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The Kinematics Analysis of Webbed Feet during Cormorants' Swimming

Jinguo Huang, Xiao Gong, Zeyu Wang, Xiaoqiang Xue, Xingbang Yang, Jianhong Liang, Daibing Zhang

***Abstract*— to reveal the flippers propulsion and the self-adjustment mechanism, which can be used to inspire the design of submersible aircraft. This article makes some research on the bionic observation on the movement of cormorant's flippers during the surface take-off process, bringing forward a flippers propulsion theory, which there is a new undulate propulsion besides the common flapping propulsion. Observation use the video image processing technology to analyze the trajectory of cormorant' flippers and the forced characteristics, revealing the mechanism of effective propelling force of cormorant's flippers. It provides a new train of thinking for people to develop the submersible aircraft with high efficiency.**

I. INTRODUCTION

Submersible Aircraft as a new concept vehicle can freely shuttle between the sea and air have been proposed, which has flight and underwater stealth modes. A study of the US Navy shows that if the Navy want to gain advantage in battle with the enemy, it must place variety of sensors out of the ships and submarines, of which the most important is to have air superiority. This has "Hunter - fly" dual function submersible aircraft can satisfy this demand; it will change future operational model and played a significant impact on the future development of the war pattern.

Undoubtedly, Military strategists have been looking forward this new concept of aircraft for long time. As early as 1934, the Soviet Union, Polisia. Yushakov proposed a vision of cross-sea airship, after which some people have been proceeding bold studies and tries. The Defense Advanced Research Projects Agency (DARPA) of the Pentagon is trying to develop a new concept weapon that can be used in underwater and air application [1, 2]. During the year of 2005 and 2006, DARPA has allocated $ 16 million for the demonstration and design of "Cormorant" submarine- aircraft. University of Michigan developed the take-off and landing unmanned aerial vehicle "flying fish" in 2009 with the support of DARPA [3]. Lincoln Laboratory in MIT announced a swept-wing test prototype aircraft splashing into the water on April 1, 2012[4]; our team designed a 90-degree swept wing based on the concept of the diving aircraft and the mechanism of water splashing in 2009.

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Jinguo Huang is a Ph.D. student in Robotics Institute, Beihang University, Beijing, 100191, China (corresponding author to provide phone: 010-82338033; fax: 010-82338271; e-mail: huangjinguo2012@126.com).

Xiao Gong is with the Research Center for Computer and Microelectronics Development of MIIT (China Software Testing Center) (e-mail: gongxiao@cstc.org.cn).

Zeyu Wang is a B.E. student in Institute of mechanical engineering and automation, Beihang University, Beijing, 100191, China (e-mail: wdyxwzy@126.com).

Xiaoqiang Xue is a M.E. student in Institute of mechanical engineering and automation, Beihang University, Beijing, 100191, China (e-mail: xuexiaoqiang1992@163.com).

Xingbang Yang is a Ph.D. student in Robotics Institute, Beihang University, Beijing, 100191, China (e-mail: xingbang1987@ 163.com).

Jianhong Liang is with the Robotics Institute, Beihang University, Beijing, 100191, China (e-mail: dommy_leung@263.net).

Daibing Zhang is a Research associate in National University of Defense Technology, Hunan, 410073, China (e-mail: swimsord@163.com).

With the support of the National Science Foundation of China, Our team have proceed a series of studies concentrating, and have designed a swim-like submersible aircraft since 2011[5]. It is obvious that the development of submersible aircraft will enter an unprecedented period and intensify the development of submersible aircraft in China, which has great application value and profound strategic significance.

However, because of the huge difference in the physical properties of water and air, leading to huge difficulties in water-air media transition. There has not yet been a craft which can really fast and freely access to the interface between the sea and the air. As for water diving, our group studied the phenomenon of boobies' variable structure and variable plumage including feathers, down and air when diving into the water. We propose the variable structure bionic design methods of crossing water-air interface to realize the basic theories and methods [6-8] of submersible aircraft quickly diving into the water. As for the water take-off, there has not been any relatively efficient and practical method reported, pending further scientific research.

