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# Mechanical design and dynamics system identification of two-section Flapping Wing Aircraft

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**Abstract.** The mechanical design and system identification of the Flapping Wing Aircraft (FWA) has always been a problem. In this paper, we design a two-section FWA through the study of bird flight, where the wing structure is divided into the inner wing and outer wing, which can imitate the flight of birds. When flapping upward, the wings can be folded to reduce resistance, and when flapping downward, the wings can be expanded to increase lift. This flying method can improve the flight efficiency. The aircraft we designed has achieved flexible flight under human operation. Aiming at the complex problem of dynamic modeling of FWA, this paper proposes a linear system model by analyzing the force of the aircraft. We use the collected flight data to train the system model. The training of the model uses the gradient descent method to minimize the loss function, and the accuracy of the model is verified with the test data. The experimental results show that the system model can accurately calculate the acceleration, velocity, angle velocity and orientation of the aircraft based on the current control input.

## 1. Introduction

FWA is an aircraft that can fly like a bird by flapping its wings. Its principle is different from multi-rotor wing and fixed wing aircraft. The flight principle and the mechanical structure of the multi-rotor and fixed wing aircraft is simple. However, there are common problems with the multi-rotor and fixed wing aircraft, such as high noise, low flight efficiency and short battery life. In contrast, the FWA has the advantages of quietness, bionics, and high flight efficiency: the FWA flies through the wings, making less noise; it flies like a bird, so it is camouflaged for some missions; the FWA generates lift and thrust by flapping its wings and can glide with the help of airflow, so it has higher flight efficiency. Due to the unique advantages of the FWA, it attracts much attention in recent years [1][2].

After 150 million years of evolution, birds have grown feathers, learned how to flutter, finally learned fly. Their wings can stretch during flight. When birds fluttering upward, they pick up wings to reduce resistance. When fluttering down, they expand wings to increase lift. The bones of birds are also important. It consists of three parts, the humerus, ulnas and carpals. The humerus and ulnas can realize flapping action. The literature[3] points out that the function of carpals is also important to control turning. Many documents have designed FWA, but the wings are simple. It has a single bone (single section) that can only rotate around the fuselage, this causes it unable to control the roll. Send et al[4] first designed the two-section FWA SmartBird, which analyzed the design structure and flight principle of two-section FWA, but did not research the modeling and system identification of FWA. Like the bones of bird's wings, the wings of FWA are designed into three parts, the inner wing, the



outer wing and servo on the wing tip, which similar to the bird's humerus, ulnas and carpals. During the flapping process, the inner and outer wings are linked, when the bird flutters upward, wings are folded, then the wings are gradually extended. At the highest point, the wings are fully opened, then keep moving to the lowest point. A servo is mounted on the tip of the outer wing, similar to the wrist of a bird, so that roll of the airfoil can be controlled by the servos.

System identification of flapping wing dynamics is also a difficult problem. It is a complex system because the aircraft generates lift and thrust through the deformation of wings, so the calculations are complicated. The literatures[5][6][7] analyze the thrust and lift of the FWA, and present the current progress and challenges for the FWAerodynamics. System identification can simplify the modeling problem. By system identification, we can calculate the acceleration and angular velocity according to the current input from the remote control, and then calculate the velocity and orientation. For system identification of aircraft, Abbeel et al[8] propose system identification based on acceleration and angular velocity prediction, and verified the correctness of the model on the helicopter. Chand et al[9] analyze the model of the FWA and verify the correctness of model in simulation, but did not verify with real flight data. Oh J et al[10] proposed a linear system identification method and achieved attitude control in flight, and have made experiment on the single-stage FWA. Its structure is simple and difficult to control. The article also mentions that it has been flying to the right because it cannot control the roll of the aircraft. In this paper, a two-section FWA is designed, and a linear system model is proposed through force analysis. By training with the real flight data, the model can calculate the acceleration, velocity, angular velocity and orientation of the aircraft based on the current control input, and can verify the prediction ability in the test data.

