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Submersible Unmanned Aerial Vehicle: Configuration Design and Analysis Based on Computational Fluid Dynamics

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Abstract. Submersible aerial vehicle is capable of both flying in the air and submerging in the water. Advanced Research Project Agency (DARPA) outlined a challenging set of requirements for a submersible aircraft and solicited innovative research proposals on submersible aircraft since 2008. In this paper, a conceptual configuration design scheme of submersible unmanned aerial vehicle is proposed. This submersible UAV lands on the surface of water, then adjusts its own density to entry water. On the contrary, it emerges from water by adjusting its own density and then takes off from the surface of water. Wing of the UAV is whirling wing. It is set along aircraft's fuselage while submerging for lift reduction. We analysis aerodynamic and hydrodynamic performance of this UAV by CFD method, especially compare the hydrodynamic performance of the whirling wing configuration and normal configuration. It turns out that whirling wing is beneficial for submerging. This result proves that the configuration design scheme proposed in this paper is feasible and suitable for a submersible unmanned aerial vehicle.

1 Introduction

A vehicle called submersible aerial vehicle that is flight-capable and submersible is wildly concerned around the world for its great advantages that it is capable of submerging to avoid missiles and taking off from water surface to attack enemy. It should combine the key capabilities of three different platforms: 1) the speed and range of an aircraft; 2) the loiter capabilities of a boat; 3) the stealth of a submarine [1]. Submersible aerial vehicle is a kind of aerial weapons which maybe used to enhance tactical ability of armies. Several interesting conceptual schemes and principle prototypes are proposed to verify the feasibility of a hybrid vehicle that combines an aircraft and a submarine together.

The first concept design named "flying submarine" was shown by Dzerzhinskiy Ushakov in 1934, which is a weapon that submerges and attacks enemy's ships underwater and then escapes by taking off from the surface of water. In 1962, a flight-capable submarine was presented by Convair. The submarine was designed in detail and tried to build. However, the plan could not accomplished due to some technical problems. In 2008, a set of requirements for a submersible aircraft was outlined by Defense Advanced Research Project Agency (DARPA) [2]. DAPRA was calling for innovative research proposals on submersible aircraft from 2008 to 2011, but few feasible proposals were submitted, which leads to the project be canceled in 2011. These three submersible aerial vehicles need complex life supporting system to keep crews safe. Compared with these manned vehicles, unmanned submersible aerial vehicles without life supporting system are easier to come true [3].

Actually, a submersible UAV called "cormorant" is developed by US, which is launched from submarine. Then sailing in water pushed by a rocket engine. After through water surface, its air-breathing engine works. What's more, a submersible UAV named "fly-boat" that imitates flying fish was proposed and built up by a research team in Beihang University. Their submersible UAV is similar to a biological flying fish [4]. It adopts soft landing type to land on water surface and also takes off from water surface. This UAV adopts sweptback wing. So the wing provides enough lift in the air for vehicle to fly and folds back to reduce the resistance underwater.

Although some concept designs are made to provide feasible proposals on the submersible aircraft, there is still a large gap between these schemes and products for practical utilization. Accordingly, it is still very valuable and meaningful to research the complex technological problems on the submersible UAV persistently.

2 Technological problems

To satisfy the requirements that both flying in the air and diving under water several technological problems have to be solved. Firstly, flying requires a large wing area to provide enough lift but large wing area will cause large resistance and excess lift under water. Secondly, in one hand, for flying the density of UVA should be as light as better, in the other hand, diving under water requires that the density of UVA is similar to it of water. Thirdly, a flying UVA are made up by light structures. However, shell structures of a submarine are thick to resist the high pressure caused by water. Fourthly, power system is also special in a submersible vehicle. Fuel engines can't be used underwater. And the shape of propellers for air propulsion and water propulsion are different. Fifthly, the fuselage of UVA will not cause large drag in the air, but the resistance caused by fuselage should not be ignored while sailing underwater. In Table 1, the contradictions are enumerated.

Table 1. Contradictions for flying and submerging.

