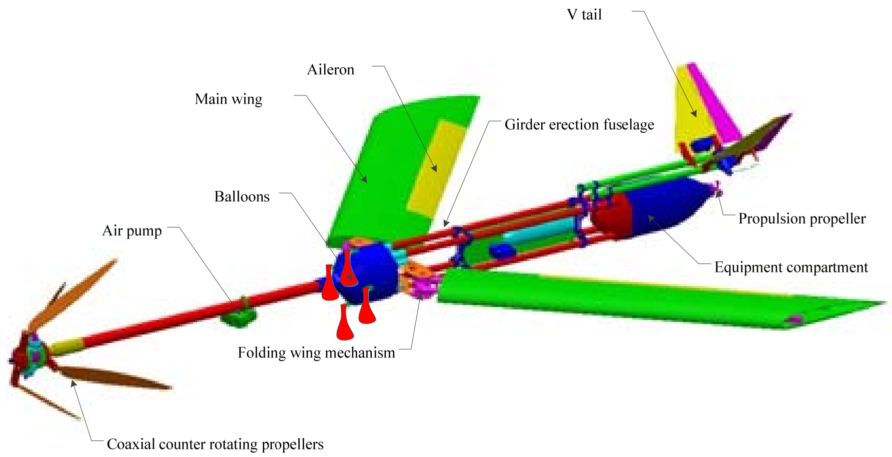

Figure 6. The prototype of the submersible UAV.

As shown in Fig. 6, the characteristics of the structure to adapt to both of the air and the water environment are the grider erection fuselage and the hollow and no-rib wings for the rapid water injection and drainage to adjust its average density, and the foldable device for the wings to fold back to reduce drag in the water. To keep the gravity constant after the UAV stains with water, the material of every exposed parts should be nonabsorbent. Simultaneously, considering the strength and the quality, the carbon fibre composite is chosen to construct the grider erection fuselage, the wings, the V tail, and the hull of the equipment compartment.

A. Grider Erection Fuselage

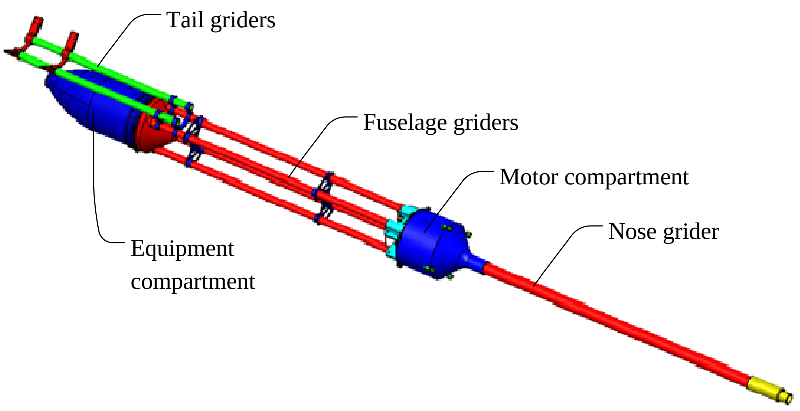

Figure 7. The grider erection fuselage.

As shown in Fig. 7, the fuselage of the UAV is constructed with four carbon fibre tubes which are used to support the body, link the front and the rear of the UAV, and mount the auxiliary equipment to perform the folding of the wings. Two tail griders are used to link the tail and the fuselage. The V tail is mounted on the rear of the tail griders. The nose grider is used to hold the transmission shaft between the motor and the coaxial reverse oars, which should be long enough to perform the vertical take-off from the water surface.