The paper is divided into the following sections. The second section introduces the mechanical design and electronic system of the two-section FWA. The third section describes the formulas and steps for dynamic system identification, and the calculation of velocity and orientation. The fourth section shows the results of our experiments. The final section is the analysis and summary.



Figure 1. two-section FWA.

## 2. Aircraft design

The two-section FWA designed in this paper is shown in figure 1. The size of the aircraft is magnified three times according to the actual data of the seagull. It consists of three parts: the fuselage, the wings and the tail. The middle of the fuselage is hollowed out for the battery and electronic system, and the outer surface is wrapped with foam to protect the body. The wing is divided into three parts: the inner wing, the outer wing and the servo on the wing tip. The inner and outer wings imitate the fluttering of birds, and the servos on the wing tip control the roll of aircraft. The tail is composed of a flat tail and a vertical tail, which controls the pitch and yaw of the aircraft, respectively. The aircraft skeleton is cut from carbon fiber and the fuselage skin is cut from 2mm thickness of foam. The design parameters of the two-section FWA are shown in table 1.

Table 1. Design parameters.

property	value
Fuselage length	82cm

Wingspan	170cm
Weight	514g
Flapping frequency	1~6Hz
Battery	800mAh,3S

The most complicated part of the aircraft is the mechanical structure, which consists of a motor, gears, rocker arms and connecting rods, as shown in figure 2. The power of FWA comes from the brushless motor which is hidden behind the gear C1. The motor drives the gear C1, the gear C1 drives the gear C2, and the gear C2 drives the gear C3. It should be noted that C1 does not drive C2 and C3 at the same time because they rotation in opposite directions. There is a 2-stage deceleration between the motor and gear C3, with the reduction ratio  $i$  of 1:25.8. A rocker arm is fixed on the gears C2 and C3, which will drive the rocker arm to rotate together. The connecting rods L1 and L2 are mounted on the rocker arm, the X point of L1 is fixed on the fuselage, and the other section of the connecting rod is fixed at the joint of the inner wing and the outer end wing. Both ends of the connecting rod are fixed by bearings and can be rotated. L1 and L2 as a whole form a long and narrow quadrilateral.

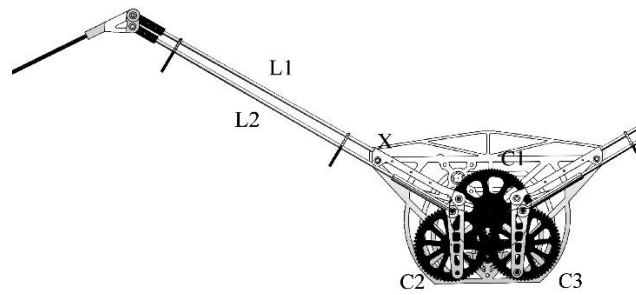


Figure 2. The FWA mechanical drawing.

When C1 rotates clockwise, C2 rotates counterclockwise, and drives the rocker arm to move periodically and flap the wings like a bird. When the rocker arm on the C2 gear rotates clockwise in the right half circumference, the rocker arm moves from the highest point to the lowest point. By leveraging, L1 and L2 rotate clockwise around point X, and the wings flap upwards. At the same time, the quadrilateral is deformed, and the rocker arm pulls the L2 to move inward, so that there is an angle between the inner wing and the outer wing, similar to the bird wings shrinking when fluttering upwards. Similarly, when the C2 gear moves in the left half of the circumference, the rocker arm drives L1 and L2 to rotate counterclockwise, pushing L2 to move outward, so that the angle between the inner and outer wings becomes smaller, similar to the birds. The flapping process of the aircraft is shown in figure 3.





Figure 3. The flapping process of the aircraft.

The electronic system of the aircraft consists of a brushless motor, four servos and a Pixhawk Mini[11] flight control system. The brushless motor is used to drive control the flapping of the wings. Two servos are mounted on the tip of the wings to control the roll by driving the twisting of the wings, similar to the ailerons in the fixed wings. The other two servos are mounted on the flat tail and the vertical tail to control pitch and yaw. The Pixhawk Mini is the flight control center. The specifications of the system are shown in table 2.

Table 2. Specifications of the electronic system.

