Research on Birds Flapping-Wing Bionic Mechanism

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Abstract

By analyzing physiological structure and motion features of bird wings, this paper aims to design bird wings' driving and complying planar structures from two angles of Bionics: the structure of flapping bird wings' bone and the discipline of flying. In addition, this paper studies the discipline of bird wings' tangential motion in order to design a drive mechanism which fulfills driving tangential wings' structure. At last, we researchers conduct a simulation of kinematics and get a satisfying result, so as to provide a basis for design large-scale bird bionic machine.

Keywords: Flapping-wing; Bionic, Mechanism optimizing, Motion simulation

1. Foreword

Flapping-wing air vehicle is a new conceptual aircraft which mimicry the flying modes of birds and insects. All flying creatures of nature fly by flapping their wings and according to researches of Bionics and Aerodynamics, flapping-wing flight is proved to embody more advantages than both fixed-wing flight and rotary-wing flight. These advantages conclude higher aerodynamic efficiency, bigger load, more convenient landing, higher altitude and Moderate speed. Generally speaking, this kind of product is applied in military reconnaissance field as a surveillance equipment of a single soldier. Therefore, it can be equipped with surveillance equipment with apparent application value.

2. Principles of Flapping-wing Flight

Birds' wings have four basic patterns of movement during the normal course of flat flight: Flutter, reverse, swing, and folding. "Flutter" is an angle movement around the axis with a same direction of flight; "reverse" is an angle movement around wings centre line; "swing" is an angle movement around machine's vertical axis (wings are parallel with machine's body and swing back and forth during flight); "folding" is stretching and bending of wings along the direction of span. Shown in figure 1.

For large birds, both of their reverse angle and swing angle are small, but their folding courses are much more apparent. Because, during folding courses, wings flapping up and down resulting different Lift coefficient, and this kind lift contributes a lot on adding the total lift of flapping-wing flight.

The principles of flapping-wing flight of birds are different from those of insects. In addition to flapping, some corresponding movement types of distortion and rotation also accompany birds' flights. This paper has obtained the patterns of wings' movements and the traces of wing tips of birds by analyzing the flying wings of swan, a stereotype of large bird. Show in figure 2.

After watching the traces of wing tops' movement, the authors find out that during the course of flapping up and down, wings have apparent bending and flexible deformation. Wings during the period of "down" is flat, and they become bend when they reach the lowest point; and then, during the period of up, wings bend and upward at the same time. We can also conclude the principle of wing tops' changing movement traces.

Supposing the swan's wing is approximately combined by two surfaces of wing, one wing surface does periodic flapping movements and the side of outside wing surface is connected with the outside edge of inner side wing surface by bone joint, and the former does repeating circular movements with the later), as shown in the arc of figure 2; this conclusion is the primary basic principles and basis of flapping-wing driving mechanism and the plan of wing structure designed in this paper.

3. Design of Span-wise Wing Drive Mechanism

We can simplify a large bird's pair of wings to two flat boards during the flapping course: one board is near to the root of wing, inner-wing surface; the other is the outside-wing surface. The inner one does tangential steering movements and provides flight thrust when it flats up and down while the outside one provides flight lift when it does regular bending movements. Based on the simplified model, we have measured the flapping-angle range (approximately 40° while the lowest flapping point is close to 0°) between the highest and lowest point of inner wing during a flapping cycle. Further more, we nave divided the whole flapping angle into ten equal parts (the right side are measurements during the period of flapping down, and the left side are measurements during the period of flapping up). Suggested as figure 3.

From this figure, it presents that the wing-tip movement traces suggest the positive pressure surface during flapping down is bigger than the positive pressure during flapping up (relative to ground surface). From the measurement data of the figure, we have gained the size proportion of span-wise wing. Assuming the ratio is μ, and then $\mu = 11881/767.3 \approx 1.55$. We measure the angle degrees between the two wing surfaces during those twenty equal points when wings flapping up and down, so we get twenty groups of data. After that, these twenty groups of data are put into a coordinate system while Abscissa is equal point and Ordinate is angle degree. Finally, we get a curve as figure 4.

