Global Optimization for Cross-domain Aircraft Based on Kriging Model and Particle Swarm Optimization Algorithm

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\begin{flushleft}
\hspace{1cm} (Manuscript Received , ; Revised , ; Accepted , )
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Abstract

In order to further extend the working range of existed aircrafts, a new type of water-air cross-domain aircraft based on fixed-wing aircrafts with the addition of extra tandem ducted coaxial rotors and tail ducted propulsion system was herein proposed, which was driven by a hybrid power system. Due to its layout situation, the fluid characteristics underwater was especially analyzed based on CFD simulation experiments, which mainly aimed at the thrust force characteristics influenced by different layout parameters of tail ducts and different rotational velocities. In order to figure out the optimal layout which can reach the best performance underwater, a global layout optimization was accomplished with the former analysis results, which employed an optimization method based on PSO algorithm with the compensation of orthogonal test and Kriging model to decrease computational complexity and improve interpolation accuracy. The global optimal layout solution was finally obtained and validated to be reasonable through extra simulation experiments, and the proposed optimization method was also proved to be effective through the utilization for this studied case.

\textit{Keywords}: Cross-domain aircraft; Kriging model; PSO algorithm; Orthogonal test; Global optimization

1. Introduction

During the World War II, an idea to design a weapon which combined the functions of both bomber and submarine was proposed, but it finally failed due to the limit of technology in that period [1]. After decades, with the technology highly developed, the ambition to develop water-air amphibious aircrafts, which effectively improve the working space, environment adaptability as well as application range, is come up again [2].

Nowadays, one successful design strategy for cross-domain aircrafts is bio-inspired way, which combines the features of aircrafts and amphibious creatures using morphing structures and advanced materials. Gao et al. in MIT proposed a robotic flying fish with the pectoral fins made up of polyurethane coated nylon [3]. Fabian et al. in MIT [4] and Liang et al. in Beihang University [5] respectively designed gannet-inspired submersible aircrafts with morphing fixed wings which can be folded during the water entry process for further decrease of drag underwater. By imitating flying squids, Siddall et al. in Imperial College London imported a jet propeller to gannet-like amphibious aircraft to improve the efficiency of water-exit process [6, 7]. Chen et al. in Harvard University presented a hybrid aerial-aquatic micro-robot inspired by flapping-wing insects, which was driven by a pair of pair of piezoelectric actuators with extra buoyant adjustment device based on electrochemical reactions [8, 9].

Another typical design thought is based on multi-rotor technology, which has been widely utilized in Unmanned Aerial Vehicles (UAVs) and Remotely Operated Vehicles (ROVs). Alzu’bi et al. in Oakland University improved traditional quadrotors with additional water pumps for buoyancy and depth control underwater [10, 11]. Based on X-4 configuration, Maia et al. in Rutgers University utilized dual air rotors in each vehicle-arm with a column gap between the top and bottom motors, which highly improved effective lift force [11- 14]. Brazilian researchers Drews et al. changed bottom 4 air rotors into water ones in order to obtain better underwater performance [15, 16]. Feng et al. in Air Force Engineering University improved Drews’s design by importing two X-4 frames with replaceable column, due to which the height between two layers of rotors can be adjusted during the trans-media process [17, 18]. Lu et al. in Shanghai Jiao Tong University proposed a design concept combined with quadrotors and underwater gliders, which extended working endurance [19].

Obviously, the bio-inspired designs require high implementation cost, and the open-frame multi-rotor designs show unfriendly hydrodynamic performances. Therefore, a type of water-air cross-domain aircraft with duct propulsion system was herein proposed. The fluid characteristics underwater was especially analyzed, since the layout was mainly based on airplanes. In order to figure out the optimal layout which can generate the best performance underwater, a Kriging-based PSO algorithm was em-
ployed for the global optimization process, which finally resulted in an optimal solution with satisfying performance.