Submersible aircraft works includes water diving and water take-off two key processes, our group have studied the mechanism of the phenomenon partially into the water which been based on high-speed boobies splashing into the water, which is used to guide the water diving feature design and implementation of submersible aircraft; As for the water take-off problem, at home and abroad are still lack of theoretical research. Therefore, the project proposes to research programs of imitating webbed-helped short takeoff of cormorant. According to historical records, at home and abroad in the basilisk lizard, water strider and other insects, attitude adjustment has been made from a number of ground-breaking research results. In recent years, many articles papers published in top international journals on SCIENCE and NATURE, revealing the corresponding movement mechanism and achieving the bionic design and experimental mechanism verification. By drawing on research in these areas, the project will contribute to research on cormorant's water propulsion and attitude of self-adjusting mechanism to help advance this project bionic water bodies and complex self-adjusting

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mechanism design attitude, and ultimately to promote submersible aircraft achieve rapid short-distance take-off capabilities.

Through the phenomenon observed that the rapid short-distance surface take-off of cormorant utilizes webbed feet and produces forward and upward thrust, the cormorant controls the speed and angle of the flippers beating water surface, resulting obliquely forward and upward thrust. By flapping wings against most of gravity, the cormorant achieves to balance the attitude control through the coupling body parts. This proves the feasibility and potential value of the cormorant's take-off mechanism in terms of the use of the project.

Fig. 1.Cormorants

Therefore, the paper proposes the bionic design methods of submersible aircraft copying cormorant effluent process, through the study of webbed feet propulsion in the process of rapid short-distance surface take-off. Finally design the imitation cormorant's flippers propelling mechanism and achieve theoretical foundation and bionic design methods for the future submersible aircraft.

II. EXPERIMENT OF FLIPPER'S MOVEMENT OBSERVATION

A. *Experimental Scene*

Experiments was carried out in an aquarium of 1.2 meters wide and 1.8 meters long. Install lighting above the aquarium and fix the camera with the proper angle to the water surface. The cormorant was placed into the water in the aquarium to imitate cormorant's surface take-off process, as well as some fish, the food of the cormorant. The observation experiment used two photron fastcam ultra high speed camera in the speed of 1000 capture per second to record videos of the motion morphology of each joint of cormorant's flippers when it caught fish and jumped out of the water. The two cameras are placed at a 90 degree angle to each other, while with the front of glass surface of the tank their at a 45 degree angle.[9-11]