In this curve, we can find out that the angle change is rather flat during the period of flapping down but it varies greatly both after the period of flapping down and during the period of flapping up. This phenomenon is consistent with the principle of wing-tip's movement trace in experiment. We can use this as reference of parameters on designing flapping-wing board.

The drive force of flapping-wing comes from the wing surface connected with wing root, and it provides drive force for the flapping movements of the whole wing. So we have to firstly consider the design of drive mechanism before designing bionic mechanism. This drive mechanism should meet a reciprocating movement with a swing angle of 40° between wing root and wing surface and it should also guarantee quick-return movement in order to achieve a movement using more time on flapping down than flapping up. Therefore, we can use crank and rocker mechanism as the drive mechanism of the whole flutter mechanism. Shown in figure 5.

Bar ① can be used as actuating arm which closes to wing root and board in bionics mechanism. Bar ② can be used as connecting lever in crank and rocker, and it works as shrinking muscle in wing root, which can pull carpal. Bar ③ is driven by direct current machine.

This paper adopts crank and rocker of type Ⅰ which possesses quick-return characters (Wu, 2008, P.68-69). We get a solution: a:b:c:d=1:5.34:2.62:6.56.

Under the hypothesis of geometrical similarity, we can connect these various physical quantities related with flight by dimensional analysis. For example, for uniform horizontal flight, the bird's weight is W, lift L can be expressed as a formula of characteristic length.

So we get the bionics formula of parameters and weight m:

Wing span $u=1.237m^{0.368}$

Aspect ratio AR=9.339m$^{0.069}$ (Liu, 1997, P.46-48)

This bionics formula is an approximate formula in traditional sense, so it cannot completely coincide with actual birds or micro flapping-wing aircrafts. And it only aims to determine the approximate range of various flight parameters.

According to bionics formula of bird flight, the weight of flapping-wing aircraft, *m*, is the basic variable parameters of designing other flight parameters. From the bionics formula and the size of large birds, we initially design those various parameters of flapping-wing aircrafts as this: if the total length of wing-span u=1.64m, lengths of two wing surfaces in the hypothesis separately are $u \times 1/(1+\mu) = 0.64$ m and 1m. This proportion can be used as lengths of bars which drive two wings in designing wing-span mechanism. The length of bar ① adds the length of bar ④ is 0.64m, and the length of bar ⑤is 1m as in the following figure:

From this figure of mechanism, we may find that if bar ⑤ can move as regularly as outside wing moving towards wing root, simulation of bird chord movements' discipline will come true. That's say if the course of flapping down changes more slowly than the course of flapping up while the angle between bar ⑤ and bar ④ moving with the whole machine, bird-like flapping-wing movements can come true.

Design of such a mechanism must meet a condition: mechanism of actuating arm ⑤'s movement cycle should be in accordance with the whole mechanism's movement cycle. In that case, we can use the same motor as the drive. Considering the mechanical properties connecting with these five bars, we design a mechanism as figure 6.

In this design, bar ⑨ and bar ③ are fixed together, the same as bar ⑦ and bar ⑤, bar ① and bar ④. In that case, bar ① + ④, ⑦, ⑧, ⑨ and the supporter form a five-bar mechanism parallel connecting with crank and rocker mechanism. In this mechanism, the angle between bar ① + ④ and bar ⑦ approximately meet the regularity of the angle's changes between two wing surfaces. That's the desired result.

Consequently, in the planar mechanism we get each bar's length: bar ① + ④≈156.31, ②≈38.52, ③≈7.16, ⑤≈231.92, ⑦≈76.32, ⑧≈80.72, ⑨≈29.83, the distance between point 1 and point 4 is 47.36. The measurement unit is "mm".

We simulate two-dimensional layer movement by using this optimized data, and the result is presented in figure 7. The simulated wing-tip span trace is in accordance with the discipline of actual bird's wing-tip span trace.

And then, we fit the graphic mechanism and the wing's flapping animation of actual bird together in proportion. At last, the result suggests that if we omit the deviation of actual bird's flexibility, this mechanism can accurately simulate the flapping-wing movement during bird's flight. So, it proves that this mechanism design is a success. It is shown as figure 8.