2. System architectures and working principles

2.1 System architectures

The proposed ducted cross-domain UAV can be regarded as a mixture of a fixed-wing aircraft with tandem ducted coaxial propellers and a submarine, and the layouts of the body, which consists of four ducts, two airtight cabin doors and a water storage, is shown in Fig.1.

Fig.1. The layout of the aircraft and the coordinate systems

In the flying condition, the lift force in the air is mainly provided by coaxial rotors in bigger and smaller ducts, which are also called main ducts, and the flight direction can be controlled by blade pitch adjustment devices shown in Fig.2 in each duct: the swash plates driven by linear actuators at bottom directly control the blade pitches of upper rotors. When the blade pitch angles are changed by forward flight directions, the upper rotors will tilt forward, which compels the rotating cone to tilt as well and generates forward aerodynamic forces. In the underwater condition, the architecture of airtight cabin doors is herein adopted to seal the bigger and smaller ducts. The tail propulsion ducts are designed to provide the thrust force for surging and yawing motions underwater. And the water storage can regarded as depth control system: its mass changes by storing different quantity of water, which will create a pitching torque in $X_O Y_O$ plane with the participation of buoyancy.

Fig.2. The detailed architecture of coaxial rotors in the ducts

Compared with the single rotor architecture, the coaxial rotors architecture consume less power to reach the same lift force requirements. Furthermore, it can help keep the balance of the whole system by offsetting a pair of opposite torques caused by the upper and lower rotors as well as compacting the entire duct architecture. Both of the main ducts share the same architectures, and they all adopt NACA 4415 airfoil profile. The tail propulsion ducts adopt the water rotors of 4415 profile, which can perform better in the underwater condition. And the two side-wings, which extra equip the former and latter rafters, spars and rips, adopt NACA 2412 airfoil profile according to their features of bend and tension and the coordination with the shape design.

As for the power source, a hybrid system with fuel engine and electromotor is applied: fuel engine mainly works in the air and the electromotor works underwater. There are two output shafts of the torque divider gearbox which is the core component of the system: the input shaft is connected with the engine through clutch 1; one of the output shaft directly transfers the power to the differential gear box which drives the coaxial air rotors in the main ducts; the other output shaft attaches the electric generator through clutch 2, which will charge the battery pack for underwater use. The battery powers the electromotor driven the water rotors in tail ducts and the water storage located the head of the aircraft, which follow the directions from the controller. And the schematic of the power system is depicted in Fig.3.

Fig.3. The schematic of the hybrid power system

2.2. Working principles

When the UAV works in the air, the life force is all provided by the main ducts and the flight attitude is controlled by the blade pitch adjustment devices in the ducts with the airtight doors open. Under this condition, the whole system is powered by fuel engine with both clutches engaged. When it flies near the water, the airtight doors soon close tightly with the engine shut down while the system will be powered by the battery pack with both clutches cut off. While it is diving into water, the water storage opens itself and starts to store water to change its self-mass. Meanwhile, the tail propulsion ducts start to provide the thrust force for the UAV and control the yawing directions with the adjustment of their rotational velocity.

3. Mathematical models

Different architectures of ducts and couplings of lift forces bring great difficulties to build the dynamic models of the UAV, and the main tasks of the analysis and simulation is to select a suitable coordinate system and establish its dynamic model.

3.1 The selection of the coordinate system

The coordinate systems including the ground one and the body one are selected as shown in Fig.1. $O_6$ is any point on the ground; $X_6$ axis represents the flight direction; $Y_6$ axis represents the vertical direction and $Z_6$ axis is concluded by right-hand prin-
ciples. $O_b$ is the barycenter of the body and the directions of coordinate axes are shown in the schematic. The angle around $Z_b$ axis is the pitch angle $\theta$; the angle around $Y_b$ axis is the yawing angle $\phi$ and the angle around $X_b$ axis is the rolling angle $\gamma$.