Parameter	Flying	Submerging
Wing area	Bigger enough to provide lift	Smaller enough for resistance reduction and avoiding excess lift
Density	Much smaller than water	Similar to water
Structure	Light shells and beams	Thick shells
Propelling system	Fuel engine	Electric motor
Fuselage	Contributes a little drag	Causes much drag
Water discharge	Small	About 100%

Except for the contradictions mentioned above, how to transfer modes between water and air should be considered seriously. Based on the previous studies, there are two main feasible modes to transfer between different media. The first mode is plunge-diving and vertical take-off mode. This mode simulates prey process of aquatic birds, which was firstly public aroused by Hawkes on 2010 [5]. After that, some researchers, coming from Beihang University carried out lots of pioneering experiments to study the mechanism of gannet's plunge-diving process [6], [7]. The second is soft landing and taxiing take-off mode. The researchers, coming from Beihang University created a submersible unmanned flying boat named Flying Fish and verified this mode by "Flying Fish" first time in the world [4]. They made further experiments to research this kind of submersible UAV, which already verify the second mode is feasible, but they do not give a perfect explanation for all the technological problems caused by this mode.

3 Concept design of submersible UAV

Because the submersible UAV is mainly used in the air, so traditional method about aircraft design is suitable for determining variables of submersible UAV. However, there are two special problems should be considered. One is about the density, another one is about the Reynolds number.

3.1 Density adjustment

In order to suitable for flying, the density of UAV should be small. On the contrary, the density should be adjust similar to water for sailing underwater. Some parameters are shown in Table 2 to state this problem.

In Table 2, $V_{structure}$ means volume of all the solid objects in the UAV. So, in the fact, ρ_{air_model} is the average density of the UAV while flying in the air. While sailing in the water, the submersible UAV is capable of keeping water away from its inner space. So V_{whole} stands for the whole volume of the submersible UAV.

Table 2. Parameters about density adjustment.

Parameter	symbol	Parameter	symbol
Cross weight	W_{c_w}	Water tanks cubage	C_{tank}
Density in the air	ρ_{air_mode}	Volume of solid parts in the UAV	V_{solid}
Density underwater	ρ_{under_mode}	Water density	ρ_{water}
Density control coefficient	η	Volume of the whole UAV	V_{whole}

Two inequalities are used to introduce principles of density adjustment:

$$\rho_{air\_mode}=\frac{W_{c\_w}}{V_{structure}}\leq\eta\cdot\rho_{water} \tag{1}$$

$$\rho_{under\_mode}=\frac{2C_{tank}\cdot\rho_{water}+W_{c\_w}}{V_{whole}}\geq\rho_{water} \tag{2}$$

From inequality (2), we get inequality (3):

$$C_{tank}\geq\frac{\rho_{water}\cdot V_{whole}-W_{c\_w}}{2\rho_{water}} \tag{3}$$

Inequality (2) and (3) are two constraints conditions for the design of submersible UAV.

3.2 Relationships between cruising speed and Reynolds number

Based on the flow similarity principle, Reynolds numbers in the air and underwater should be the same:

$$\frac{\rho_{air}\cdot V_{c\_air}\cdot L}{\mu_{air}}=\frac{\rho_{water}\cdot V_{c\_underwater}\cdot L}{\mu_{water}} \tag{4}$$

From (4), we get:

$$\frac{V_{c\_air}}{V_{c\_underwater}}=\frac{\rho_{water}}{\rho_{air}}\cdot\frac{\mu_{air}}{\mu_{water}} \tag{5}$$

In equations above, V_{c_air} and $V_{c\_underwater}$ indicate the cruising velocity. The reference length is indicated by L. μ_{air} and μ_{water} indicate the dynamic coefficient of viscosity.

Equation (4), which shows the relationship between cruising velocities, is important for the design.

3.3 Configuration of the submersible UAV

A new concept design scheme of unmanned submersible aerial vehicle is proposed in this paper in order to suitable flying and diving requirements better.