4. Design of Chord-wise Wing's Driving Mechanism and Modeling of Three-dimensional Space Mechanism

Although the lift enhancement of large birds depends mainly on its span wings' bent, the flight forward thrust generates from the rotation of its chord-wise wings. So, a wing-simulated mechanism should generate chord-wise rotation. And based on graphic mechanism design, we should allocate three-dimensional mechanism which can do chord-wise movement, driven by three-dimensional drive.

In order to design chord-wise driving mechanism, we have to make the principle of bird wings' chord-wise movement clear. Wings' chord-wise movement is presented as figure 9.

In region T of flapping-down, wings keep open and flat; in region R of the ending of flapping-down, wings make chord-wise angular motion and they lift (holding the same angle) in region T; region R is the ending of flapping-up and beginning of flapping-down, and in this region, wings open and flatten again and prepare for the next cycle of flapping-wing movement (G.J, 2007, p.118). It can be seen wings' chord-wise movement and span-wise bending and flat movement seem alike, so it requests similar control curve. From the above, we get an idea of designing driving mechanism based on chord-wise movement-designing a space mechanism which can make use of span-wise movement's principles.

From the analysis of graphic mechanism, we find the regular changes of the angle between two wing surfaces drive span-wise machine to move regularly. Therefore, we can design a space mechanism, transferring the regular changes of angle to a mechanism whose flat is vertical with the flat of this graphic mechanism. Based on this idea and analysis of geometric space, we use the theory of equilateral triangle to modeling this three-dimensional mechanism and simulate movement by using of three-dimensional software. Marks are set in appropriate place of the space mechanism; from span-wise wing tip to trailing edge of chord-wise wing there exists a movement trace which is output as shown in figure 10.

In this simulation, we see the trace of trailing edge's marks in chord-wise wings moves downward along the outside of edge line when wings flapping down while the trace moves upward along the inner side of edge line when wings flapping up. It proves that the principle of chord-wise wings' plane motion is flapping down openly and flatly while flapping up bending with reduced air resistance. Also, it proves the space mechanism design is reasonable. The structure of this space mechanism is as shown in figure 11.

As shown in figure 11, during the course of flapping, the angle between bar 4 and bar 5 can change regularly along with rotation. We design those parts marked separately as 1, 4, 5, and 6 in this mechanism. Part 5, 6 are separately fixed on bar 4, 5 crossing through screwed hole as shown in this figure; T-bar 1 can slide in axial direction and rotate in radial direction along the two pilot holes of part 6; T-bar 4, which is fixed in the pilot hole of part 5, can rotate in radial direction along the hole; and one end of T-bar 1 is inserted in T-bar 4's pipe sleeve, in which it can slide in the axial direction. In that case, we design a space structure whose right angle is formed by bar 4 and bar 5. Furthermore, we design part 2 and 3 to form another space structure, in which part 2 and 3 fit the same two straight edges of the above right triangle but this space structure is vertical with the above one. It should be mentioned that the two right triangles are designed to be congruent triangles.

In this mechanism, angle 1 and angle 2 are always the same in flapping, that's say the movement principle of flat formed by part 2 and bar 4, 5 is the same as the relative movement principle of bar 4 and bar 5. As shown in the following figure, from the angle changes' curve of angle 3 and angle 2, a same time of angle-change principles of angle 1 and angle 2 is achieved, so we realize a similar trace between span-wise wing tips and chord-wise wing edges. As shown in figure 12.

In this design, we design a drive mechanism for chord-wise pitching motion by using the theory of two congruent right-angled triangles. Besides, this drive machine is put near to "forelimb" and "ulna" of wing, and this method makes forelimb to reverse and chord-wise wing to turn, both of them are driven by wedge bone which is between forelimb and ulna.

This simulated space mechanism is a good simulation of movement principle of span-wise and chord-wise wing surfaces in birds flying. In the end of this paper, based on motion simulation, we adjust the animation of space mechanism to a proper ratio which is close to the size of a flying bird. And then, we separately make frequency division of the two animations and fit them together in flash software and output one animation at last. Consequently, the differences between the mechanism design and actual birds' flapping-wing can be vividly reflected and seen. The fitting animation is shown in figure 13.