According to the knowledge of coordinate system transformation, the transition matrix from the ground coordinate system to the body one is concluded.

$$
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix} =
\begin{bmatrix}
  \cos \theta \cos \phi & \sin \theta & -\cos \theta \sin \phi \\
  -\cos \theta \sin \phi & \cos \theta & \sin \theta \sin \phi \\
  \sin \phi & 0 & \cos \phi
\end{bmatrix}
\begin{bmatrix}
  x_o \\
  y_o \\
  z_o
\end{bmatrix}
$$

(1)

3.2 The establishment of the dynamic model

The ducted water-air cross-domain UAV is regarded as a ideal rigid body, and its motion equations are constituted by the movement and rotation dynamic equations of the barycenter.

The translational dynamic equations of the barycenter are shown as followed:

$$
\begin{align*}
\frac{d}{dt} \left[ \begin{array}{c}
V_x \\
V_y \\
V_z
\end{array} \right] &= \left( \begin{array}{c}
I_{xx} \frac{d\phi}{dt} \\
I_{yy} \frac{d\theta}{dt} \\
I_{zz} \frac{d\gamma}{dt}
\end{array} \right) + \sum F_x \\
\frac{d}{dt} \left[ \begin{array}{c}
\phi \\
\theta \\
\gamma
\end{array} \right] &= \left( \begin{array}{c}
\frac{1}{I_{yy}} \left( V_y - \frac{dV_x}{dt} \right) \\
\frac{1}{I_{zz}} \left( V_z - \frac{dV_y}{dt} \right) \\
\frac{1}{I_{xx}} \left( V_x - \frac{dV_z}{dt} \right)
\end{array} \right) + \sum M
\end{align*}
$$

(2)

Where, $m$ represents the mass of the UAV; $V$ and $w$ represent the absolute velocity and rotational angular velocity under the body coordinate system relative to the ground coordinate system and $F$ represents the aerodynamic force.

The rotational dynamic equations of its barycenter are shown as followed:

$$
\begin{align*}
\frac{dx}{dt} &= u_x + u_y (w_z - w_y) - u_z (w_y - w_z) + \sum F_x \\
\frac{dy}{dt} &= u_y + u_z (w_x - w_z) - u_x (w_z - w_x) + \sum F_y \\
\frac{dz}{dt} &= u_z + u_x (w_y - w_z) - u_y (w_z - w_x) + \sum F_z
\end{align*}
$$

(3)

Where, $I$ represents the inertia moment of the body mass to each axis; $I_{xy}, I_{yz}, I_{zx}$ are the products of inertia and $M$ represents the moment acted on the aircraft.

And the relationship between the rotational angular velocity and Euler angular velocity under the body coordinate system is depicted as followed:

$$
\begin{bmatrix}
\dot{\phi} \\
\dot{\theta} \\
\dot{\gamma}
\end{bmatrix} =
\begin{bmatrix}
\phi \sin \theta + \dot{\theta} \\
\phi \cos \theta \sin \gamma + \dot{\phi} \\
\phi \cos \theta \cos \gamma + \dot{\phi}
\end{bmatrix}
= \begin{bmatrix}
\dot{\phi} \\
\dot{\theta} \\
\dot{\gamma}
\end{bmatrix}
$$

(4)

4. Fluid characteristics analyses underwater

The whole layout of the cross-domain UAV is based on fixed-wing aircrafts with tandem ducted coaxial propellers, therefore it’s more necessary to analyze its underwater characteristics rather than aerial ones. The thrust force underwater is mainly influenced by the lateral distance and longitudinal distance of two tail ducts and their rotational velocity. In this chapter, the fluid characteristics analyses underwater, which mainly aim at the impact factors mentioned above, are accomplished.
4.1 The model of the body with tail ducts

As mentioned in the section of working principles, the main ducts in the middle of the aerial vehicle will be tightly sealed when UAV works underwater so that the details of the main ducts can be simplified in the establishment of the model underwater. The schematic of the lateral distance $d$ and longitudinal distance $h$ are both depicted in Fig.4.