According to the previous studies, solutions are proposed in this paper to realize technological problems shown in part 2. Whirling wing is designed to keep large wing area in flying mode and reduce the area of wing which generates excess lift while submerging. Two float bowls that contain water tanks inside are installed beside the fuselage in order to adjust the density of UVA by injecting water into water tanks or pumping water out of water tanks. Two different power systems are used to drive the UAV. One system combines fuel engine and air propeller to drive the UAV in the air. The other system combines electric motor and water propeller together to drive the UAV under water. And the structure is designed enough strong to resist pressure caused by water while the UAV sailing underwater.

In this paper, our conceptual submersible UAV will choose the second mode which is introduced in part 2 to transfer media. Differently, we add two float bowls on both sides of the UAV, which are capable to stretch out and pick up. When the submersible UAV is going to land on the water surface, float bowls will be stretched out to provide drag to contribute to reduce velocity. And stability is increased by stretching float bowls out to resist waves while floating. On the contrary, the float bowls will be picked up while flying in the air or diving under water to reduce resistance. In addition, water tanks are designed inside the float bowls in order to adjust the density of UAV. A solenoid value is installed in the head of the float bowls. When it opens, water will be injected into the water tanks. A pump is installed in the water tank and links with media outside by pipeline. When the pump works, water will be driven out from the water tanks. In order to keep the air pressure balance between the water tanks and outside, air duct is used to link water tanks to the air hole.

Fuselage of the submersible UAV is an important component. In order to design a perfect shape for the fuselage, two aspects of things have to be considered. For one thing, the density of water is larger than air, so reducing resistance becomes very important. The shape of fuselage is similar to a submarine that just like a drop of water. For another thing, take-off mode of the submersible UAV proposed in this paper is taxiing take-off from water surface. While taxiing on the water, the fuselage of submersible UAV will cause large resistance. If the taxiing process is ignored in the design, the UAV will fail to take off. Inspired by amphibious planes, the shape of fuselage is modified for drag reduction.

Wing and tail wing are also key parts of an aircraft. Airfoil effects wing's performance. The software named "Profili" is used to choose airfoils for the UAV. In the end, CLARK-Y is picked for the wing and NACA4412 is picked for the tail wing.

The principal design parameters of the submersible UAV is presented in Table 3. The configuration of the submersible aircraft is presented in Fig. 1, Fig. 2 and Fig. 3.

Table 3. Principal design parameters of the submersible UAV.

Parameter	Value	Parameter	Value
Cross weight	45kg	Body length	3.0m
Wing span	4.1m	Aspect ratio	8.0
Wing area	2.05m	Flight-speed	216km/h
Sail speed	15km/h	Conventional cruising depth	3m
Conventional flight attitude	20~600m	Load capacity	8kg

As shown in Table 3, values of some key parameters are given.

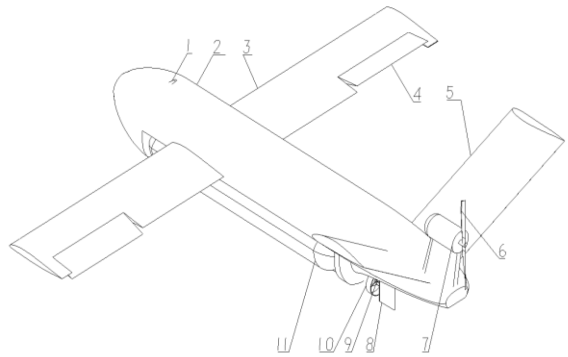

Figure 1. Configuration (In the air).

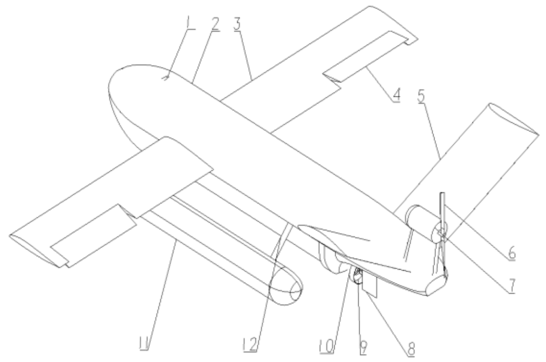

Figure 2. Configuration (On the surface of water).