5. Conclusion

From the point views of mechanism and bionics, this paper designs and simulates the mechanism of bird wings' movement. This mechanism can actively realize various bending and rotating movements which are equal to the wings' deformations of flapping-wing flights in previous study. However, there exist differences between them: the most significant advantage of this mechanism is more precise and convenient wing-deformation with adjustable parameters by using active driving mechanism, so as to provide basis and references for designing large-scale birds' flapping-wing bionic machine.

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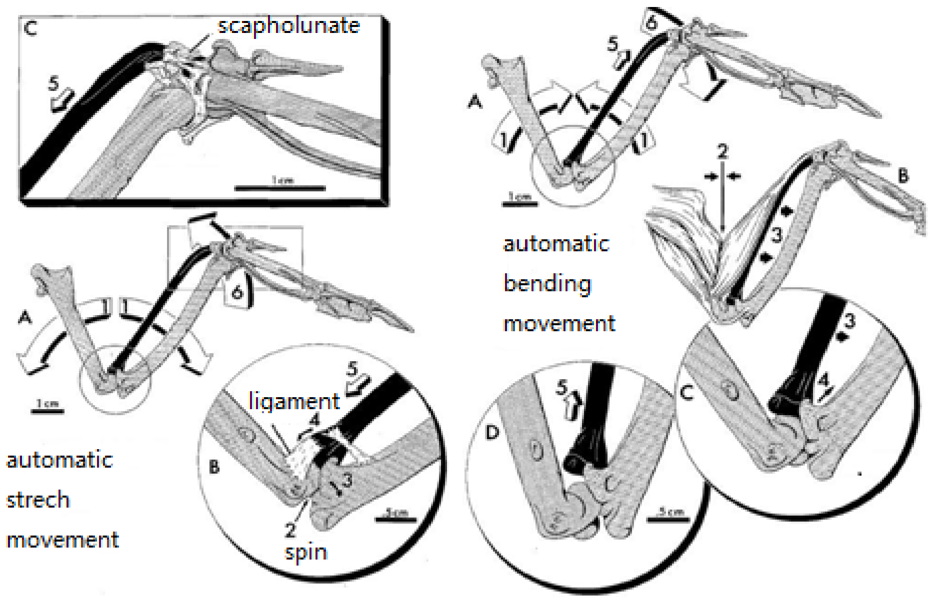