Name	Specification
Motor	ECO 2308C brushless dc motor
Servos	EMAX ES08MDII
ESC	HOBBYWING SKYWALKER 20A
MCU	STM32F407VGT6

### 3. System Identification of the Dynamic Model

We establish the system model of the aircraft through the analysis of the aircraft. The input of the system model is the input from the remote control. The output is the acceleration and angular velocity of the aircraft, and then the velocity and orientation of aircraft in the spatial coordinates are calculated.

The state of the flapping wing includes position( $x, y, z$ ), velocity( $\dot{x}, \dot{y}, \dot{z}$ ), acceleration( $\ddot{x}, \ddot{y}, \ddot{z}$ ), orientation( $\phi, \theta, \psi$ ), and angular velocity( $\dot{\phi}, \dot{\theta}, \dot{\psi}$ ). In order to distinguish different coordinates, we use subscript  $s$  to represent the spatial(world) coordinates, and use subscript  $b$  to represent the body coordinates. The speed in spatial coordinates ( $\dot{x}_s, \dot{y}_s, \dot{z}_s$ ) indicates the speed relative to the east, north, and sky, respectively. The speed in the body coordinates ( $\dot{x}_b, \dot{y}_b, \dot{z}_b$ ) indicates the forward, rightward, and downward speeds of the aircraft. The orientation ( $\phi, \theta, \psi$ ) represent the roll, pitch, and yaw of the aircraft. The four-dimensional input of the FWA from the remote control is:

- $u_1$ : The throttle value. It controls the speed of the brushless motor, ranging from 0 to 1. The higher the value, the faster the speed.
- $u_2$ : The roll input value. It controls the angle of servos on the tip of the outer wing, ranging from -1 to 1.
- $u_3$ : The pitch input value. It controls the angle of servos on the flat tail, ranging from -1 to 1.
- $u_4$ : The yaw input value. It controls the angle of servos on the vertical tail, ranging from -1 to 1.

$u_1$  controls the speed of the motor through the output voltage of the ESC. For example, when  $u_1$  is equal to 1, all the battery voltage is supplied to the brushless motor. When  $u_1$  is equal to 0.5, half of the battery voltage is supplied to the motor. The specification of the brushless motor is 1180kv, which means that for every 1v increase in voltage, the speed increases by 1180r/min, without load. Therefore, the flapping cycle of the aircraft can be obtained.

$$T = \frac{i}{C_f * u_1 * Bat * kv} * 60 \text{ s} \quad (1)$$

In the formula,  $u_1$  is the throttle value,  $Bat$  is the battery voltage, which can be measured by the electronic system,  $i$  is the reduction ratio, 60 is a minute to second conversion. It was found in the experiment that the motor torque is small due to the small throttle, and only when the throttle value  $u_1$  exceeded 0.16, the wings began to flutter. According to the formula of the cycle to the angular velocity, the expression of the angular velocity can be obtained:

$$\omega = \begin{cases} \pi * C_f * u_1 * Bat * \frac{kv}{30 * i} & u_1 \geq 0.16 \\ 0 & u_1 < 0.16 \end{cases} \quad (2)$$

Based on the actual flight data,  $C_f$  can be calculated to be approximately equal to 0.836. According to the input of 4 dimensions of the remote controller, the formula for calculating the angular velocity of the aircraft can be proposed[12]:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} a_{11} \sin(\omega + a_{12}) + a_{13}u_1 + a_{14}u_2 + a_{15}u_3 + a_{16}u_4 + a_{17} \\ a_{21} \sin(\omega + a_{22}) + a_{23}u_1 + a_{24}u_2 + a_{25}u_3 + a_{26}u_4 + a_{27} \\ a_{31} \sin(\omega + a_{32}) + a_{33}u_1 + a_{34}u_2 + a_{35}u_3 + a_{36}u_4 + a_{37} \end{bmatrix} \quad (3)$$

In the formula,  $\omega$  is the angular velocity of the aircraft flapping. After the angular velocity is obtained, the orientation is obtained by integrating the angle velocity.