The UAV needs to aviate in the air with ease, which demands the airframe is designed to be light enough. Also, the UAV needs to navigate freely in the water, which demands the average density of the whole airframe to be designed approximately to that of the water. The contradiction between the two media draws higher requirements for the structure design. Commonly, for an autonomous underwater vehicle, a variable density or variable buoyancy device is devised to adjust the buoyancy to perform the ascending and the diving action, which is active and needs more energy. In this prototype, a passive variable buoyancy idea is adopted. When the UAV submerges into the water, the space among the griders and in the wings will be flooded rapidly, which decreases the buoyancy of the whole UAV and makes the average density of the whole body approximate to that of the water. Though the fluid resistance is enlarged due to the non-streamlined body shape and the fluid immersion into the UAV body, this structure is helpful for the air-water transition, the water-air transition, and the underwater navigation.

When the fuselage and the wings are designed to be floodable, the average density of the UAV can be calculated as

$$\rho_1 = \frac{M}{V_{\text{displaced}}}. \tag{1}$$

When the fuselage and the wings are designed to be unfloodable, the average density of the UAV can be calculated as

$$\rho_2 = \frac{M}{V_{\text{displaced}} + V_{\text{space}}}. \tag{2}$$

Therefore the density increase due to the design of floodable fuselage and wings can be represented as

$$\Delta\rho = \frac{\rho_1 - \rho_2}{\rho_2} = \frac{V_{\text{space}}}{V_{\text{displaced}}}. \tag{3}$$

In the preliminary design, V_{space} and $V_{\text{displaced}}$ can be adjusted to make the UAV obtain a proper average density for air cruise and underwater navigation. Theoretically, approximate to the density of the water is the best choice when the UAV cruises in the water.

B. Hollow and No-rib Wings

In order to ensure the transition between the air and the water successfully and rapidly, the wings should be hollow with the capability of rapid water injection and water drainage. As shown in Fig. 8, the wings are designed without ribs. When the UAV performs the air-water transition, the water can be injected into the space in the wings rapidly to increase the density of the whole UAV, which is beneficial for the underwater operation. When the UAV takes off vertically from the water (water-air transition), the water in the space of the hollow wings can be drained out the wings easily due to the absence of wing ribs. This kind of design is useful for the density adjustment in the two contradictory fluids of the air and the water.

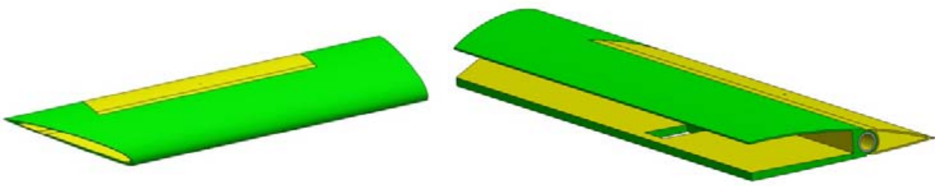

Figure 8. The hollow and no-rib wings.

C. Foldable Device

When the UAV is flying in the air, the wings should produce enough lift to counter the weight of the UAV. When the UAV is navigating in the water, the waterward area should be decreased to reduce the drag of the water. This can be realized by deploying or folding the wings. Fig. 9 shows the foldable device for the wings. The high pressure gas in the air tank is used to drive the gear cylinders. The gear cylinder drives the tumbler to rotate around the fixed axis (the wing is fixed on the tumbler) to deploy or fold the wings. The selector valves, which are driven by the steering engine, are used to control the direction of the air into the gear cylinder. Fig. 10(a) shows the state of the wings when the UAV is flying in the air. In this case the wings are deployed to produce lift in the air. Fig. 10(b) shows the state of the wings when the UAV is navigating underwater. In this case the wings are folded to reduce drag in the water.

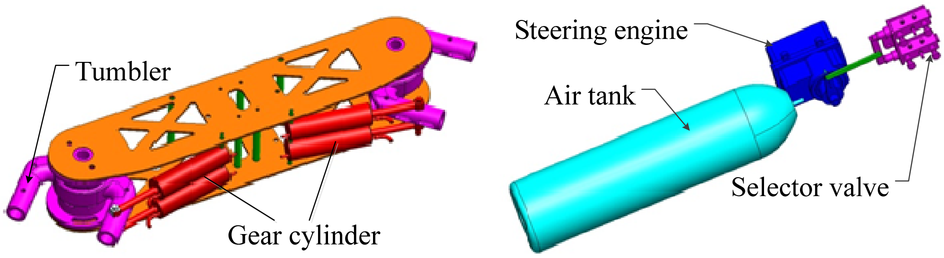

Figure 9. The foldable device.

