Design And Analysis of Flapping Wing Aircraft Based on Crank Mechanism

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Abstract. This paper is proposed a flapping wing aircraft based on the crank slider mechanism to solve the problems of the two flapping wing structures, such as synchronization and excessive local stress common to existing ornithopters. MATLAB is used to solve the equations to determine the dimensions of the individual components, and the 3D model is designed by SolidWorks software. The static analysis on flapping wings, the static stress, and the static strain distribution map of flapping wings are carried out. Moreover, the mechanism of flapping wing aircraft is modeled in Adams software, which simulates the actual structure by designing the kinematic constraint relationships between the components. It was concluded that the flapping wing could achieve a flapping angle of 30 degrees in one cycle, which was consistent with the simulation results by MATLAB. Furthermore, it was found that the first principal stress of the danger point was less than the yield strength of the material to determine the rationality of material selection. Finally, the fluid trace distribution on the upper and lower sides of the flapping wings was analyzed, which was consistent with the actual situation.

Keywords: Flapping wing aircraft; Mechanical analysis; Crank mechanism; SolidWorks; MATLAB; Adams.

1. Introduction

RAND proposed the concept of the Micro Air Vehicle (MAV), a leading US military think tank [1], which was promoted by the Defense Advanced Research Projects Agency (DARPA) in 1996 [2]. Therefore, its great potential in civil and military fields has attracted the attention of research institutes in various countries. According to the original DARPA requirements, the maximum size of the MAV is about 15 cm long, the weight (including payload) is less than 100 grams, and the flight duration should be 20 to 60 minutes [3]. Several MAV concepts have been proposed, including fixed, rotary, and flapping wings [4]. However, the small size of MAVs becomes an insurmountable obstacle for developing miniature and even future nano-type high-efficiency vehicles [5]. Here, the flapping wing type developed based on birds and insects has a very high aerodynamic lift coefficient and high flight efficiency at a low Reynolds number.

Recently, the common flapping wing mechanisms have been divided into the following categories based on bionic principles: piezoelectric ceramic drive mechanism, electromagnetic drive mechanism, and crank rocker type mechanism [6]. The crank-rocker type mechanism is the most intensively studied, which is subdivided into the single-degree-of-freedom drive mechanism and the drive mechanism's multi-degree-of-freedom drive mechanism. The advantage of the single-degree-of-freedom drive mechanism is its simple structure and lightweight, while the advantage of the multi-degree-of-freedom drive mechanism is that the wing can be twisted and folded and perform complex movements. The single-degree-of-freedom drive mechanism is the most widely used, including the single crank double rocker mechanism, double crank double rocker mechanism, crank slider mechanism, cam spring mechanism, etc. Many applications have been involved, such as

aerodynamics, microelectronics, sensors, microelectromechanical systems (MEMS), and micro-fabrication [7].

The aircraft has a flapping structure similar to bird wings, which can provide lift and thrust. However, the flight effect is not good, and the fuselage is broken repeatedly [8]. Due to the great changes in the world environment, the research on flapping-wing aircraft has experienced a long period of stagnation. However, continuous flight tests were not completed in subsequent tests [9]. It can be seen that the flapping-wing aircraft made based on the imitation of bird flight is not suitable for flying with heavy loads. Moreover, with the in-depth development and combined application of bionics, micro-manufacturing, micro-control, MEMS technology, and other disciplines and technologies, flapping-wing aircraft once again became the research trend. They continued to develop in the direction of miniaturized design [10]. The researchers focused on birds with excellent maneuverability due to their large aerodynamic lift coefficients, which can provide a more precise research and development direction. Further detailed research on their flight mechanisms is conducted to develop high-efficiency and high-performance miniature flapping wings.