$$\begin{bmatrix} \phi \\ \theta \\ \varphi \end{bmatrix} = \begin{bmatrix} \int \dot{\phi} dt \\ \int \dot{\theta} dt \\ \int \dot{\varphi} dt \end{bmatrix} \quad (4)$$

It is difficult to obtain the acceleration and velocity in the spatial coordinates directly through the system model. Generally, the aircraft is subjected to force analysis to obtain the acceleration under the fuselage coordinates, and then the acceleration and velocity in the spatial coordinates are calculated according to orientation of the aircraft. The calculation formula of the acceleration under the fuselage coordinates is as follows:

$$\begin{bmatrix} \ddot{x}_b \\ \ddot{y}_b \\ \ddot{z}_b \end{bmatrix} = \begin{bmatrix} b_{11} \sin(\omega + b_{12}) - b_{13}g \sin(\theta) + b_{14}u_1 + b_{15} \\ b_{21} \sin(\omega + b_{22}) - b_{23}g \sin(\phi) + b_{24}u_1 + b_{25} \\ b_{31} \sin(\omega + b_{32}) - b_{33}g \cos(\theta) + b_{34}u_1 + b_{35} \end{bmatrix} \quad (5)$$

In the formula (5),  $g$  is the acceleration of gravity. However, formula (5) calculates the acceleration of the aircraft in the fuselage coordinates, that needs to obtain the acceleration in the spatial coordinates through coordinate transformation. The coordinate transformation matrix is calculated by quaternion[13], and the transformation matrix is as shown in formula (6). The acceleration in the spatial coordinates system can be calculated according to formula (7).

$$R = \begin{bmatrix} 1 - 2(q_2^2 + q_3^2) & 2(q_1q_2 - q_0q_3) & 2(q_1q_3 + q_0q_2) \\ 2(q_1q_2 + q_0q_3) & 1 - 2(q_1^2 + q_3^2) & 2(q_2q_3 - q_0q_1) \\ 2(q_1q_3 - q_0q_2) & 2(q_2q_3 + q_0q_1) & 1 - 2(q_2^2 + q_1^2) \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} \ddot{x}_s \\ \ddot{y}_s \\ \ddot{z}_s \end{bmatrix} = R \begin{bmatrix} \ddot{x}_b \\ \ddot{y}_b \\ \ddot{z}_b \end{bmatrix} \quad (7)$$

Similarly, the acceleration of the spatial coordinates system can get the ground speed.

#### 4. Experimental result

In the experiment, the pilot controls the aircraft and collects data through the on-board electronic system, including acceleration, angular velocity, velocity, orientation, battery power. A total of 34 seconds of data were collected. After removing the unstable flight data such as takeoff and landing, there were 23 seconds of flight data left. The first 20 seconds were used as the training of the system model, and the remaining 3 seconds were used for testing. The data collection frequency is 100Hz, so there are 2000 training samples and 300 test samples. The flapping of the wings during flight will

cause very large vibrations, which will cause great interference to the acceleration and angular velocity, so the acceleration and angular velocity need to be filtered before training the model. The value of the acceleration changes drastically, and there are many high-frequency noises. The acceleration is filtered by a low-pass filter. The cutoff frequency of the low-pass filter is 40 Hz, which can filter out most of the noise. In order to smooth the data, we use the sliding window filter to process the acceleration and angular velocity. The filtering window for acceleration is about 100ms, and the filtering window for angular velocity is 60ms. The data comparison before and after filtering is shown in figure 4.