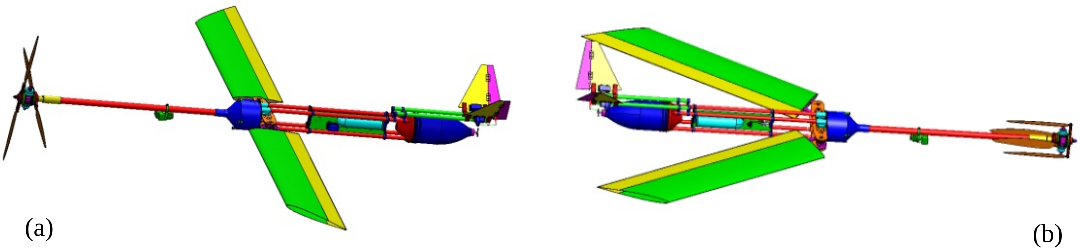

Figure 10. The state of the wings in the air and underwater. (a) The wings are deployed in the air; (b) the wings are folded underwater.

IV. Propulsion and Balloon Upright System

A. Propulsion System in the Air

Fig. 11 shows the propulsion system in the air, which are the coaxial counter rotating propellers. The propellers should provide enough power and force to thrust the UAV out of the water. Also, the power producer should provide enough energy to thrust the UAV in forward flight for a long range.

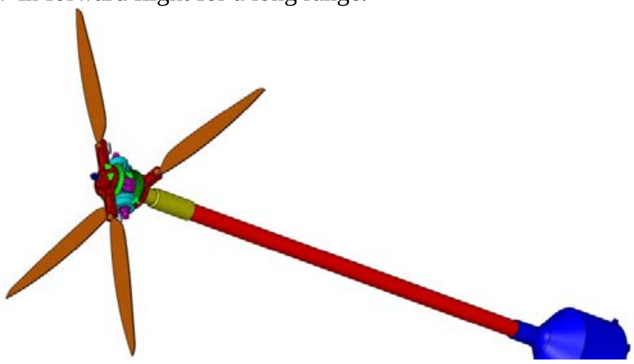
Figure 11. The coaxial counter rotating propellers.

1. *The demand for the propulsion system when the UAV takes off from water*

When taking off from the water, adhesive force of the water and the increased weight due to absorbing the water will make the take-off weight more than *Mg*. Here a safety factor, *k*, is used to consider these effects. Thus the take-off weight W_{T} can be estimated by

$$W_{\mathrm{T}} = kMg\,. \tag{4}$$

$k > 1$, and *k* can be calculated by using the prototype model to do several water-exit tests.

The thrust of the coaxial reverse oars can be estimated by

$$T = T_{\mathrm{U}} + T_{\mathrm{L}} = \sigma\alpha\omega_1^2 + \sigma\beta\omega_2^2 = \sigma C_{\mathrm{T}_1}\pi R_{\mathrm{E}}^4\rho\omega_1^2 + \sigma C_{\mathrm{T}_2}\pi R_{\mathrm{E}}^4\rho\omega_2^2\,, \tag{5}$$

where T_U and T_L are the thrust generated by the upper and lower propeller respectively[9]. σ is a loss coefficient with the value of 0.8-1. α and β are functions of the original thrust coefficients C_{T_1} and C_{T_2}. ω_1 and ω_2 are the rotation speed of the upper propeller and the lower propeller respectively.