Fig.4. the schematic of the lateral and longitudinal distance

4.2 Mesh generation and boundary condition selection

4.2.1. Mesh generation

With the help of ANSYS ICEM CFD [20], the meshes are generated. In order to reduce the number of the meshes without reducing the quality of the meshes or increasing the size of each single mesh, the mesh model needs tailoring. The body of the UAV is perfectly symmetrical about the middle plane so that it’s feasible to only generate the mesh of a half body as shown in Fig.5(a), based on which the simulation result of the whole body can be calculated. The mesh of the tail rotors is also generated in Fig.5(b) to analyze the effects of the tail duct distance and tail rotor rotational velocity on thrust force.

Fig.5. The mesh generation

After the mesh generation of those main parts of the UAV, the meshes of each rotor are assembled into the mesh of body. A much larger calculation zone is selected to simulate the fluid environment, which is also meshed in the same way. In order to simplify the calculation, a smaller cubic structure with small meshes, which properly encases the mesh assembly, is generated. And then it’s assembled into a bigger cuboid with bigger meshes. All of the meshes above constitute the assembly building which is used for further simulation by Fluent.

Before the simulation, this assembly building needs testing and ICEM can also help delete those improper meshes and smooth the correct meshes automatically during the test. As shown in Fig.6, most meshes are satisfying for further operations with their quality above 0.3, which is a threshold proved to be acceptable by common solvers in Fluent.

Fig.6. The inspection of the mesh of the assembly building

Besides, the principle to select the minimum size of each mesh is the superficial area of each surface. If the primary selection of the minimum size doesn’t lead to a satisfactory test result, then a new mesh generation is needed.

4.2.2. Boundary condition selection

The boundary conditions in Fluent are selected as followed in table 1.

Table 1. The selection of boundary conditions

4.3. Flow field characteristics analyses

From the partial enlargement vision of pathlines in Fig.7, it’s clearly seen that the directions of streamlines turn disordered after the water flow passing the body, which is especially obvious near the tail part of the body.

Fig.7. The partial enlargement vision of water pathlines

From the pressure contours of the body in Fig.8, high-pressure areas are formed near the front parts of body, the joints between those two airtight doors and the body, the front parts of the wings and the front lips of the tail propulsion ducts, because of the resistances created by the water.

Fig.8. The pressure contours of the body

4.4. Fluid characteristics analyses

4.4.1. The effects of different lateral distances of tail ducts on thrust force

When the UAV works underwater, its working condition is supposed to be horizontal navigation with the front and tail wings fixed relative to the body. Keep the rotational velocity of the rotors at 500rpm and 1000rpm as well as the longitudinal distance at
200\text{mm}, and change the lateral distances into 280\text{mm}, 320\text{mm}, 360\text{mm}, 400\text{mm} and 440\text{mm} to finish the simulation and the analysis of the fluid characteristics underwater in Fluent. The changes of the thrust forces impacted by the lateral distance are concluded in Fig.9 and Fig.10.

Fig.9. The thrust force with a rotational velocity at 500rpm
Fig.10. The thrust force with a rotational velocity at 1000rpm

It’s obviously seen in those two figures above that the forces first increase and then decrease with the increase of the lateral distance, and the ducts can improve the thrust force for the UAV. As the rotational velocity grows, the forces also grow. And the joint force reaches its maximum when the lateral distance selects 360\text{mm}.

4.4.2. The effects of different longitudinal distance of tail ducts on thrust force

Keep the rotational velocity of the rotors at 500\text{rpm} and 1500\text{rpm} as well as the lateral distance at 280\text{mm}, and then change the longitudinal distances of those two tail ducts into 180\text{mm}, 190\text{mm}, 200\text{mm}, 210\text{mm} and 220\text{mm} to analyze the fluid characteristics underwater in Fluent and select the most suitable longitudinal distance. The changes of the thrust forces impacted by the longitudinal distance are shown in Fig.11 and Fig.12.

Fig.11. The thrust force with a rotational velocity at 500rpm
Fig.12. The thrust force with a rotational velocity at 1500rpm

It’s clearly shown in those two figures above that the forces change irregularly with the increase of the longitudinal distance, and the ducts also improve the thrust force for the UAV. As the rotational velocity grows, the forces also grow. And the joint force reaches its maximum when longitudinal distance selects 200\text{mm}, which is also a half of the height of the entire body.