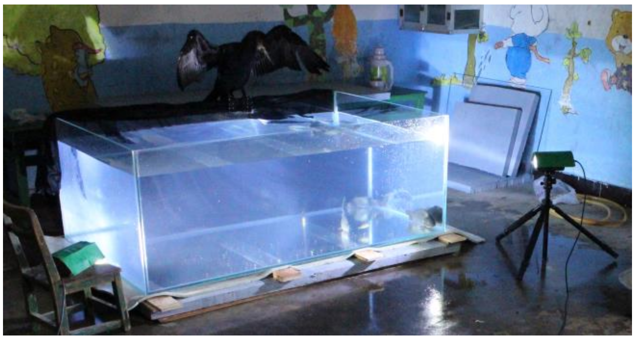

Fig. 2.Experimental Scene

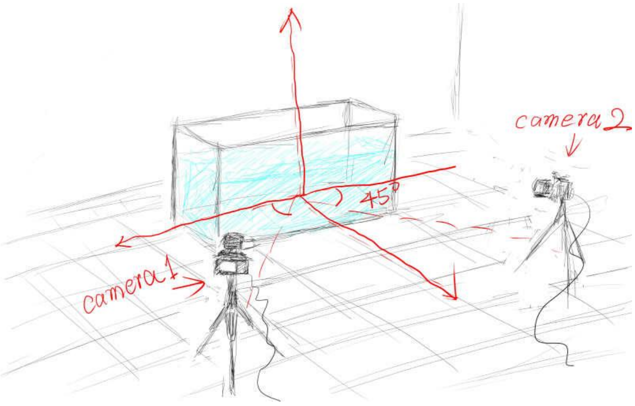

Fig.3.Experimental scene model

B. *Experimental Procedure*

Firstly, make observations and records of the flying behaviors of the flippers in the state of flying with the help of the high-speed videoing technology. When using the high-speed camera to observe cormorant behaviors, we need to mark each joint and collect the data in the future. We will analyze the sequence of images by extracting the key points[12] and we can get the complete motion parameters of each joint in the process of the cormorant's surface take-off.

(a)Marking for the Cormorant's Flippers (b) Cormorant state of motion in water

Fig.4.Collecting motion parameters

The experiment started from 2D images, and it analyzed the forms of motion of the five joints of cormorants' right foot the outer-most toes. In the experiment, 900 images were tracked for each joint, including steering, watering and all the other watering movements. [13]

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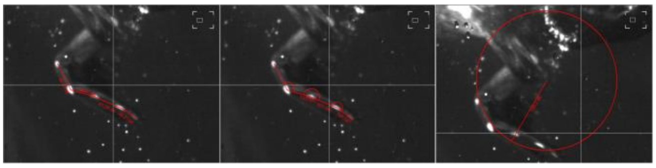
C. Experimental Results

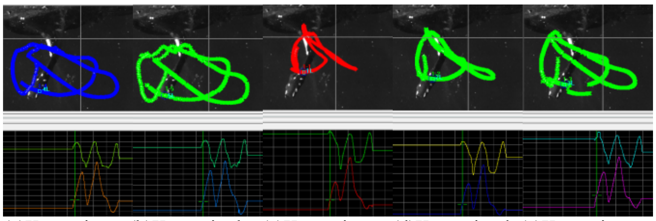
According to the analysis of the previous coordinate system calibration, two identical cameras can be used to definite any point in the space. Using the calibration plate made before, the relative coordinates of the black dots on the calibration plate can be quoted into the calibration coordinate system in the form of files by strict measurements.

We can clearly see the correspondence between the actual coordinate of each marker and the 2D images of each marker. We can get the following three figures by calculating. The two blue blocks on the top of the right corner represent the positions of the two cameras, while yellow blocks and red blocks are constructed based on the two scenarios of 2D coordinate system. The higher degree of the overlap of the two colors, the more accurate the coordinate system were established.[14-16] According to the detailed analysis, the system error of coordinate system was between 0.2853 millimeter and 9.0255 millimeters.



(a)Tracking data Analysis (b)The analysis of the key point in the angle (c)The Fits of the key points in coordinates

Fig.5.Flapping process of ProAnalyst and its 2D tracking



(a)Key point a (b)Key point b (c)Key point c (d)Key point d (e)Key point e

Fig.6.ProAnalyst for 2D tracking of the five key points in the flapping process

We made tracking analysis of the five joints of the cormorant's first toe on the left foot when the cormorant took off from the water surface. The above five figures are the moving tracks of the five joints in the chosen time. The image coordinates of each joint can be generated in order to solve the problems of velocity and acceleration vector according to the moving tracks [17].

We can observe the state of the surface flapping of the cormorant directly, and according to the captured video sequences' extraction and analysis, the cormorant can achieve water skiing in the water by the flapping of the flippers. When flapping, two flippers move alternatively, it moves slowly and slightly. And the states of the flapping flippers is the main moving form for the cormorant. In general, moving forward, moving backward and turning or other sports of the cormorant are achieved by flapping into different directions using different intensity with the help of flippers.