In order to ensure the reliability of the take-off from the water, the maximum thrust-weight ratio should be more than 1.5, i.e., $\frac{T_{max}}{W_T} \geq 1.5$. T_{max} is the maximum thrust produced by the propellers. The maximum output power of the power supply is calculated by

$$P_{max} = \frac{T_{max} \cdot V_0}{\eta_1 \eta_2} = \frac{1.5 W_T \cdot V_0}{\eta_1 \eta_2} = \frac{1.5 kMg \cdot V_0}{\eta_1 \eta_2}. \tag{6}$$

η_1 and η_2 are the efficiency of the electromotor and the coaxial reverse oars respectively. V_0 is the cruise speed in the air.

The propeller can be designed by using the software XFOIL and QMIL. E850, a commonly used airfoil section for the folding propeller, can be chosen as the airfoil for the coaxial reverse propellers. As shown in Fig. 12, the input parameters for QMIL can be calculated by the XFOIL software.

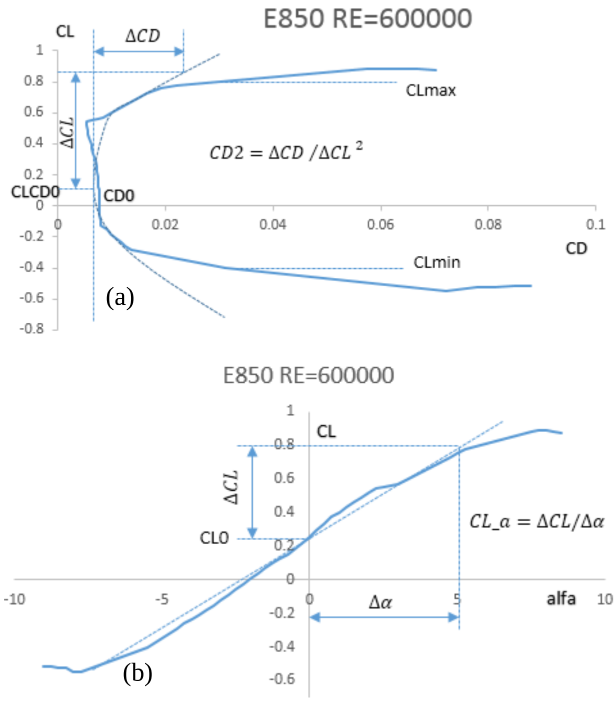

Figure 12. The aerodynamic coefficient curve in the XFOIL. (a) The lift-drag ratio curve. (b) The lift curve.

2. *The demand for the propulsion system when the UAV levels off with the cruise speed*

As shown in Fig. 13, when the UAV cruises with the speed of V_0 and the attack angle of α in the air, the following two requirements should be met.

$$T_c \cos\alpha = L \sin\alpha + D, \tag{7}$$

$$T_c \sin\alpha + L \cos\alpha = G. \tag{8}$$

T_c is the thrust generated by the propellers, L and D are the total lift and the total drag of the cruising UAV respectively, G is the total weight of the UAV with the value of Mg. L can be estimated by $L = \frac{1}{2} C_L \rho V_0^2 S$. C_L and S are the lift coefficient and the area of the wings. The cruise output power of the power supply is estimated by

$$P_c = \frac{T_c V_0 \cos\alpha}{\eta_{1c}\eta_{2c}}, \tag{9}$$

where η_{1c} and η_{2c} are the efficiency of the electromotor and the coaxial reverse oars respectively when the UAV is cruising.

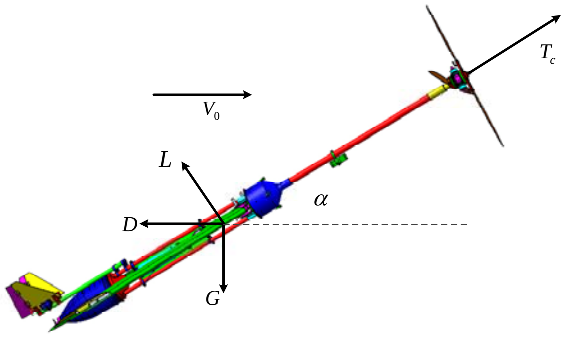

Figure 13. The cruise diagram of the UAV.