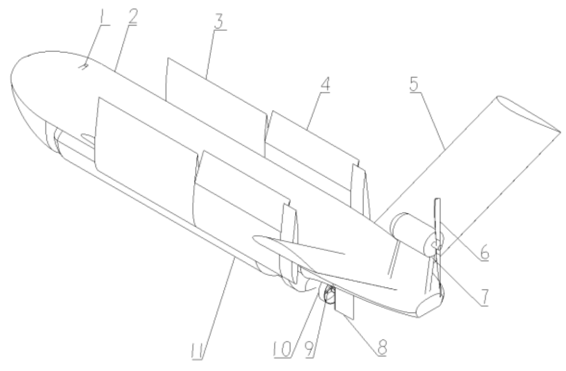

Figure 3. Configuration (Underwater).

Fig. 1 indicates the mode in the air. Fig. 2 shows the mode on the surface of water. Fig. 3 shows the mode underwater. Numbers in these picture means: 1. spiracle (contact with float bowls); 2. fuselage; 3. whirling wing; 4. aileron; 5. empennage; 6. air propeller; 7. diesel engine; 8. rudder; 9. underwater propeller; 10. electromotor; 11. float bowls; 12. connecting rod.

4 Configuration analysis based on CFD

4.1 Working conditions

In order to prove that the configuration of submersible UAV proposed in this paper is feasible and the scheme of whirling wing is effective, CFD method is used to analysis aerodynamic and hydrodynamic performance of the submersible UAV. 3D model is built by Catia. ICEM is used to repair geometrical model and generate mesh. Fluent is the solver.

Whirling wing is a key component. The wing keeps in the original place while flying in the air. In this mode, the UAV just like a fixed wing aircraft. While submerging underwater, the wing is set along the fuselage in order to reduce lift. If the lift is too large, the submersible UAV will not dive into water. Whirling wing's performance in different modes is mainly concerned, so we simply the model that is used in CFD analysis in order to improve computational efficiency.

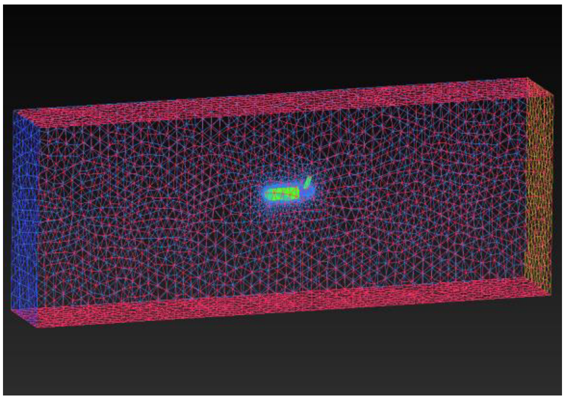

Figure 4. Computational domain.

As shown in Fig. 4, computational domain is 10 times larger than the UAV model.

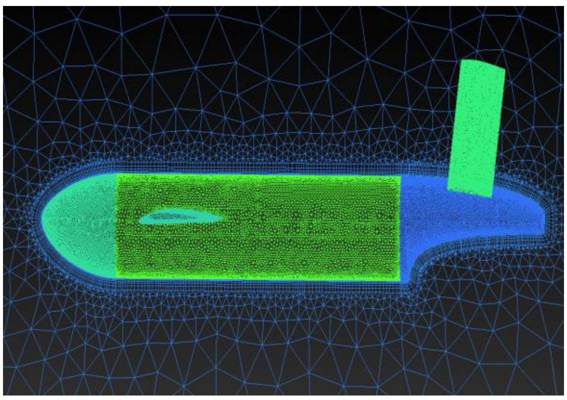

Figure 5. Mesh of configuration in the air.

Mode 1 of the submersible UAV is suitable for flying in the air and mode 2 of the submersible UAV is suitable for sailing underwater. Mesh for different modes are presented in Fig. 5 and Fig. 6.