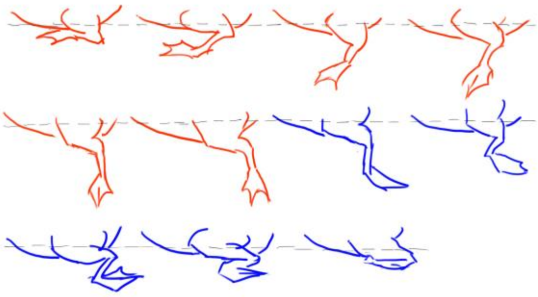
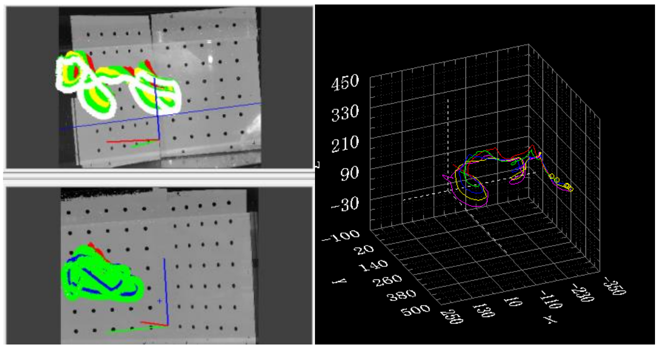


Fig.7.Flippers' flapping motion attitude for water skiing

The regulation of movement is shown above when the cormorant's flippers flap. When one flipper of the cormorant moves forward, the leg forces and the flipper slides back. Because of the water pressure, the flipper is open, which equals to increasing the contact area with the water, so, the greater impetus is produced. In that case, the force between the flipper and the water benefits the movement, while the movement appears as a whole outer arcuate motion. Similarly when another flipper moves forward, the flipper packs up and closes because of the impact of the water, which decreases the contact area with water. In that case, the force between the flipper and the water hinders the movement. The retraction of the flipper is more gently when sliding backwards. So, the resistance is small, while it appears as a whole within the arc motion.

3D reconstruction synthesis is the logogram of reconstruction of three-dimensional motion， aiming to transfer the 2D screen coordinates of the constructed image into 3D objects. After drawing check, we illustrate trajectory substantially within the calibration coordinates. After calculation, the trajectory of five joints in space is as shown below.



(a)The relative position of the key points of the trajectory of the coordinate system (b) The key point in 3D space trajectory

Fig.8.The reconstruction of flapping motion process of three-dimensional posture [13]

III. THE EXPERIMENTAL DATA PROCESSING AND ANALYSIS

A. The flapping propulsion of flippers' movement

The above analysis can finally get five joints in the physical space of each time frame image with respect to the

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calibration of the three-dimensional coordinate space. The curve can be described with parametric equations：*X=x(t)*，*Y=y(t)*，*Z=z(t)*，Let's assume x(t), y(t), z(t) is three polynomial functions about the parameter t，then supposing: .If given a set of parameters, there is a curve, we can calculate the total variance of this curve and data points and use optimization algorithms to minimize the total variance, then the curve fitting parameters can be got. Of course, it is the equation of the curve. Because of the meaningless of parameter t for this research, you can eliminate parameter t in the final curve equation, getting an equation about parameters x, y and z.

Three-dimensional nonlinear curve fitted as follows:

Setting the objective function M, it can be arbitrary, for instance, set A is a two-dimensional array, placing all of the three-dimensional coordinates x, y and z, the third dimension z = [x, y], column vector x = data (:, 1), y = data (:, 2), z = data (:, 3). *f=a(1)*x.^2+a(2)*y.^2+a(3)*x.*y+a(4)*x+a(5)*y+a(6)* Here the parameters from a (1) to a (6) are the coefficient values of the objective function, f corresponds to the fitted value of z.

X=[*x y*] ，integrate the two column vector into an array; *z1*=fx (*beta*, *X*); of which the parameter z1 is a predicted value. Given data of vector x, y and z as well as the fitting function [beta, R, J] = nlinfit (X, z, fx, beta0), draw the parameter x, y, z and z1 in the coordinate system at the same time when graphing.