Figure 1. The mechanism of bird wings' bone

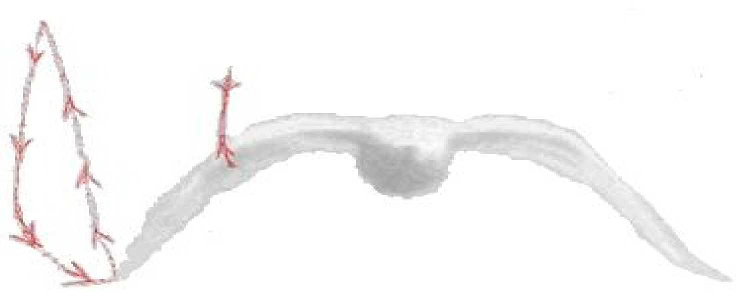

Figure 2. Flying movements of swan's wings and wing tops

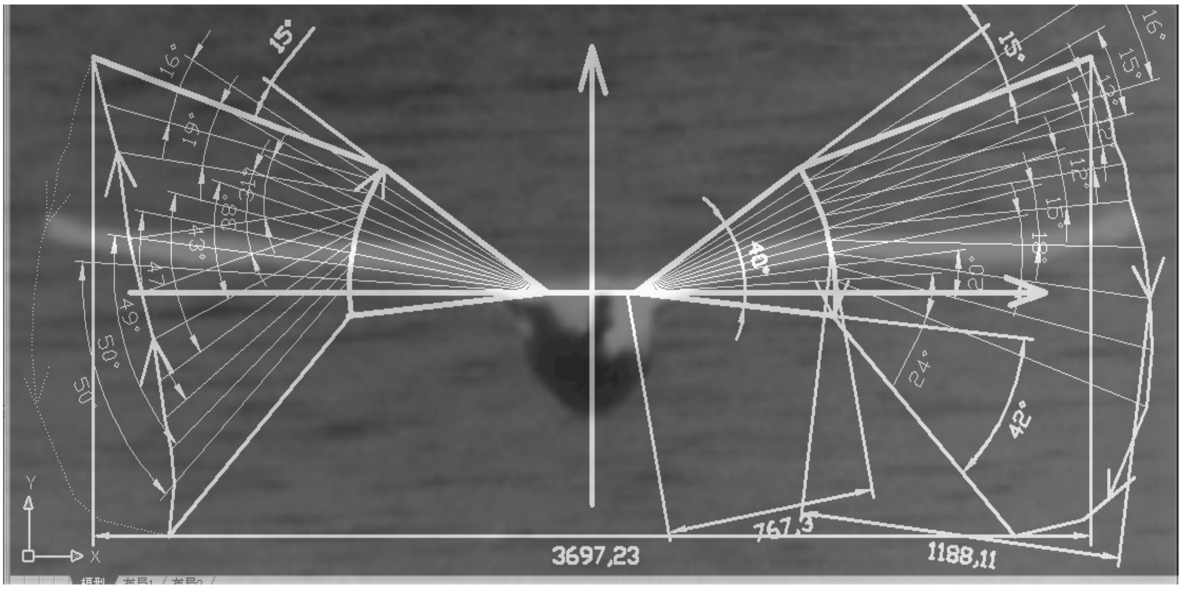

Figure 3. Angle changes of right and left wings during flapping

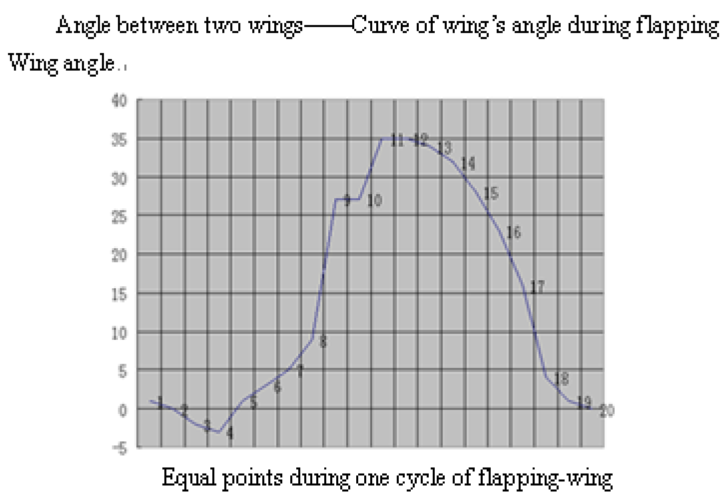

Figure 4. Wing-angle during flapping—curve of equal points

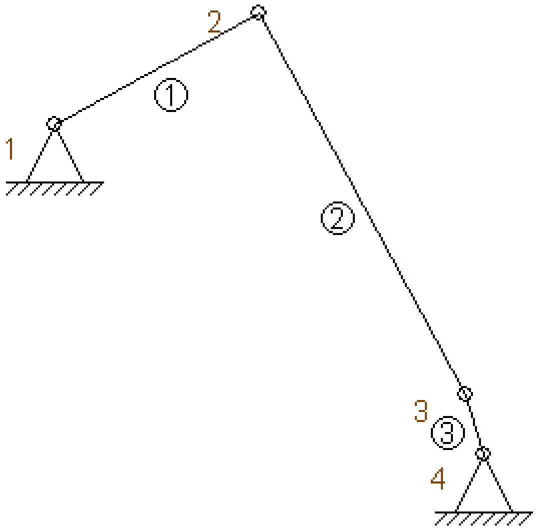