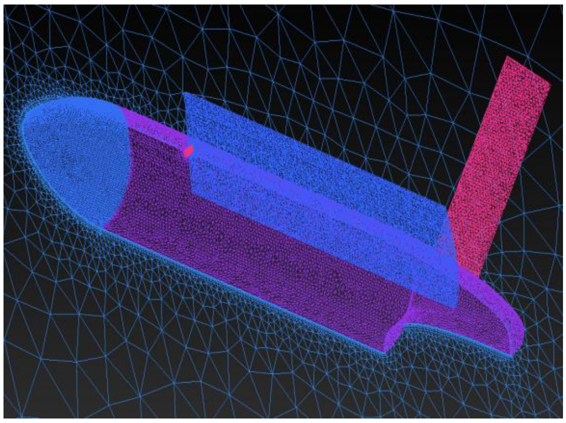

Figure 6. Mesh of configuration underwater.

The boundary conditions: surface of the UAV is set as "Wall" boundary condition, the far field is set as "Wall" boundary condition. Inlet of the computational domain is set as "Inlet". Outlet of the computational domain is set as "Outlet" boundary condition.

Import geometry model of the submersible UAV in Fluent. Based on pressure method, turbulence model is S-A model in the air and $k-\varepsilon$ model underwater. Set velocity values and attack angle values based on working conditions of the UAV. Choose second-order upwind scheme and coupled method. Set the monitors to get lift coefficient and drag coefficient. Reference area of wing is $3.5m^2$, the length of average aerodynamic chord is 0.5m. Do not stop iterate until the results converged. After this, we can get data of the submersible UVA about its aerodynamic and hydrodynamic performance. The attack angle of working conditions is from 0 degree to 30 degree. The conceptual scheme proposed in this paper is designed for low speed, so we set the speed cases as 45 m/s and 60 m/s in the air, 2 m/s and 4 m/s underwater.

4.2 Analysis of aerodynamic and hydrodynamic performance based on CFD

As introduced before, to satisfy flying and submerging requirements, the submersible UAV has two different configurations. The configuration in the air is mode 1, the configuration underwater is mode 2.

By CFD method, in this paper, a serials of data are got about mode 1 and mode 2. Lift coefficient, drag coefficient and lift-drag ratio about the UAV in different working conditions will be shown as follows.

4.2.1 Aerodynamic performance

Pressure distribution in the case of "15 degree attack angle and 60m/s in the air" is presented in Fig. 7. Aerodynamic properties curves are presented in Fig. 8, Fig. 9 and Fig. 10.

According to the pressure distribution shown in Fig. 7, we can find the high pressure part and low pressure part, which is a visual display of lift and drag.

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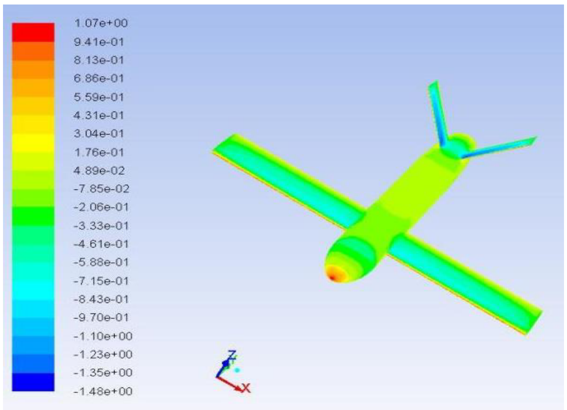

Figure 7. Pressure distribution of mode 1.

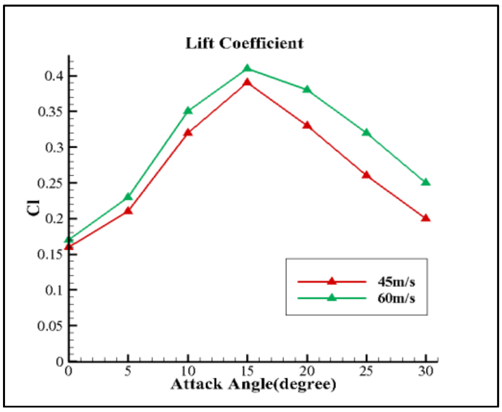

Figure 8. lift coefficient of mode 1 in the air.