4.4.3. The effects of different rotational velocity on the characteristics of rotors

The head direction of the UAV is supposed to be the positive direction and the rotor side that faces this positive direction is regarded as the face side. Keep the longitudinal distance at 360\text{mm} and the longitudinal distance at 200\text{mm}, and then change the rotational velocities into 500\text{rpm}, 1000\text{rpm}, 1500\text{rpm}, 2000\text{rpm} and 2500\text{rpm}. And the pressure contours under different rotational velocities are shown in Fig.13.

Fig.13. The pressure contours under different rotational velocities

It’s clearly shown in the figure that the pressures of the face side and the reverse side grow larger as the rotational velocity rises. The increase of the water flow velocity relative to the rotors leads to this phenomenon. And the pressure of the reverse side is always larger than that of the face one due to the flow velocity differences between these two sides, which also provide the thrust force when the UAV navigates underwater.

Keep the longitudinal distance at 200\text{mm} as well as the lateral distance at 280\text{mm} and 360\text{mm}, and change the rotational velocities into 500\text{rpm}, 1000\text{rpm}, 1500\text{rpm}, 2000\text{rpm} and 2500\text{rpm}. The force characteristics are obtained as shown in Fig.14.

Fig.14. The force characteristics under different lateral distances and rotational velocities and the same longitudinal distance

It’s easily concluded that all the forces increase as the rotational velocity rises, and the joint force of rotors in ducts, which is a bit larger than that of the body, is much larger than the thrust force of single rotors. The resistances are created during the navigation so that the joint force of the body is smaller than that of the rotors in ducts, and the duct architecture can improve the flow characteristics, which results in the thrust force differences between the rotors with ducts and the ones without them.

Keep the lateral distance at 320\text{mm} as well as the longitudinal distance at 180\text{mm} and 190\text{mm}, and keep the condition changes of rotational velocities same as the simulation above. Then the force characteristics are obtained as shown in Fig.15.

Fig.15. The force characteristics under different longitudinal distances and rotational velocities and the same lateral distance

It’s obviously seen from the figures that the simulation results are nearly same as those above. And it can also concluded that the effects of different rotational velocities on thrust force are not relative to the lateral and longitudinal distances. With the increase of the distances, the force characteristics remain a certain rising trend.
5. Optimization design and comparison

Based on the simulation results in the last section, an optimization design of different architecture layouts underwater is accomplished with the help of orthogonal test, Kriging model, and PSO algorithm in this section.

5.1. Orthogonal test

This orthogonal test [20] is designed to reduce the number of the simulations aimed at certain factors and levels. In this analysis, there are three factors which include lateral distance, longitude distance, and rotational velocity, and there are five levels in each factor, which means $5^3 \times 25 = 100$ times of simulation will be simplified if an $L_{25}$ orthogonal list is herein employed.

5.2. Kriging model

The Kriging model is a method of meta model based on the space correlation function, which can lead to the relationship between the spatial position and relevance of the data points got from the simulations in order to obtain the minimal variance. According to the simulation results based on orthogonal test, a kriging model [22-24] is established, which adopts the output force of the tail propulsion ducts as the objective function with the help of constant regression model. And the simulation arrangements based on this orthogonal test and the results of each simulation are depicted in Table 2.

<table>
<thead>
<tr>
<th>Table 2. The results of the orthogonal test and Kriging fitting</th>
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<tr>
<td>Fig. 16. The comparison between the simulation results and the fitting results</td>
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</tbody>
</table>

The comparison between the simulation results and the fitting results of kriging model is clearly depicted in Table 2 and Fig. 16, and they are perfectly coincident except the 22th simulation, which means the global error between them is quite small.