Figure 5. Abbreviated drawing of crank and rocker mechanism

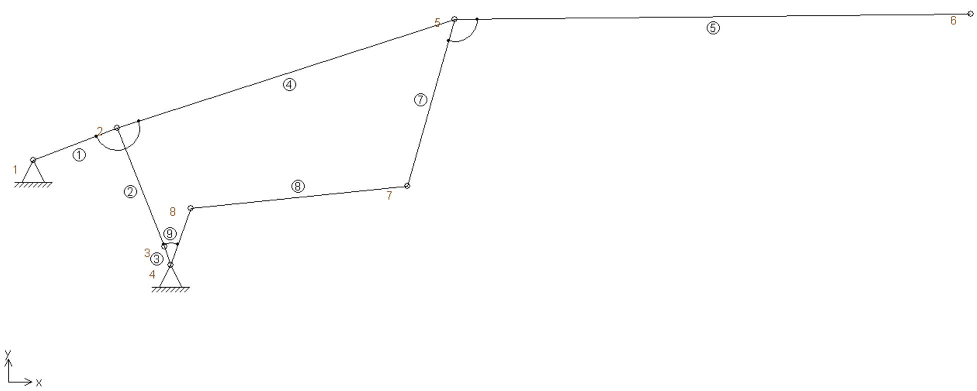

Figure 6. Graphic mechanical design based on five-bar mechanism

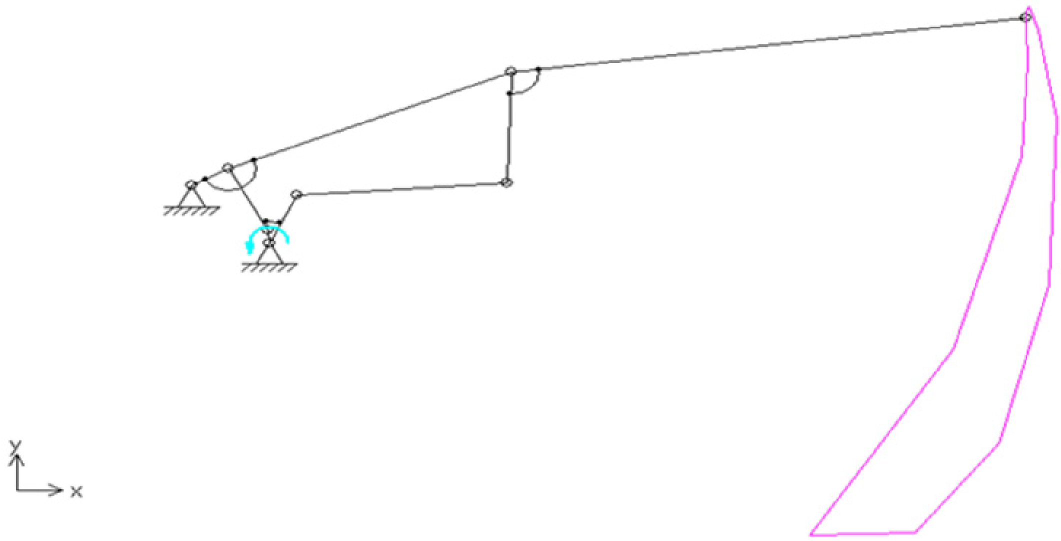

Figure 7. Graphic simulation movement based on five-bar mechanism

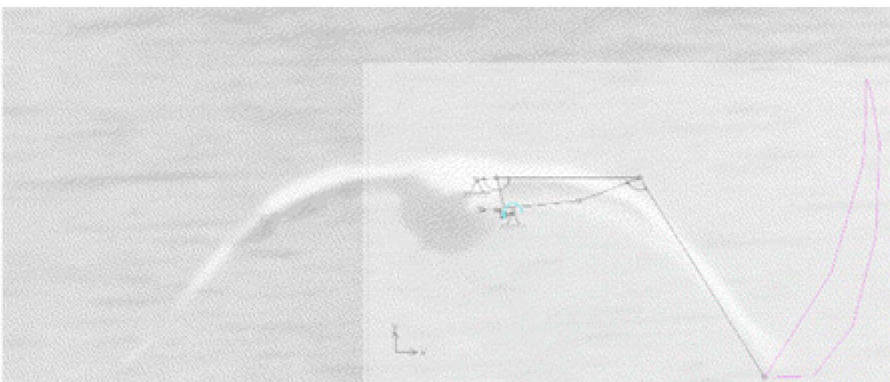

Figure 8. experiment of fitting graphic mechanism and bird wings' movement