Thereby we obtain the trajectory equation of five key points fitting as following:

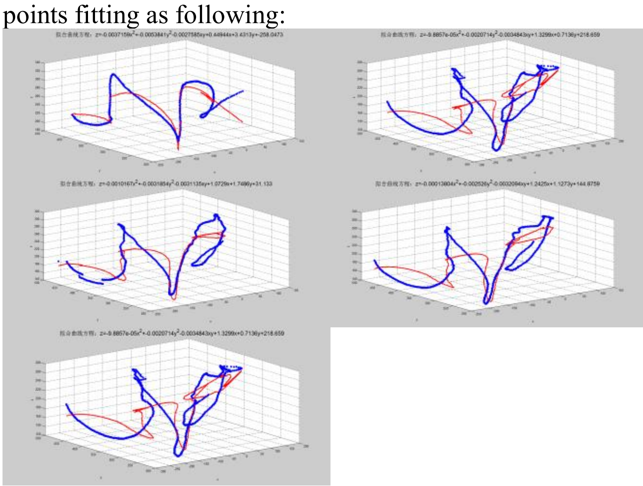


Fig.9.The equation fitting of flippers flapping process

B. The undulate propulsion of flippers' movement

In the experimental observations, we found that in addition to the cormorant's flippers flapping motion with high speed, there is also a low velocity motion. When the cormorant heads into the water to forage, it will adjust the position and posture through the low velocity propulsion of the flippers. The study of the cormorant's behavior shows that the flippers splash into the water from side to side, for its use of anti-generated force to make the body forward. As the fish swimming in the water. The cormorant's swimming form is similar to a sine wave. We call it the undulate propulsion. Based on the results of the motion analysis when the flipper's first toe takes undulate propulsion forward, this section puts forward the basic geometry of the flippers' undulate propulsion advance, and establishes the motion equations. The undulate propulsion of the cormorant was first proposed by video physical experimental approach.

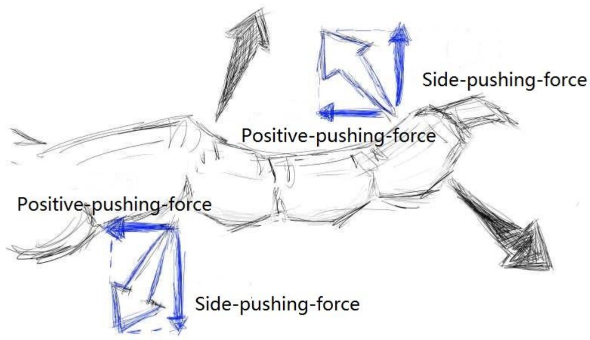
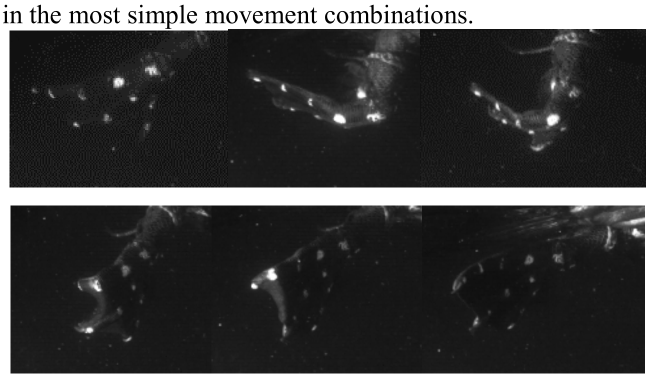


Fig.10. The joint force analysis under the undulate propulsion state

It is widespread in animals using limbs fluctuations to thrust, from protozoan using flagellated to swim to dolphins and eel, undulate propulsion has been used for thousands of years by animals. The history that human understand this phenomenon and study its propulsion mechanism can be traced back to the 1960s. In the aspects of fluid dynamics modeling and computational, scientist Lighthill took the lead on the slender body of the fish and made a long thin body model, getting the quasi-steady solution of thrust, output power, useful power and fluid propulsion efficiency.