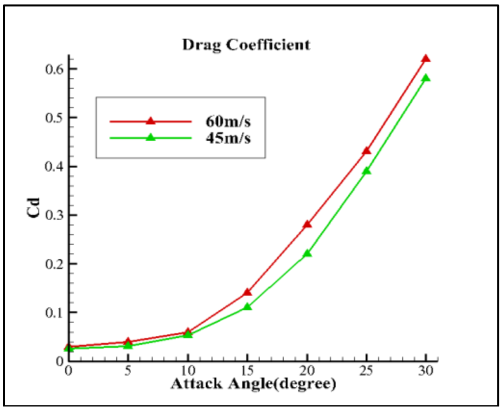

Figure 9. Drag coefficient of mode 1 in the air

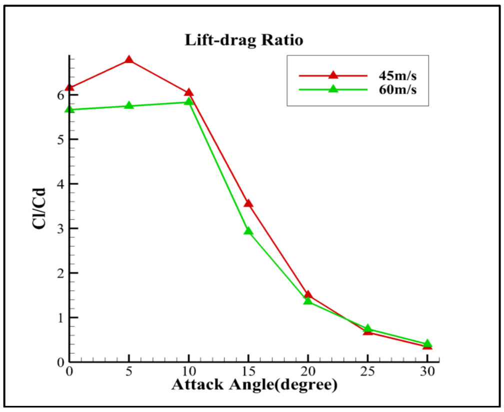

Figure 10. Lift-drag ratio.

From the aerodynamic properties curves, we know that the lift coefficient doesn't stop increasing with the attack angle's increase until 15 degree. After 15 degree, the lift coefficient is decreasing with attack angle's increase. Peak value of the lift coefficient appears in 15 degree. Drag coefficient is increasing with the attack angle's increase. In the whole process of attack angle's increase, the drag coefficient increases ceaselessly. The lift-drag ratio is an important parameter. Its peak value appears before 10 degree. Before 10 degree, the ratio nearly increases with attack angle's increase. After 10 degree, the ratio is decreasing with attack angel's increase.

Accordingly, mode 1 of the submersible UAV is feasible for its flying.

4.2.2 Hydrodynamic performance

Computational domain of hydrodynamic performance analysis is as same as it of aerodynamic performance analysis. And the mesh built in the former case can still be used in the new analysis. Of course, the boundary conditions are different. In the underwater simulation, turbulence mode should be set as $k-\varepsilon$ turbulence model [8]. And a bigger relaxing factor is set to improve the velocity of convergence.

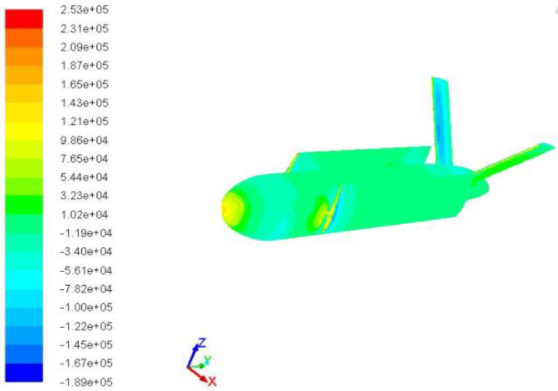

Figure 11. Pressure distribution of mode 2

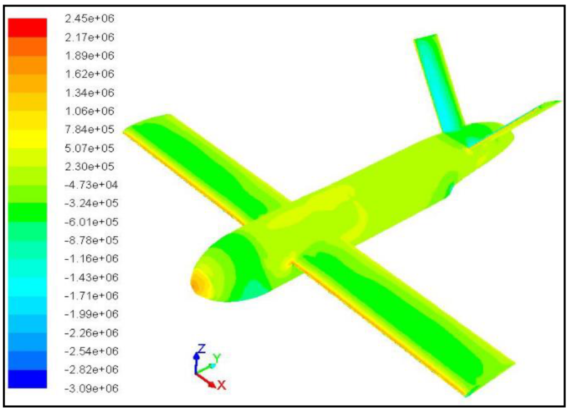

Figure 12. Pressure distribution of mode 1 underwater

In the first, we use mode 2 of the submersible UAV to make a hydrodynamic performance analysis. Fig. 11 shows the pressure distribution of mode 2 that the wing is already be whirled. The working condition is 4m/s with 15 degree attack angle underwater.