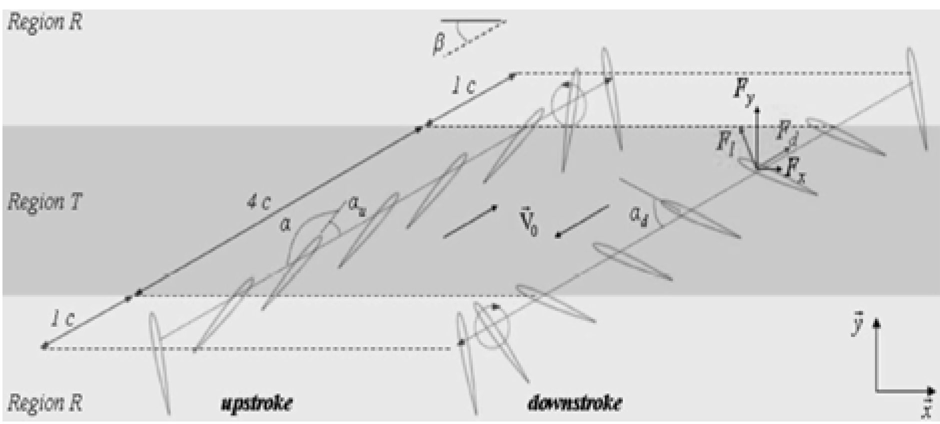

Figure 9. Abbreviated drawing on principle of wings' chord-wise movement

Figure 10. Simulation of space mechanism's movement trace

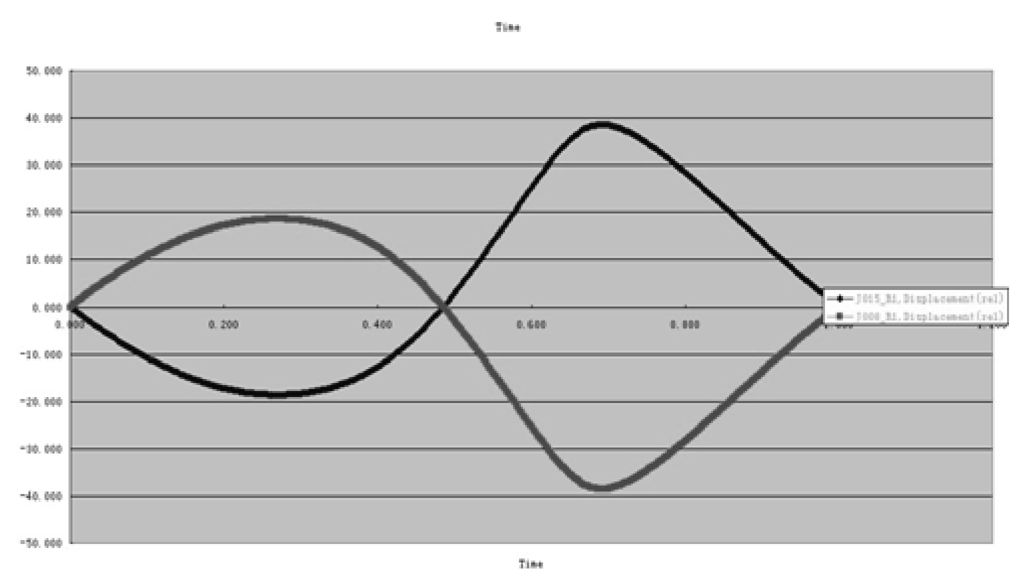

Figure 11. Curve of angle changes of angle 2 and angle 3 during a flapping cycle

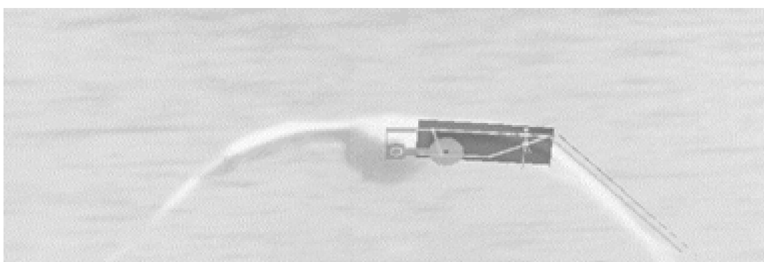

Figure 12. A fitting animation of space mechanism and birds' flapping-wing