Optimization design and dynamic analysis on the drive mechanisms of flapping-wing air vehicles based on flapping trajectories

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Abstract. The optimization designs and dynamic analysis on the driving mechanism of flapping-wing air vehicles on base of flapping trajectory patterns is carried out in this study. Three different driving mechanisms which are spatial double crank-rocker, plane five-bar and gear-double slider, are systematically optimized and analysed by using the Mat lab and Adams software. After a series debugging on the parameter, the comparatively ideal flapping trajectories are obtained by the simulation of Adams. Present results indicate that different drive mechanisms output different flapping trajectories and have their unique characteristic. The spatial double crank-rocker mechanism can only output the arc flapping trajectory and it has the advantages of small volume, high flexibility and efficient space utilization. Both planar five-bar mechanism and gear-double slider mechanism can output the oval, figure of eight and double eight flapping trajectories. Nevertheless, the gear-double slider mechanism has the advantage of convenient parameter setting and better performance in output double eight flapping trajectory. This study can provide theoretical basis and helpful reference for the design of the drive mechanisms of flapping-wing air vehicles with different output flapping trajectories.

1. Introduction
Because of the high concealment and maneuverability, the practical flapping wing air vehicles can be broadly used in the military industry and livelihood industry in the near future (Fang and Wu, 2013). In the past decades, the research on the flapping wing air vehicles has a remarkable progress. However, some challenges still exist and needed to be further studied. One of them is the design of drive mechanisms of the flapping wing air vehicles. Many scholars have done lots of related studies and get some useful results. Michelson (2000) used the crank-slider mechanism to achieve the simple flapping-wing movement. Kinkade (2002) used the gear-bar mechanism to achieve the flapping trajectory of arc. Madangopal (2004) used the plane crank-slider mechanism to achieve a two-dimensional flapping-wing movement. They used the spring to provide more energy and improve the lift. Wang (2006) used the piezoelectric actuator and the four-bar mechanism to make a biomimetic and flexible flapping wing air vehicle. Their drive mechanism has some special advantages such as little friction and high sensitivity. Zhu (2007) designed the seven-bar mechanisms to achieve the flapping trajectory of “eight” and class oval. These researches and achievements provide the huge contribution to the development of flapping wing air vehicles. However, most above study focus on
the movement performance and the feasibility of drive mechanisms. The investigation of flapping trajectory is infrequent, especially lacked of the flapping trajectory of double “eight”. In addition, their drive mechanisms’ flapping trajectory is single. Accordingly, we aim to increase our understanding of flapping trajectory and find a drive mechanism which can achieve varied flapping trajectories expediently. Three mechanisms which are spatial double crank-rocker, plane five-bar and gear-double slider, are employed by the drive mechanisms. The type and characteristics of flapping trajectories of these drive mechanisms will be analyzed in detail.

2. Analytical method
The pattern of flapping trajectory of flying creatures found by previous studies mainly contain oval, ‘eight’ and double ‘eight’ (Dalton S., 2004). Especially, the waving patterns of most insect wings are ‘eight’ and double ‘eight’. As an example, the flapping trajectories of dragonfly are “eight” and double “eight”, and the flapping trajectory of cicada is class oval (Sudo S. et al., 2005), as shown in Figure 1 and 2. This is likely related to the excellent flying skills of insects and can provide inspired ideas for the artificial flying vehicles. Therefore, it is worthy of further study about this trajectory mechanism. In this study, the optimized design on three drive mechanisms can output three trajectories are firstly carried out. The detail components of mechanisms are optimized by using MATLAB based on four output flapping trajectories which are arc, oval, and ‘eight’ and double ‘eight’. Then, ADMAS is used to simply simulate and validate the feasibility of mechanism.