5.3. PSO algorithm

PSO stands for Particle Swarm Optimization [25-27], a type of evolution algorithm similar with iteration algorithm like genetic algorithm, which can help figure out the global optimal solution. Using the PSO algorithm, the optimization design is accomplished with MATLAB based on the Kriging model built in the last section. The calculating parameters are selected as shown in Table 3; the training values of PSO are shown in Fig. 17 and the optimal solutions of each factor obtained by PSO are shown in Table 4.

<table>
<thead>
<tr>
<th>Table 3. The calculating parameters of PSO algorithm</th>
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<tbody>
<tr>
<td>Table 4. The optimal solutions of each factor</td>
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</tbody>
</table>

5.4. Optimization comparison

A Fluent simulation based on a new model built according to the optimal solutions $d = 363.2321\, \text{mm}$ and $h = 196.5593\, \text{mm}$ is accomplished with the rotational velocity at 500rpm and 1000rpm. And the optimization comparison of joint forces is depicted in Fig. 18.

| Fig. 18. The optimization comparison of joint forces |

It’s obviously concluded that the joint force reaches the maximum when the lateral distance selects the optimal solution under the conditions of certain rotational velocity and longitudinal distance, and the circumstance of the longitudinal distance is just the same as this. It’s true that faster rotational velocity can provide higher thrust force, but faster velocity means higher requirements of the architecture. According to the optimal solutions, the rotational velocity $n = 1732\, \text{rpm}$ is the most suitable value that can not only provide enough thrust force but also protect the whole architecture.

6. Conclusion

The conclusions can be drawn as follows:

1. The overall layout of the architecture and the power system have been designed based on the particularities of the water-air cross-domain UAV, and the mathematical model and dynamic model are also built;
2. The fluid characteristics under submergence mode are analyzed by the CFD simulation, which mainly aims at the effects on thrust forces due to the differences in lateral distance, longitudinal distance and rotational velocity. According to the pressure contours of the body and rotors, the parts which need reinforcing are confirmed. It is concluded that the joint force will reach the
maximum when the lateral distance selects 360mm and the longitudinal distance selects 200mm. And it's also proved that the joint force will grow with the increase of the rotational velocity under the certain lateral and longitudinal distances;

(3) The architecture under submergence mode is optimized based on the PSO algorithm: the orthogonal test is designed and accomplished, based on which a series of simulations are finished; the Kriging model is built according to the results of those simulations mentioned above; and the PSO algorithm is applied on basis of the simulation results and the fitting results according to the Kriging model to figure out the optimal solutions that the lateral distance selects 363.2321mm, the longitudinal distance selects 196.5593mm and the rotational velocity selects 1732rpm. On the basis of the results of optimization comparison, all of the optimal solutions are proved to be reasonable.

Acknowledgment

This project is supported by Jilin Province Key Science and Technology R&D Project under Grant No: 20180201040GX, National Natural Science Foundation of China under Grant No:51505174, Scientific and Technological Development Program of Jilin Province of China under Grant No: 201701012060C, Foundation of Education Bureau of Jilin Province under Grant No: JJKH20170789KJ, Research Fund for the Doctoral Program of Higher Education of China under Grant No: 20130061120038, National Key Research and development program of China under Grant No: 2017YFC0602002.

References


Appendix

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Fig. 4. The schematic of the lateral and longitudinal distance

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(b) the mesh of the rotor

Fig. 6. The inspection of the mesh of the assembly building
Fig. 7. The partial enlargement vision of water pathlines

Fig. 8. The pressure contours of the body

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(a) the thrust force of the rotors
(b) the joint force of the rotors in ducts

Fig. 10. The thrust force with a rotational velocity at 1000rpm
(a) the thrust force of the rotors
(b) the joint force of the rotors in ducts
Fig. 11. The thrust force with a rotational velocity at 500rpm

(a) the thrust force of the rotors

(b) the joint force of the rotors in ducts

Fig. 12. The thrust force with a rotational velocity at 1500rpm

(a) the thrust force of the rotors

(b) the joint force of the rotors in ducts

Fig. 13. The pressure contours under different rotational velocities

The face side

The reverse side

(a) the rotational velocity at 500rpm

(b) the rotational velocity at 1000rpm

(c) the rotational velocity at 1500rpm
Fig. 14. The force characteristics under different lateral distances and rotational velocities and the same longitudinal distance