Therefore, many miniature flapping-wing aircraft with high efficiency and high performance have been developed. For example, Zhang et al. adjusted the parameters of the mechanism through the genetic algorithm, and the phase difference of the flapping structure on both sides was greatly reduced after the test flight [11]. In order to eliminate the phase difference of the flapping motion of the single-crank rocker mechanism, a mechanical transmission mechanism that can realize the complete symmetry of the flapping wings on both sides is applied to the design of the aircraft. It was found that the double crank rocker mechanism is the most widely used drive mechanism. The movement principle of the mechanism is to use the motor to drive the center pinion to rotate. It can eliminate the phase difference of the driving mechanism and significantly improve the flapping aircraft's aerodynamic performance. The angle of the wings can be adjusted by twisting the motor to achieve a right-wing angle for take-off and dive. The micro air vehicle adopts a double-crank rocker mechanism. [12]. The overall performance of the flapping aircraft is not widely used [13]. In addition to the traditional mechanical transmission structure, many piezoelectric drive structures are gradually used. Zhijian Tao et al. have designed a piezoelectric drive amplifying mechanism, designs a corresponding drive amplifying mechanism, which realizes the small displacement output of piezoelectric drive transformation. It can meet the particular rotation and flapping motion forms and provide better force transmission performance for micro-flapping aircraft [14].

2. Design of Crank Mechanism

2.1. Design of the drive mechanism

According to the degree of freedom of the mechanism, flapping wing mechanisms can be divided into two types: the single-degree-of-freedom flapping wing aircraft mechanism that only realizes up and down fluttering and the multi-degree-of-freedom flapping wing aircraft mechanism that realizes movements such as rotation and bending.

The existing single-degree-of-freedom flapping mechanism is shown in Figure 1. [15]

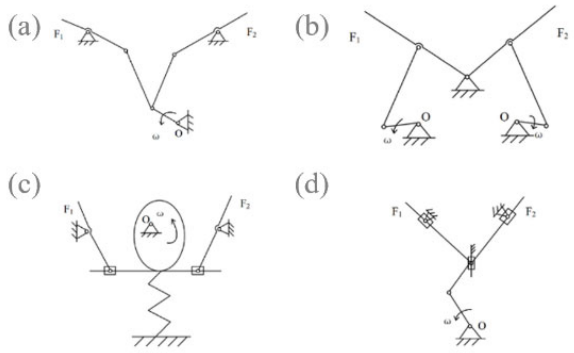


Figure 1. Schematic diagram of a mechanism commonly used in single-degree-of-freedom flapping wing aircraft

Figure (a) shows the single crank double stick mechanism. In the single crank double stick mechanism, the crank uses the connecting rod to drive the left and right rockers up and down. This mechanism is light and easy to miniaturize, but due to the asymmetry of the mechanism, its left and right wings are non-synchronous, which can easily cause the flapping wing aircraft to shake and fall during movement.

Figure (b) shows the double crank double rocker mechanism. The double crank double rocker mechanism is driven by two motors to the movement of the connecting rod mechanism on both sides, which can theoretically realize the synchronization of the flapping wings on both sides, but due to the existence of errors such as installation and motor speed, it may cause asymmetry in the movement of the two sides. Moreover, the use of multiple motors will increase the weight and size of the aircraft, and it is difficult to achieve the miniaturization of the mechanism.

Figure (c) shows the cam spring mechanism. The cam spring mechanism is a kind of movement law that needs to be flapping wings by designing the contour curve of the cam, but the cam contour curve design to achieve the required movement is more complicated, the cam contour accuracy requirements are high, the point contact makes the cam easy to wear, and it is difficult to achieve miniaturization. In addition to this, there is a single pusher mechanism, which uses one pusher to drive the movement of two wings and is mounted on the crank by a center pin connection. The single pusher mechanism allows the wingspan to be symmetrical at all times, which improves the low-speed stability of the aircraft. But because it must drive both wings at the same time, it makes the stress in the single actuator greater. In addition, since the wing flapping is completely in phase, the stress on the electronic components, including the motor and electronic speed controller, will also be greater, and the loading force will be more concentrated in the single pushrod mechanism.

Figure (d) shows the crank slider mechanism. The slider can move up and down under the drive of the crank, and the up and down movement of the slider drives the joystick to achieve flapping movement. The mechanism has good synchronization and strong stability between the left and right flapping wings, which can make up for the shortcomings that the movement of the two wings of the single crank double stick mechanism and the double crank double stick mechanism cannot be synchronized. Compared with the cam spring mechanism that is difficult to design, the structure of this mechanism is simpler, it is relatively easy to implement, and it is easy to achieve miniaturization. Since the crank slider mechanism can better compensate for the defects and problems of the above mechanisms, we choose the crank slider mechanism for the design of the flapping wing aircraft.