3. Mechanism modeling

3.1. The spatial double crank-rocker mechanism for outputting an arc flapping trajectory
First, a spatial double crank-rocker structure is used by the drive mechanism to produce the arc flapping trajectory. The schematic illustration of the drive mechanism is shown in figure 3. A fixed Cartesian reference coordinate frame is attached at A. The bar AE, AB, BC, CD and ED are represented by l1, l2, l3, l4 and r. The angle between the r and the plane XAY is α, and the angle between the l2 and l3 is β. l1 and l2 are fixed, and r is the drive bar. The coordinates of the points B, C, D and E are (0, 0, z2), (0, yc, zc), (xd, y1, zd) and (0, y1, 0). Among, yc=l3sinβ, zc=z2-l3cosβ, xd=-rcosα, zd=rsinα.
According to the length of $l_4$, the solve equation can be built as:

$$
(0 - x_d)^2 + (y_c - y_1)^2 + (z_c - z_d)^2 = l_4^2
$$

(1)

Further, equation (1) becomes:

$$
(r \cos \alpha)^2 + (l_3 \sin \beta - y_1)^2 + (z_2 - l_3 \cos \beta - r \sin \alpha)^2 = l_4^2
$$

(2)

Equation (2) becomes:

$$
l_2^2 + (r \cos \alpha)^2 + y_1^2 + (z_2 - r \sin \alpha)^2 - l_4^2 = 2l_3 y_1 \sin \beta + 2(z_2 - r \sin \alpha) l_3 \cos \beta
$$

(3)

The equation of auxiliary angle is given by

$$
a \sin x + b \cos x = \sqrt{a^2 + b^2} \sin \left( x + \arctan \frac{b}{a} \right)
$$

(4)

Then, the solution of $\beta$ can be got as follows.

$$
\beta = \arcsin \left( \frac{l_2^2 + (r \cos \alpha)^2 + y_1^2 + (z_2 - r \sin \alpha)^2 - l_4^2}{2l_3 \sqrt{y_1^2 + (z_2 - r \sin \alpha)^2}} - \frac{\arctan \frac{z_2 - r \sin \alpha}{y_1}}{y_1} \right)
$$

(5)

When the $\alpha$ is definitive, the $\beta$ can be solved, so the coordinates of the points C can be got. Finally, the output trajectory of drive mechanism (i.e. movement of point C) can be solved.

There are two constraint conditions in this drive mechanism. One is the restrict on the flapping angle of $l_3$. So the equality constraints can be set as follows. The maximal flapping range is 70°. When the maximize downward flapping range of the mechanism is 40°, $\beta$ is kept at 50°. The other constraint condition is that $l_4$ should not contact with the runner. Then the inequality constraint can be set as $y_c > y_1$.

The max angle and min angle of $l_3$ in the coordinate system is described by $\beta_s$ and $\beta_x$. When the $\alpha$ is 90°, the $l_3$ has the maximal upward flapping angle. Then the equation (5) becomes:
\[ \beta_i = \arcsin\left( \frac{l_z^2 + y_l^2 + (z_2 - r)^2 - l_4^2}{2l_z \sqrt{y_l^2 + (z_2 - r)^2}} \right) - \arctan\left( \frac{z_2 - r}{y_l} \right) \] (6)

When the \( \theta \) is 270°, the l3 has the maximal downward flapping angle, Then the equation (5) becomes:

\[ \beta_i = \arcsin\left( \frac{l_z^2 + y_l^2 + (z_2 + r)^2 - l_4^2}{2l_z \sqrt{y_l^2 + (z_2 + r)^2}} \right) - \arctan\left( \frac{z_2 + r}{y_l} \right) \] (7)

Because \( \beta_i = 50^\circ = 5\pi/18 \) and \( \beta_i = 120^\circ = 2\pi/3 \).