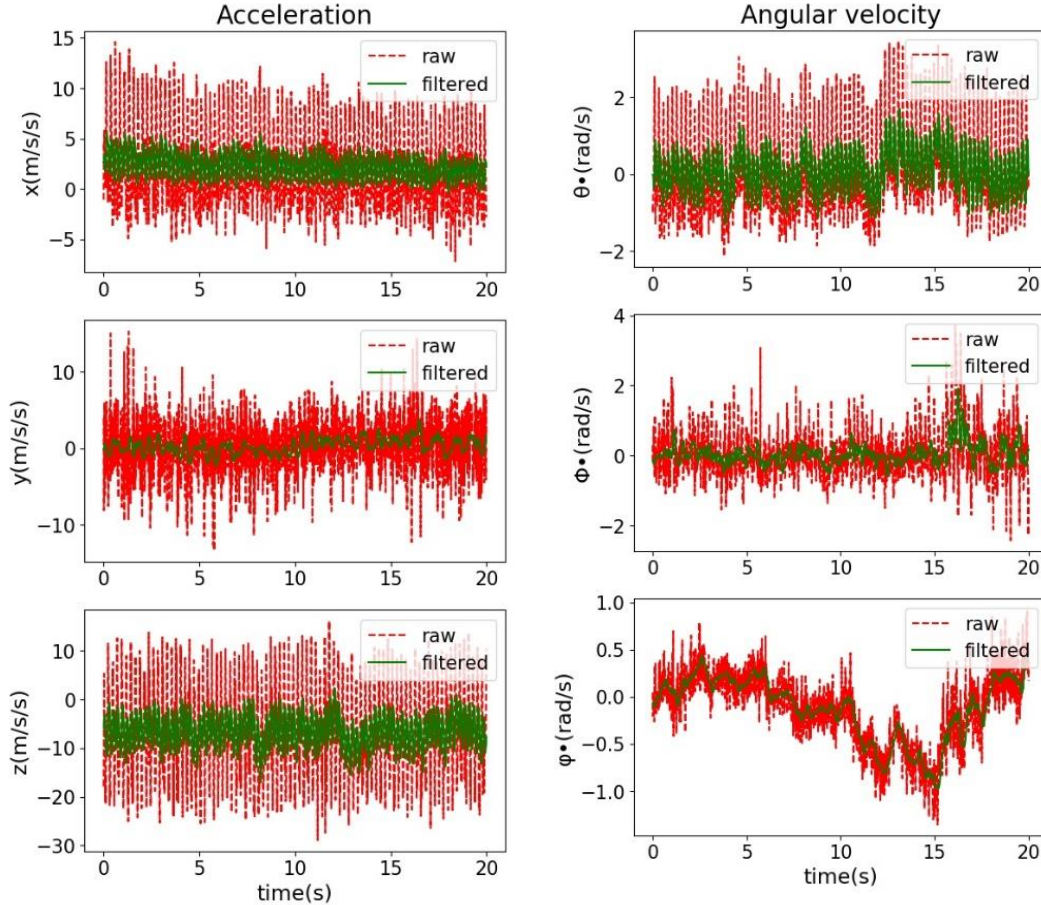


Figure 4. The data of acceleration and angular velocity before and after filtering.

It can be seen that the filtered data is smoother than the original data and can represent the acceleration and angular velocity of the aircraft, which is suitable for the training of the system model. In the system identification, 20 seconds (2000 samples) of data is used for training. The input is the 4-dimensional action space of the remote controller, the output is the acceleration and angular velocity of aircraft. Since the formulas of acceleration and angular velocity are different, this paper splits into two models to train, their loss function is shown in formula 8 and 9:

$$\text{loss}_{Acc} = \frac{1}{N} \sum_{i=1}^N (Acc_i - \hat{Acc}_i)^2 \quad (8)$$

$$\text{loss}_{AngV} = \frac{1}{N} \sum_{i=1}^N (AngV_i - \hat{AngV}_i)^2 \quad (9)$$

In the formulas,  $N$  is the number of training samples, the value is 2000.  $Acc_i$  and  $\hat{Acc}_i$  are the true and predicted value of the acceleration in the  $i$ th sample, respectively; similarly,  $AngV_i$  and  $\hat{AngV}_i$  are the true and predicted angular velocity, respectively. The training goal of the system model is to minimize the loss function. This paper uses the gradient descent training method. The trained model is verified on the test data. The comparison between the real value and the predicted value of the system



model is shown in figure 5 and figure 6.