In order to prove that our scheme is effective, we also analyze the hydrodynamic performance of mode 1. Fig.

12 shows the pressure distribution of mode 1. The working condition is 4m/s with 15 degree attack angle underwater.

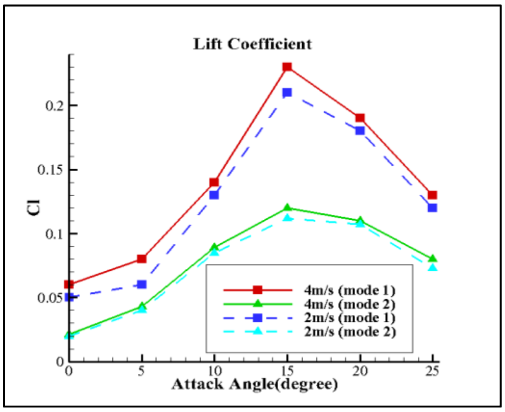

Figure 13. Comparison of lift coefficient

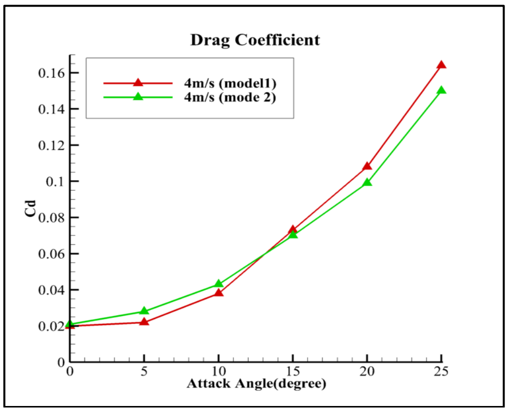

Figure 14. Comparison of drag coefficient

We get relevant data of the two modes and plot curves to compare their hydrodynamic performance. Fig. 13 shows the comparison of lift coefficient. Fig. 14 shows the comparison of drag coefficient. Fig. 13 contains 2 two working conditions of each mode. Fig. 14 contains only one working condition of each mode. The sailing velocity of the first case is 4m/s. And the velocity of the second case is 2m/s.

According to the curves shown in pictures above, lift coefficient increases before 15 degree and decreases after it. If velocity increases, lift coefficient will increase. Lift coefficient of mode 1 is much bigger than it of mode 2. Drag coefficient increases with the increase of attack angel. There is not a big gap between the drag coefficient of mode 1 and mode 2.

The analysis above means our design is effective. Whirling wing reduces the lift coefficient of submersible UAV underwater, which helps the UAV submerging underwater. And this design doesn't cause much increase of drag.

5. Conclusion

Some technological problems of submersible UAV are discussed in this paper. And a conceptual design scheme of submersible UAV that adopts whirling wing is proposed. The submersible UAV has two modes. By CFD analysis, we get a serials of data about aerodynamic performance and hydrodynamic performance of the UAV. Based on these data and property curves that plotted by these data, we conclude:

• Aerodynamic and hydrodynamic performance analysis of submersible unmanned aerial vehicle is useful for engineers to build feasible configurations of submersible UAV during the phase of scheme design.

• CFD analysis method is an excellent method to get lift coefficient, drag coefficient and pressure distribution of a UAV, which helps engineers to improve the performance of a UAV.

• Whirling wing configuration is capable of providing enough lift for flying and reducing lift for submerging by changing the mode of wing. This configuration is feasible for a submersible UAV.

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