2.2. Single-degree-of-freedom crank-slider drive mechanism

After investigating and analyzing the design of various types of flapping wing aircraft with the same size specifications, we refer to the structural design of Rajkiran Madangopal et al. at the University of Delaware [16], whose design draws on the body structure of a large number of insects and small birds, which is more in line with our target requirements. Considering our demand for less mass, a simple structure, and less space occupied by the drive mechanism, we removed the spring to simplify

their design and made some size adjustments to fit our wing and flutter plane, and the design is shown in Figure 2.

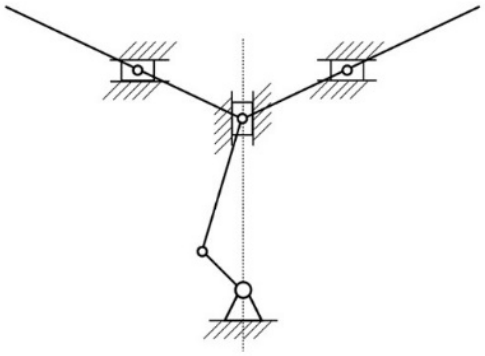


Figure 2. Schematic diagram of the drive mechanism

In our design, the crank located at the fuselage axis makes a circular motion, and the connecting rod drives the slider on the central axis to make a vertical reciprocating motion. The left and right symmetric structures drive both sides of the wing to flap symmetrically to reduce the impact of unbalanced lift on flight stability. The structure is designed symmetrically on both sides to eliminate the phase difference in the motion of the flapping wings while still achieving simplicity and practicality. Meanwhile, the problem of more frictional losses when using a sliding pair [17] is well solved using a PEEK-filled PTFE composite material, which benefits from its extremely low coefficient of friction and other characteristics [18].

2.3. Kinematic analysis of the crank mechanism

In the structure shown in Figure 3, l_1 is the length of the crank AO, l_2 is the length of the connecting rod AB, f is the length of BD, c is the length of BC, e is the distance from O to the projection of C on the x-axis, φ_1 is the crank turning angle, φ_2 is the turning angle of the connecting rod AB, and φ_f is the flap angle. According to the design values, the lengths of l_1 and e are 1 cm and 4 cm, respectively. Here, it takes $c = 2$ cm.

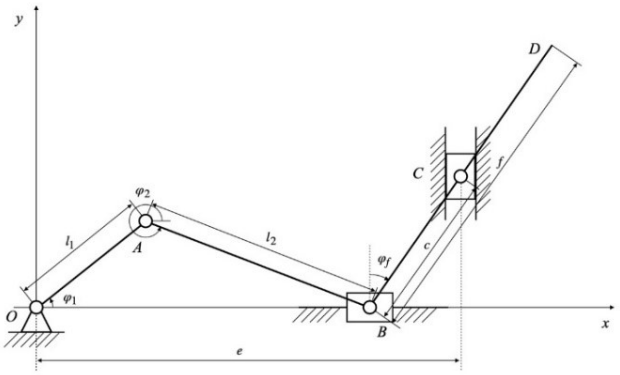


Figure 3. Schematic diagram of the motion of the drive mechanism

After the crank rotation angle φ_1 is known, the displacement s and flap angle φ_f of the slider can be obtained by the following derivation. By projecting each component to the x-axis and y-axis, we can obtain the system of equations.

$$\begin{cases} s = l_1 cos\varphi_1 + l_2 cos\varphi_2 \\ 0 = l_1 sin\varphi_1 + l_2 sin\varphi_2 \end{cases} \tag{1}$$

By solving the system of Equation (1), we can obtain the displacement s of the slider and the angle of rotation φ_2 of the connecting rod AB.