It can be concluded from the results of figure 5 and figure 6 that the trained system model can calculate the flutter frequency of the aircraft based on the current throttle and battery voltage, and the peaks and valleys of each flapping period in the figure can correspond. For acceleration and angular velocity, the system model can accurately calculate the values on X and Z axes, the predicted data is similar to real data. However, the error on the Y-axis is a bit large. We think that the biggest factor in this situation is the lateral wind. The aircraft has a large span area and a light weight, which is very susceptible to lateral wind when flying outdoors, so there is a certain error on the Y-axis. At the same time, the system model can also accurately calculate the current velocity and orientation, and the actual data error is not large. Although there is a certain error between the predicted data and the real data from a subtle perspective, the forecast data is the same as the real data on the overall trend. These results verify the accuracy of the dynamic system model in this paper.

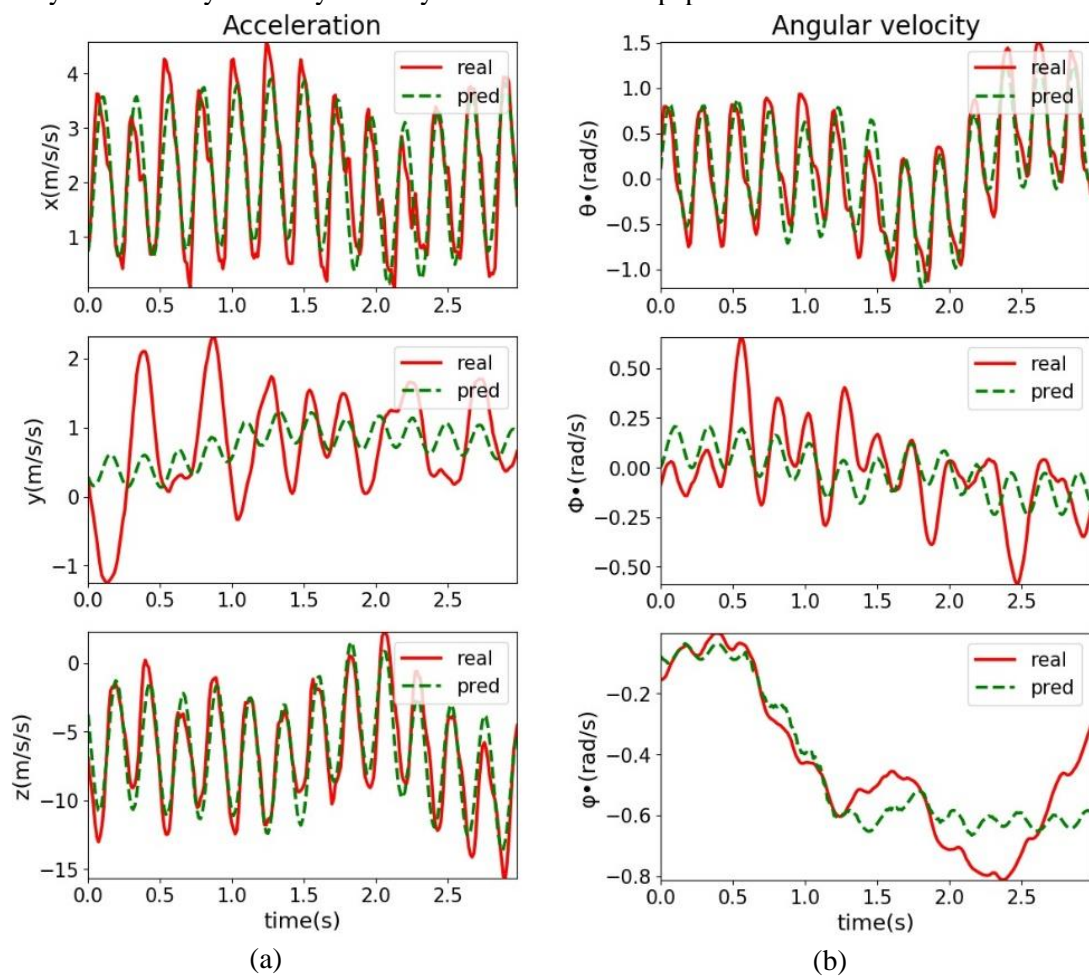


Figure 5. The true and predicted values of acceleration (a); the true and predicted values of angular velocity (b).