B. Underwater Propulsion System

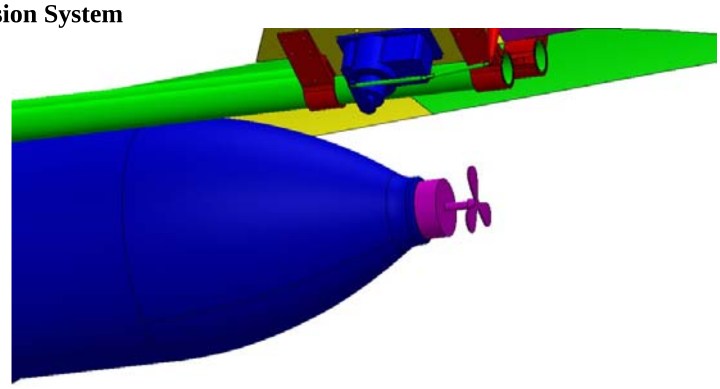

Figure 14. The underwater propulsion propeller.

As shown in Fig. 14, the underwater propulsion system is a propeller mounted at the rear of the UAV. The propeller should provide enough propulsion to accomplish the underwater cruise. Due to the complicated structure and shape, the drag is difficult to estimate by analytical or numerical method. Thus a scale model is needed to measure the drag in the water when the UAV cruises underwater with a speed of $V_{0w} = 0.5\ \mathrm{m/s}$. If the total drag of the UAV in the water is D_w, the propulsion force $T_w = D_w$ when the UAV cruises with a constant speed. Thus the cruise output power of the power supply is estimated by

$$P_{\mathrm{w}} = \frac{T_{\mathrm{w}} V_{0\mathrm{w}}}{\eta_{1\mathrm{w}}\eta_{2\mathrm{w}}}, \tag{10}$$

where $\eta_{1\mathrm{w}}$ and $\eta_{2\mathrm{w}}$ are the efficiency of the electromotor and the underwater propeller respectively when the UAV is cruising in the water.

The power supply should store enough energy for completing the tasks both in the air and water. The take-off time is t_1, the loitering time in the air is t_2, and the loitering time in the water is t_3, then the energy of the power supply can be estimated by

$$E > P_{\max} t_1 + P_{\mathrm{c}} t_2 + P_{\mathrm{w}} t_3. \tag{11}$$

For this mission, only the electric energy may be not enough to provide the energy for the whole process. Perhaps the Petrol-Electric Hybrid is an effective way to solve the problem of low energy density of the electric power.

C. Balloon Upright System

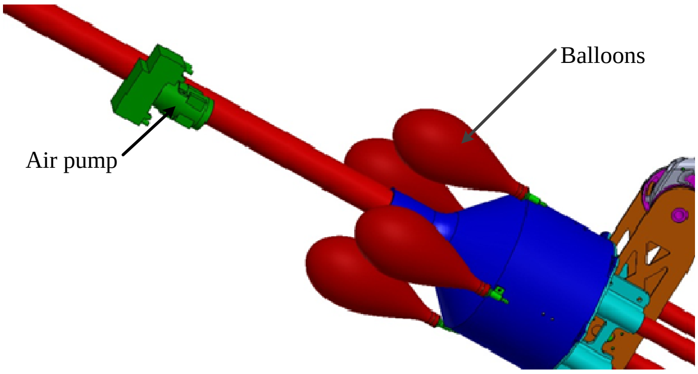

Figure 15. The balloon upright system.

As shown in Fig. 15, the balloon upright system includes four balloons and an air pump for inflating or deflating the balloons. When the balloons are inflated by the air pump, the average density ρ_{f} of the whole UAV will become less than that of the water so that the UAV can break the water surface. The upright condition is that $\rho_{\mathrm{f}} < \rho_{\mathrm{water}}$, i.e.,

$$\frac{M}{4V_{\mathrm{b}} + V_{\mathrm{displaced}}} < \rho_{\mathrm{water}}, \tag{12}$$

where V_{b} is the air capacity of a balloon. Thus the V_{b} can be estimated by

$$V_{\mathrm{b}} > \frac{M - \rho_{\mathrm{water}} V_{\mathrm{displaced}}}{4\rho_{\mathrm{water}}}. \tag{13}$$

Thus four balloons with the air capacity of V_{b} should be customized to complete the upright task.