Through the derivation of Rajkiran Madangopal et al. [1], we can obtain Equation (2).

$$\varphi_f = \frac{\pi}{2} - arccos\left(\frac{e-s}{c}\right) \tag{2}$$

From this, by associating Equation (1) and Equation (2), we obtain:

$$\varphi_f = \frac{\pi}{2} - arccos\left\{\frac{e-l_1 cos\varphi_1 - l_2 cos\left[\arcsin\left(-\frac{l_1}{l_2}sin\varphi_1\right)\right]}{c}\right\} \tag{3}$$

Then the flap angle φ_f can be found.

2.4. Mechanism motion simulation analysis

From Equation (3), it can be seen that the length of connecting rod l_2 has a direct effect on the flap angle φ_f. To determine a suitable length l_2 and to study the flap angle of the wing and its motion law, we simulate the mechanism. Based on the statistics of flapping frequency and spreading chord ratio of small birds, etc. [4], we take $f = 9.6765$ cm and the flap period $T = 1/8 = 0.125$ s, considering our target mass. The motion curve during the interception of one period T is shown in Figure 4.

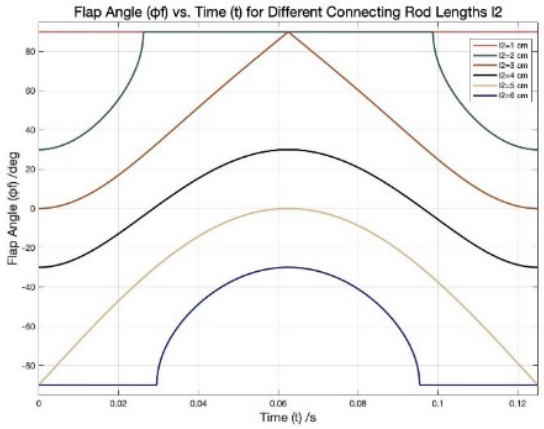


Figure 4. The curve of the flap angle (φ_f) versus time (t) for different connecting rod Lengths l_2

From Figure 4, the magnitude of the flap angle φ_f increases with the increase of connecting rod length l_2 at the same flap period, and the maximum value is located at half period. When l_2 is 1 cm, 2 cm, and 6 cm, the flap angle appears stationary, indicating that it is impossible to flap at this time, and it is challenging to meet the requirement of providing lift; when l_2 is 3 cm, the angle of flap angle changes abruptly at half a cycle, which will produce a large impact on the structure and is not conducive to long-term stable operation; when $l_2$is 5 cm and 6 cm, the value of flap angle is limited to 0 and below. It shows that the flap of the wing is limited at this time, and it can only flap below the horizontal auxiliary line, which is unsuitable for flight.

After several comparative tests, it was finally determined that the connecting rod length l_2 = 4 cm, corresponding to the maximum flap angle $\varphi_f = 30°$ at which the flap range is evenly distributed on both sides of the horizontal auxiliary line, and the angle changes gently, which is conducive to the long-term stable operation of the structure and can provide lift with high efficiency. The flap angle in this situation is 60°, which follows the statistical value of the flap angle of most birds [19].

3. Design of 3D Modeling and Motion Simulation

The crank-slider mechanism selected in the previous section is considered the drive mechanism for the flap aircraft. The design is based on a rationalization of the layout with the existing dimensions of the essential components, the SolidWorks model and the Adams motion simulation are carried out to analyze the rationality and applicability of the designed mechanism according to the calculated mechanism parameters.

3.1. Design of the 3D model

According to the design parameters obtained from the above calculation, a SolidWorks 3D model of the crank-slider mechanism as the driving mechanism was established, as shown in Figure 5. For the selection of the prime mover to drive the crank-slider mechanism, this prototype uses an aircraft-grade brushless motor; the motor replaces the traditional mechanical commutation with electronic commutation, with reliable performance, no wear and tear, and a lifetime about six times higher than that of a brushed DC motor. It has a wide range of speed regulation and a high overload capacity and can meet the required performance of the drive well [20].

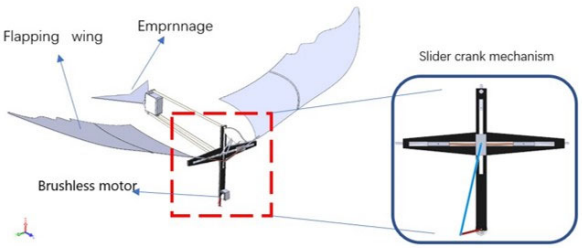


Figure 5. 3D model of the crank slider flutter configuration

Based on the unilateral crank-slider flutter structure designed in Figure3, the symmetrical crank-slider mechanism created by building a SolidWorks model enables a fully symmetrical motion when driven by both flutter structures. The main structure is the crank slider mechanism shown in Figure 5.