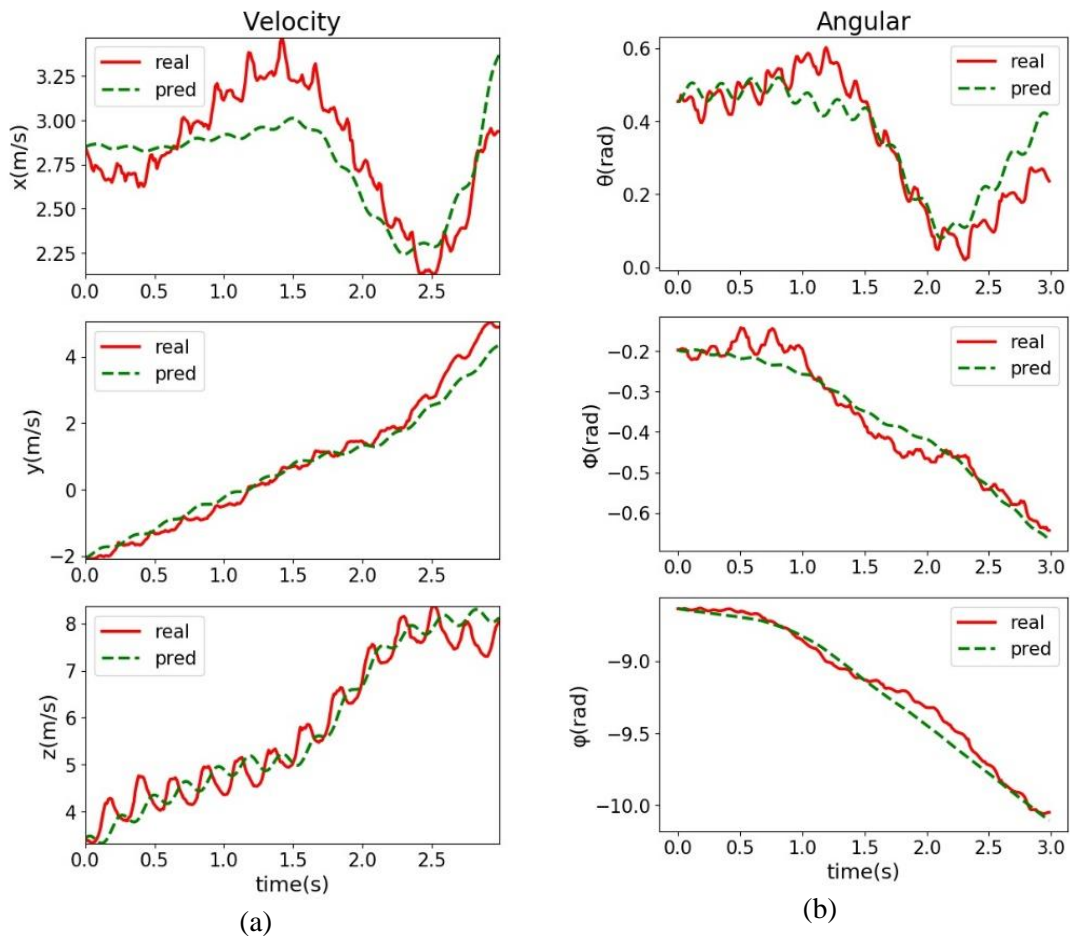


Figure 6. The true and predicted values of the aircraft speed in the spatial coordinates system (a); the true and predicted orientation of the aircraft (b).

## 5. Analysis and conclusion

This paper introduces the mechanical design and dynamic model identification of the two-section FWA. Through the study of bird flight, a two-section FWA is designed, which can fold its wings like a bird and flap its wings to realize flying. Aiming at solving the problem that the single-stage flapping wing cannot control the roll, this paper puts the servos on the wing tip to control the roll of the aircraft. For the difficulty in system identification of the FWA, the dynamic model is established by analyzing the aircraft, and we use real flight data to the train the model. Lastly, we verified the accuracy of the system model with the test data, the key values such as acceleration, angular velocity, velocity and orientation of the aircraft can be accurately predicted.

## Acknowledgments

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