If the transition time from the submerged state to the upright state is T, the pump flow Φ can be estimated by

$$\Phi > \frac{4V_{\mathrm{b}}}{T}. \tag{14}$$

Thus a proper air pump should be chosen to complete the upright within the limited transition time.

V. The Impact Acceleration during Plunge-diving

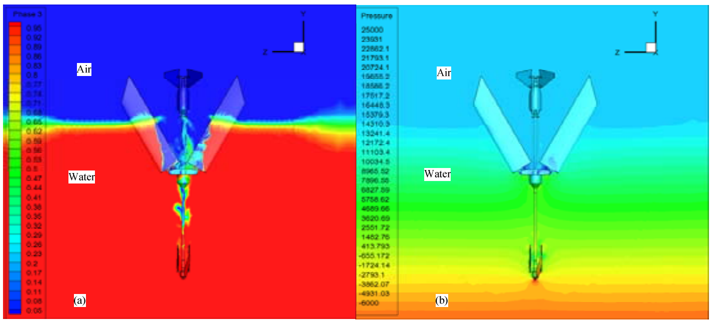

Figure 16. The phase and the pressure distribution.

When the UAV performs the transition from the air to the water, a plunge-diving process will be experienced by the UAV, which is an effective feeding method of gannets (Fig. 5). This method can complete the air-water transition during seconds. However a considerable impact acceleration will be experienced due to the collision with the water, which can cause damage to the material, the structure and the sensing elements of the UAV. Thus the preliminary estimation of this impact acceleration is significant for the selection of the material and the sensing elements and the design of the structure. Here a computational fluid dynamics method is used to predict the impact acceleration when the UAV enters the water[10]. Fig. 16 shows the pressure distribution and the phase distribution of a certain instant time. Fig. 16(a) presents the air and the water state, which indicates that the water-entry process involves three media, i.e., the air, the water and the UAV body. Fig. 16(b) presents the pressure distribution on the

UAV body surface. The pressure on the body surface mainly contributes to the impact force in the longitudinal body axis. Fig. 17 presents the impact acceleration variation. It can be seen that when the UAV plunges from the height of 10 m, the maximum impact acceleration can reach 38*g*, which has to be considered when the structure is designed.

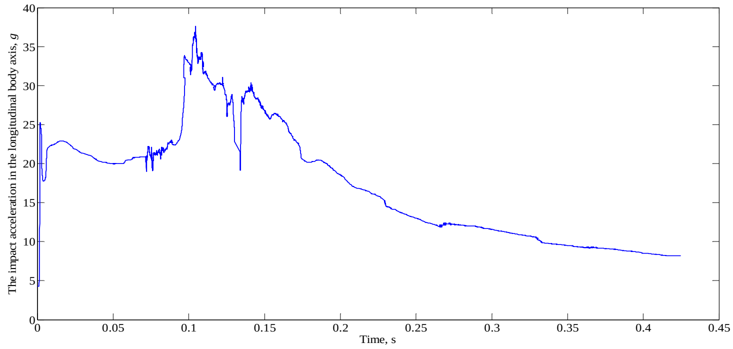

Figure 17. The time history of the impact acceleration when the dropping height is 10m.

VI. Wing Design and Configuration

The wings are mainly for generating lift to climb and cruise in the air. The control surfaces are used to adjust the attitude in the air, which are also effective when the UAV navigates in the water. The requirements in the air is the key factors that determine the wing design and the aerodynamic configuration. Thus in this vehicle, the wing and V stabilizer parameters and the aerodynamic configuration are designed according to the mission in the air. The airfoil is selected according to the flight speed firstly. Then the parameters of the wing and the control surface are determined and the wing performance is analyzed by using a 3D-vortex lattice program named Tornado[11]. The lift coefficient of this configuration is calculated by the Tornado program, and the drag is estimated by using the method in Ref. 12.