3.2. Tailplane free-form design

In the actual flight of birds, pitch and yaw are achieved mainly by the asynchronous movement of the two wings, the tail serving only to balance the body and regulate flight speed [21]. In this prototype, a fully symmetrical crank-slider mechanism is used on both sides, so to meet the steering torque required for the left and right yaw of the prototype, a tailplane degree of freedom design is designed, as shown in Figure 6. The ES08MAII miniature servo was used for the steering drive, taking into account the light weight of the flap configuration and the need for steering torque.

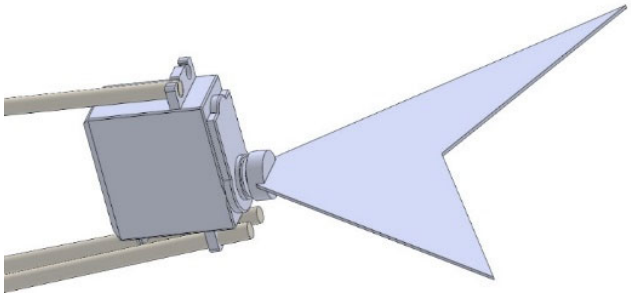


Figure 6. 3D model design of tailplane free-form

3.3. Maximum flap angle of the crank slider mechanism

The crank slider mechanism was adjusted to control the crank to turn through different rotation angles. Therefore, the flaps are in the upper limit, horizontal, and lower limit positions, respectively, as shown in Figure 7, which can reasonably achieve the upper and lower flap angles in the above design mechanism, which is in line with the statistical values of flap angles for most birds.



Figure 7. Image of flap angle of both flaps with different period

3.4. Adams motion simulation of a crank-slider mechanism

ADAMS is a software that simulates the actual structure by modeling in 3D, adding constraints, determining component materials, and adding kinematic relationships. It allows the design of mechanical structures to be analyzed in terms of kinematics and dynamics and the components' kinematic parameters and forces to verify the design's correctness [22].

Based on the parameters of the crank-slider mechanism calculated in the previous section as design parameters, the entire mechanism was modeled in Adams, and the model was built as shown in Figure 8. By designing the kinematic constraints between the components and setting the rotational motion parameters for the crank components according to the parameters of the brushless motor selected for the design, the motion simulation of the crank slider mechanism was completed. The trajectory of the endpoints of the flap was tracked, and the resulting trajectory is shown as the white arc in Figure 8. The flutter angle of the flap with the crank rotation is shown in Figure 9.

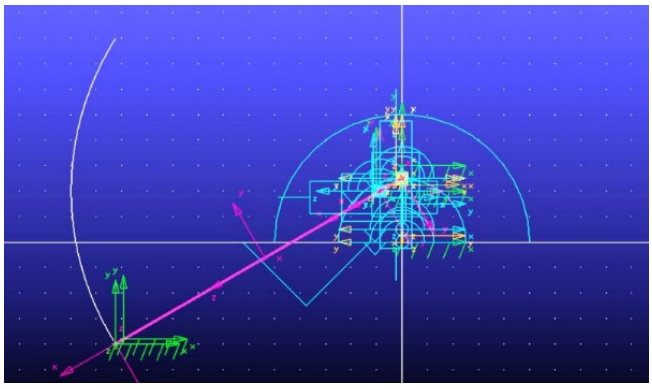


Figure 8. Result of Adams model and wing-tail trajectory

As seen in Figure 9, as the crank is turned, the flutter rotation angle is identical to the simulation curve obtained from the MATLAB calculations in the previous section. Drive the flapping wings back and forth in one cycle to achieve a flapping angle of 30 degrees up and down. It verifies the correctness of the design and calculations for the flutter twist mechanism structure.