(a) $d=280\text{mm}$

(b) $d=360\text{mm}$

Fig. 15. The force characteristics under different longitudinal distances and rotational velocities and the same lateral distance

(a) $h=180\text{mm}$

(b) $h=190\text{mm}$

Fig. 16. The comparison between the simulation results and the fitting results
Fig. 17. The training values of PSO algorithm

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Fig. 18. The optimization comparison of joint forces
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(b) Joint forces under a certain longitudinal distance and a rotational velocity at 1000 rpm with different lateral distances

(c) Joint forces under a certain lateral distance and a rotational velocity at 500 rpm with different longitudinal distances

(d) Joint forces under a certain lateral distance and a rotational velocity at 1000 rpm with different longitudinal distances
Table 1. The selection of boundary conditions

<table>
<thead>
<tr>
<th>Setting</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit conversion:</td>
<td>Transform m into mm;</td>
</tr>
<tr>
<td>Material selection:</td>
<td>Select water flow as the fluid;</td>
</tr>
<tr>
<td>Input/output selection:</td>
<td>Take the negative direction of X, axis as the velocity input and take the positive direction of X, axis as the pressure output, which have already labeled in Fig.6. As for the density-increasing area of the body shown in the figure, it stands for the mesh assembly of the body, rotors and the smaller cubic structure;</td>
</tr>
<tr>
<td>Computational domain setting:</td>
<td>Select water as the working medium, and set the rotor state as moving wall rotation, which will never rotate relative to the neighbor area;</td>
</tr>
<tr>
<td>Interface selection:</td>
<td>Include the interfaces between rotational rotors and the body and the ones between the body density-increasing area and the computation domain, and the information including the rotation of the rotors and the stationary of the body is transmitted through those interfaces;</td>
</tr>
<tr>
<td>Solver selection:</td>
<td>Select the pressure solver, which is widely applied for incompressible fluid with smaller flow velocity.</td>
</tr>
</tbody>
</table>

Table 2. The results of the orthogonal test and \textit{Kriging} fitting

<table>
<thead>
<tr>
<th>Test no.</th>
<th>(d_{\text{mm}})</th>
<th>(h_{\text{mm}})</th>
<th>(n_{\text{rpm}})</th>
<th>simulation result</th>
<th>fitting result</th>
<th>error</th>
<th>relative error</th>
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<td>1</td>
<td>280</td>
<td>180</td>
<td>500</td>
<td>3.9932</td>
<td>4.2546</td>
<td>0.2614</td>
<td>0.0655</td>
</tr>
<tr>
<td>2</td>
<td>280</td>
<td>190</td>
<td>1000</td>
<td>16.0574</td>
<td>15.2802</td>
<td>-0.7772</td>
<td>-0.0484</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>200</td>
<td>1500</td>
<td>38.0499</td>
<td>39.4275</td>
<td>1.3776</td>
<td>0.0362</td>
</tr>
<tr>
<td>4</td>
<td>280</td>
<td>210</td>
<td>2000</td>
<td>66.5626</td>
<td>65.4332</td>
<td>-1.1294</td>
<td>-0.0170</td>
</tr>
<tr>
<td>5</td>
<td>280</td>
<td>220</td>
<td>2500</td>
<td>105.0224</td>
<td>106.5510</td>
<td>1.5286</td>
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</tr>
<tr>
<td>6</td>
<td>320</td>
<td>180</td>
<td>1000</td>
<td>16.0066</td>
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<td>-0.0484</td>
</tr>
<tr>
<td>7</td>
<td>320</td>
<td>190</td>
<td>1500</td>
<td>36.7329</td>
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Table 3. The calculating parameters of PSO algorithm

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Table 4. The optimal solutions of each factor

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</table>

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