For undulate propulsion, specific performance is when swimming in the water the flippers of the cormorant moves marginally, and provided motivation by fluid ripples caused by promoting water quality. It is generally used when the cormorant steers or adjusts the direction of movement, mainly used for the cormorant fine-tuning its athletic stance.

The figure was captured animation of the flippers' undulate propulsion following the time, the characteristic of flippers' undulate motion is each joint takes circular motion with respect to the upper joint to achieve posture adjustment in the most simple movement combinations.



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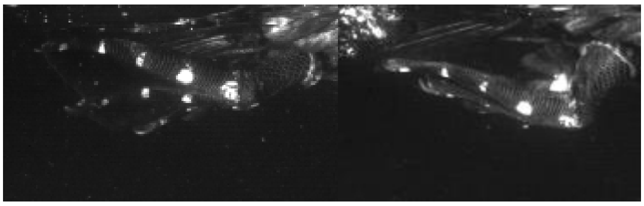

Fig.11.The motion posture of the flipper while fluctuates water skiing

First fit curve of five key points during the undulate propulsion of the flipper. As shown below:

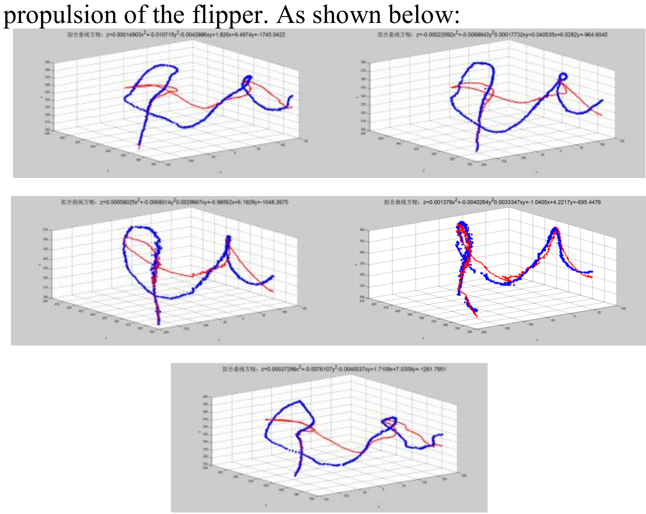

Fig.12.The equation fitting of the flipper's undulate propulsion

This section focuses on the fluctuation generated by flippers when the cormorant swims in the water. Undulate propulsion principle regards flippers of the cormorant as research object. It believes that the cormorant's flippers drives the enveloped water quality to discharge backward, resulting in the formation of thrust and thus undulate propulsion. This paper argues that the movement patterns of the movement of cormorants' flippers undulate propulsion in water is seen as a similar sine wave in the three-dimensional space. Imagine draw a sine wave in a piece of paper and the paper will be bent and folded random. This is the essence of undulate propulsion of the cormorant's flippers.

Based on the above analysis, this paper argues the motion equations of the flipper's undulate propulsion movement as follows:

$$y = A(x)\sin(2\pi t / T) + b \tag{1}$$

According inferred actual three-dimensional space equation of the flipper' undulate propulsion, the equations of motion can be assumed as following:

$$z = f(x,y) = a + b * \sin(p * pi * x) + c * \sin(q * pi * y) + d * \sin(r * pi * x * y)$$
$$+ e * \exp(-(s * x)^\wedge 2) + f * \exp(-(t * y)^\wedge 2) + g * \exp(-(u * x * y)^\wedge 2) \tag{2}$$

As shown, select a labeled joint waveform equation fitting to get on waveform equation fitting, according to the fitting results of polynomial equation:

$$z = 0.001378x^2 - 0.0040264y^2 + 0.0033347xy - 1.0405x + 4.2217y$$
$$-695.4476 \tag{3}$$