A. Airfoil Selection

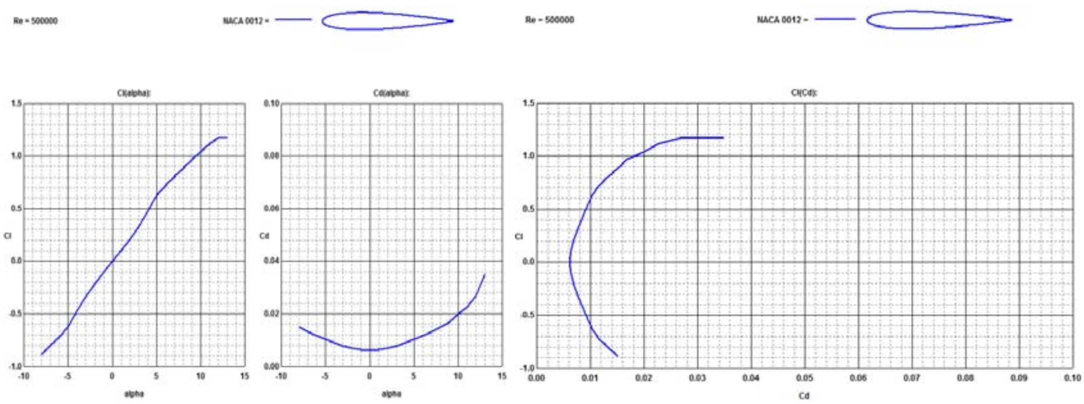

Figure 18. The lift curve, the drag curve and the polar curve of NACA0012.

The transition from the upright state to the level state needs a minimum velocity to produce lift. The velocity is achieved by the work of the gravity and the propellers. Considering that the UAV cruises at a low speed (20 m/s), the low speed airfoil series are better choice. The NACA series airfoils can meet the lift and the drag coefficient requirements. In addition, the UAV needs to have a low zero-lift angle for the vehicle to operate at a level attitude in the water. Therefore a symmetric aerofoil NACA0012 is selected as the wing section area. The zero-lift attack angle is 0°. The true angle of incidence is designed as 0° to reduce the drag of the vertical take-off and the underwater cruise.

B. Wing Performance

The area of the main wing is based on the cruise speed in the air. The area of the V tail is designed based on the method in Ref. 13. The principal hull characteristics are listed in Table 1.

Table 1 The principal hull characteristics

Gross weight	12.8kg	**Body length**	2.63m
Wing span	1.93m	**Aspect ratio**	4.09
Root chord	471.94mm	**Taper ratio**	261.08mm
Wing area	0.91 m^2	**V tail area**	0.098 m^2

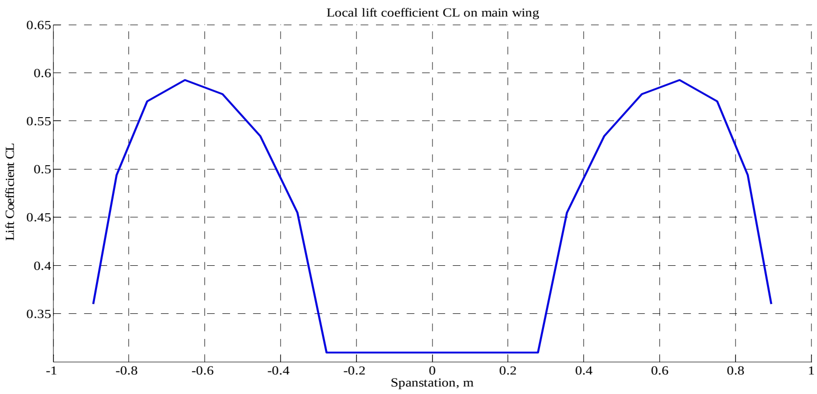

Figure 19. The local lift coefficient.