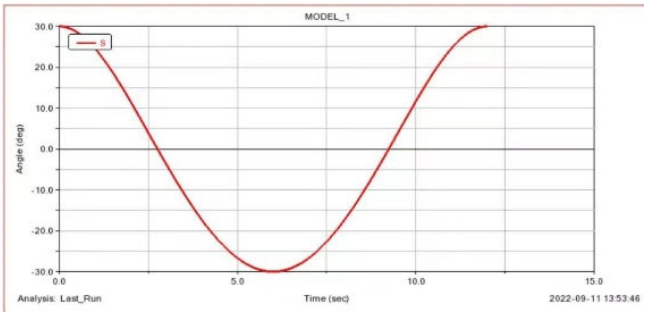


Figure 9. The curve of flutter flap angle versus time

4. Simulation Analysis of Flapping Wings Under Static Loading

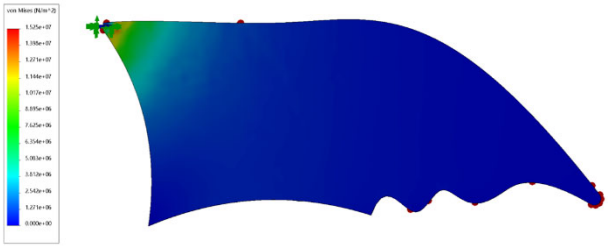
According to the above construction of the flapping wing model, the basic geometric dimensions of the three-dimensional model are summarized [23], and the specific values are shown in Table 1.

Table 1. Basic Geometric Parameters of Flapping Wings

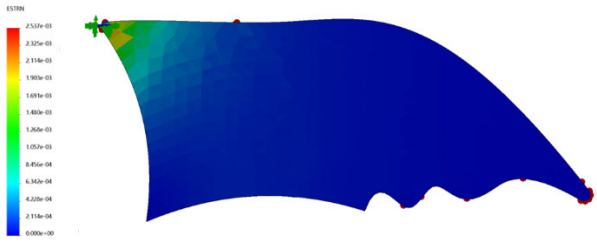
Flapping wing length (mm)	Circumference (mm)	Area (mm2)	Thickness (mm)	Average chord length (mm)	Aspect ratio
193.53	439.66	8141.62	1.00	42.07	4.60

Since the flapping wing material needs to meet strong toughness, high fatigue limit, and large yield strength, etc., after comparative analysis, we chose PET material as the flapping wing material and calculated the mass of a single flapping wing to be 12.13 grams. PET materials have good creep resistance, fatigue resistance, abrasion resistance and dimensional stability, and high hardness, which is the best toughness among thermoplastics. PET is mainly used in the production of fibers, films, engineering plastics, etc.

In order to ensure that the material performance parameters meet the requirements of routine flight, we conduct static tests on the flapping wing model. We use the Simulation module in SolidWorks, and after setting the parameters, we select the state in which the flapping wing is in a horizontal position during movement as the test analysis state, and a distributed load of 12N/m2 is applied to the flapping wings. The stress-strain distribution is shown in Figure 10.



(a)Flapping wing static stress distribution diagram



(b) Flapping static strain distribution map

Figure 10 Flapping wing static stress and static strain diagram

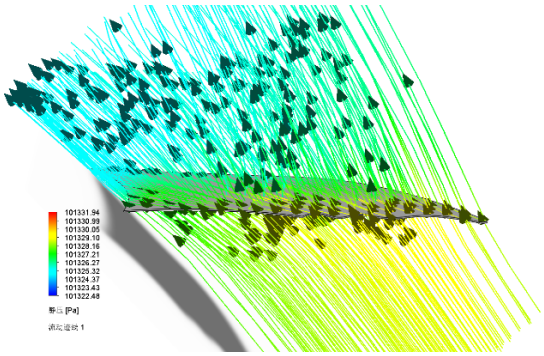
After static test analysis, it is found that the deformation of the wing tip position is relatively large, and the bending moment and torque at the wing root are relatively large, resulting in a considerable maximum principal stress value of the cross-section. The first principal stress at the dangerous section danger point of the flapping wing is 1.271×10^6 N/m^2, which is much less than the yield strength of the material of 6×10^7 N/m^2, and the material strength meets the requirements.