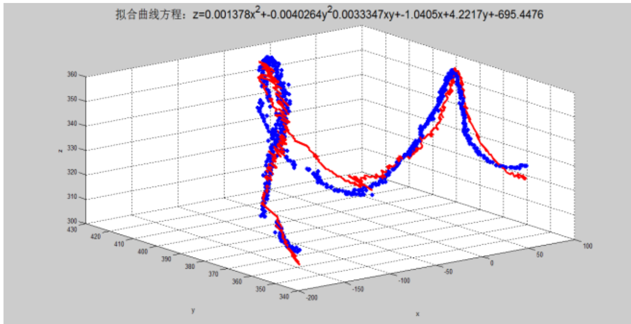

Fig.13.The equation prototype of flippers volatility curve three-dimensional propulsion

See the parameter Z as the new variable formed by the undulation by two variables x and y, while adding the component e, equivalent to axis adjustment factors, the value of which is to compensate the differences caused by coordinate rotation, fitting as follows :

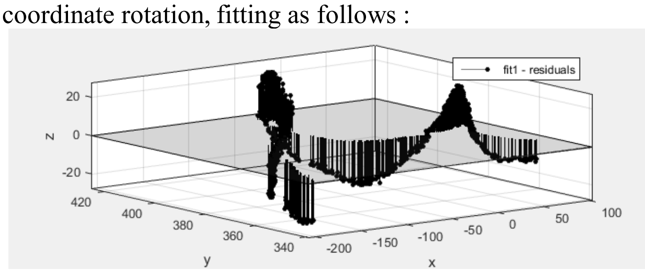

Fig.14.The equation model of Three-dimensional flippers fluctuations propulsion curve

The results are as follow:

Coefficients (with 95% confidence bounds):

$a = 336.8$, b =-2.544, c =-0.06589, $d = 0.4047$, e =-8.259, f = 0.9575, g =-5.451, p =-0.05462, $q = 0.8201$, $r = 0.7675$, s = 73.47, $t = 0.5469$, $u = 0.9971$.

Goodness of fit:

SSE: 1.728e-05

R-square: 0.99666

That is

$$z = f(x,y) = 336.8 - 2.544\sin(-0.05462\pi x) - 0.06589\sin(0.8201\pi y)$$
$$+0.4047\sin(0.7675\pi xy) - 8.259\exp(-(73.47x)^\wedge 2)$$
$$+0.9575\exp(-(0.5469y)^\wedge 2) - 5.451\exp(-(0.9971xy)^\wedge 2) \tag{4}$$

IV. Conclusion and Future Work

The project observed the surface web-assisted short - distance take-off process and got the motion parameters of each joint of the fins with the help of the high speed camera motion capture system. It can be concluded that the video in each frame of the image marks the coordinates of the point and the two cameras can realize video synthesis and 3D motion reconstruction. The form of flippers' exercise motion can be divided into flapping and undulation two kinds of forms. By fitting to the three-dimensional coordinates of the movement, we got the curve equation of the five marked

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points of flippers and achieved the description of the flapping and undulation. Finally, we defined the equation form of undulate propulsion motion in the 3D space.

In order to study the pose adjustment technology during the take-off process, there are still some problems to be deeply studied in the topic. Based on the two kinds of motion fitting equation, we can also analyze the amplitude, phase and more kinematic information of curve in detail and further reveal the internal mechanism. On this basis we can carry out the computational fluid dynamics (CFD) analysis and device test of the effect between the cormorant's flippers and the surface, through the CFD modeling, simulation and test device, it will reveal the mechanism of the cormorant's flippers to produce effective propulsion. Through analyzing the aerodynamics of the cormorant's wings, especially in the interaction of head, neck, wing, feet and tail, we study on the attitude self-adjustment technique surface of the surface take-off.

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