The attack angle for the maximum lift-drag ratio is about 6 degrees, which is chosen as the attack angle for the cruise in the air. The performance of this wing geometry and configuration is analyzed in a 3D-vortex lattice program named Tornado. Fig. 19 shows the local lift coefficient along the wing span. The total lift is 163.20 N. The shear force distribution and the bending moment distribution are presented in Fig. 20. It can be seen that the maximum shear force from lift is 31.14 N, and the maximum bending moment is 9.86 N • m. The strength and the deformation of the wing structure should be considered under the condition of this aerodynamic loading.

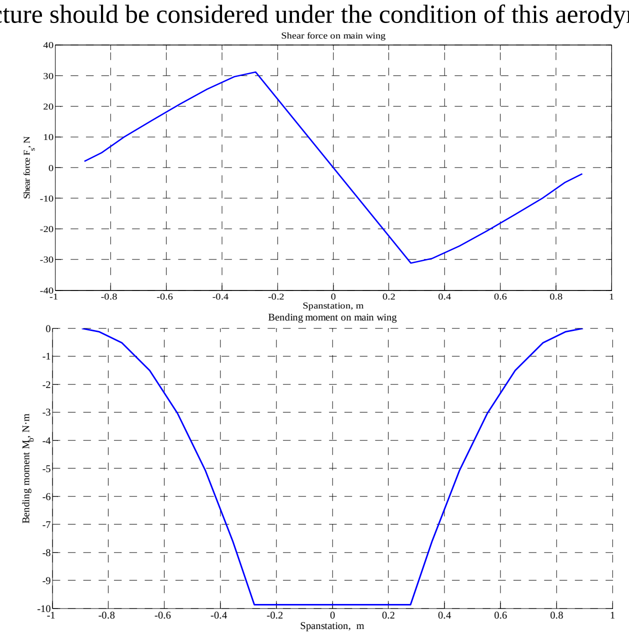

Figure 20. The shear force and the bending moment.

C. Drag Estimation of the Whole UAV

The drag on the UAV includes the zero-lift drag and the induced drag. The method in Ref. 12 is used to estimate the zero-lift drag. The zero-lift drag is mainly determined by the skin friction drag. The wing, the V tail, and the fuselage are divided into two regions according to the conditions of the laminar boundary layer and the turbulent boundary layer. Then the skin friction drag is calculated by adding the forces in the laminar and turbulent boundary layer. The corrected value of the zero-lift drag is 6.02 N. The value of the induced drag is calculated by using the result analyzed from the Tornado program. Finally, the total drag of the whole UAV is 8.12 N. Thus the propeller has to provide a thrust which is more than 8.12 N.

VII. Conclusion

A submersible UAV is proposed in this paper, which is a vehicle that can fly in the air and navigate in the water. The characteristics of the structure that are applicable to the two different fluid media are introduced. The grider erection fuselage and the hollow and no-rib wings are designed to increase the average density of the UAV in the water stage. Also, these characteristics are convenient for the water injection and drainage, which is significant for the transition between the air and the water. The foldable wings are used in this UAV to promote the flight performance in the air and reduce the drag in the water. The calculation and design for the propulsion and balloon upright system are described in detail, which are feasible within the current technology. The impact acceleration of the water entry calculated by the CFD method indicates that the UAV will experience a considerable acceleration in the longitudinal axis when it transits from the air to the water, which demands enough structure strength and sensing element overload. The aerodynamic analysis is performed using the estimation method and the Tornado program, which indicates that this wing geometry and configuration can ensure the UAV to cruise in the air with the requirement speed and gross weight.

Some other technique problems have to be solved for the submersible UAV to achieve the air cruise, the water navigation, the air-to-water transition and the water-to-air transition, including the underwater attitude control, the proper energy supply for the long range task, the seal between the moving parts, and so on. The ultimate realization of the submersible UAV that can shuttle between the air and the sea freely will revolutionize the current navy operation concept in some aspects.

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