5. Fluid Simulation Analysis of Flapping Wing

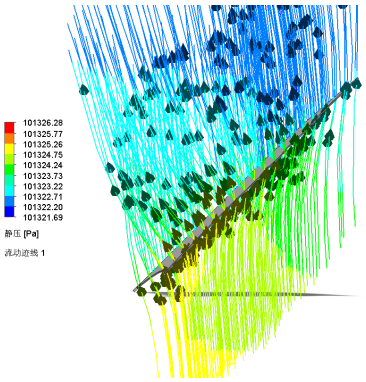
Due to the influence of the surrounding airflow field during the flapping wing movement, an unsteady incompressible fluid is formed, and the calculation process of this unsteady fluid is affected by a variety of uncertain factors and requires high hardware conditions. The flapping wing aircraft is small, lightweight, stable in flight environments, and has a low flight speed, so its Reynolds number

is relatively small. In order to make the test operable and obtain relatively valid test data, the method of converting the unsteady fluid into a quasi-constant fluid at multiple critical moments is used for computational simulation. It can not only effectively avoid the slow dynamic fluid analysis process caused by the huge amount of dynamic meshing of unsteady flow but also analyze the quasi-constant fluid as a constant fluid, which can effectively shorten the calculation time and increase the calculation effectiveness.

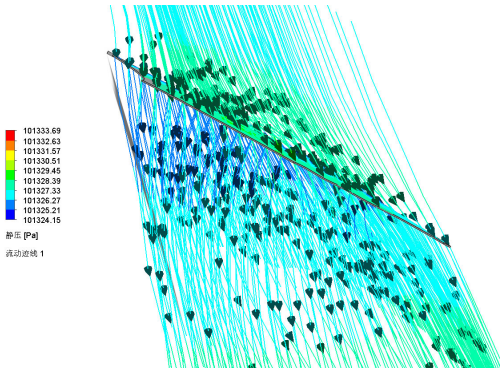
The proposed flapping wing model is primarily used for fluid simulation using SolidWorks Flow Simulation. The flapping wing transmission model is converted into a mathematical model to obtain the corresponding motion parameters, and finally, the fluid simulation is carried out by setting the fluid parameters and boundary conditions. In order to facilitate the test, we select the flapping wing at the key moments of the upward and downward fluttering stages for the test to obtain the test result chart. Here, we selected the highest moment of up flapping, the flapping horizontal moment, and the lowest moment of down flutter for fluid simulation analysis (Figure 11).



(a)flapping wings level moment



(b)the highest moment of flapping on the wing



(c)flapping down the lowest moment

Figure 11. Distribution of air-fluid traces around each particular moment

When flapping upwards, the static pressure below the flapping wing is greater than the above, forming a pressure difference, causing the flapping wing to flutter upward. When flapping down, the

static pressure above the flapping wing is greater than the lower one, causing the flapping wing to flutter downward. By analyzing the fluid test of flapping wings, the motion state of flapping wings at several important moments, the trajectory of fluid particles, streamlining, the pressure difference between the upper and lower surfaces of flapping wings, and the aerodynamic force of flapping wings can be obtained, which lays a research foundation for subsequent in-depth analysis.

6. Conclusion

Through mechanical and geometric analysis, we used MATLAB to solve the equations to determine the dimensions of the individual components of the crank slider mechanism and build a SolidWorks 3D model. We have modeled the entire mechanism in Adams and simulated the actual structure by designing the motion constraint relationship between the components. It was found that the flapping wing fluttered back and forth in one cycle, which could achieve a flapping angle of 30 degrees, which was consistent with the simulation curve obtained by MATLAB. Then, the danger point was found, and the first principal stress of the danger point was less than the yield strength of the material to determine its rationality. Finally, through the fluid simulation analysis of the flapping wing by SolidWorks Flow Simulation, the fluid trace diagram and static pressure distribution of the flapping wing at three particular points are obtained, and the fluid trace distribution on the upper and lower sides of the flapping wing is analyzed, which is consistent with the actual situation, to verify the rationality and correctness of the mechanism. As a result, a flapping wing aircraft based on the crank slider mechanism was designed.

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