So, the equality constraints are as follows

\[ g_i(x) = \arcsin\left( \frac{l_z^2 + y_l^2 + (z_2 + r)^2 - l_4^2}{2l_z \sqrt{y_l^2 + (z_2 + r)^2}} \right) - \arctan\left( \frac{z_2 + r}{y_l} \right) - \frac{5}{18} \pi = 0 \] (8)

\[ g_i(x) = \arcsin\left( \frac{l_z^2 + y_l^2 + (z_2 - r)^2 - l_4^2}{2l_z \sqrt{y_l^2 + (z_2 - r)^2}} \right) - \arctan\left( \frac{z_2 - r}{y_l} \right) - \frac{2}{3} \pi = 0 \] (9)

Another, \( y_c > y_l \) and equation (5), then

\[ y_c = l_z \sin \beta \geq y_l \] (10)

\[ l_z \sin\left( \arcsin\left( \frac{l_z^2 + (r \cos \alpha)^2 + y_l^2 + (z_2 - r \sin \alpha)^2 - l_4^2}{2l_z \sqrt{y_l^2 + (z_2 - r \sin \alpha)^2}} \right) - \arctan\left( \frac{z_2 - r \sin \alpha}{y_l} \right) \right) \geq y_l \] (11)

Finally, the equation of inequality constraints are:

\[ g_i(x) = y_i - l_z \sin\left( \arcsin\left( \frac{l_z^2 + (r \cos \alpha)^2 + y_l^2 + (z_2 - r \sin \alpha)^2 - l_4^2}{2l_z \sqrt{y_l^2 + (z_2 - r \sin \alpha)^2}} \right) - \arctan\left( \frac{z_2 - r \sin \alpha}{y_l} \right) \right) \leq 0 \] (12)

For the linkage mechanisms, the bigger the transmission angle, the better performance of the drive mechanisms can produce (Yan and Jin, 2008). The transmission angle should bigger than 40° (Sun, et al, 2007). The pressure angle is complementary with transmission angle. So a smaller pressure angle is better. For this reason, the optimized object of this mechanism is to make the maximum pressure angle as small as possible. In current study, the pressure angle locating between the straight DC and the tangential line of straight BC’s velocity direction can be calculated by

\[ \cos(\vec{a}, \vec{b}) = \frac{\vec{a} \cdot \vec{b}}{||\vec{a}|| ||\vec{b}||} = \frac{a_1b_1 + a_2b_2 + a_3b_3}{\sqrt{a_1^2 + a_2^2 + a_3^2} \cdot \sqrt{b_1^2 + b_2^2 + b_3^2}} \] (13)

Where the \( \vec{a} \) describes the vector of straight DC, and the \( \vec{b} \) describes the vector of tangential line of straight BC’s velocity direction. Further,

\( \vec{a} = (0, -l_z \sin \beta, kl_z \sin \beta - 2l_z \cos \beta + 2z_2); \quad \vec{b} = (r \cos \alpha, l_z \sin \beta - y_l, z_2 - l_z \cos \beta - r \sin \alpha) \).
And then, the mechanism may have the biggest pressure angle when \( \alpha \) is 90° or 270°, the optimized object is the sum of pressure angles in the two situation. Furthermore, the objective function is given by

\[
f(x) = \min \left( \frac{\alpha \cdot \bar{b}}{|\alpha| \cdot |\bar{b}|} \right)_{\alpha=90°} + \left( \frac{\alpha \cdot \bar{b}}{|\alpha| \cdot |\bar{b}|} \right)_{\alpha=270°}
\]

Finally, the optimized three-dimensional model of spatial double cranks-rockers drive mechanism is given in figure 4. After numerical optimization, the detail parameters of each component of the drive mechanism described in section 3.1 are \( r=7.5992 \), \( l_1=5.0021 \), \( l_2=15.0021 \), \( l_3=12.8606 \), \( l_4=10.089 \). The sum of all components is 50.553. These values are small enough and good for the miniaturization of flapping-wing air vehicles. When \( \alpha=270° \), the mechanism has the biggest pressure angle which is 43.9°, so the smallest transmission angle is 90°-43.9°=46.1°>40°. Hence, the mechanism meets the requirements.

![Figure 4. The 3D model of spatial double cranks-rockers drive mechanism](image)

![Figure 5. The velocity and displacement graph of the output terminal](image)
Figure 6. The velocity and acceleration graph of the output terminal

Figure 4 shows the flapping trajectory of the spatial double cranks-rockers mechanism. Its flapping trajectory is arc which is consistent to the expectation. Figure 5 and 6 show the dynamical parameters of this drive mechanism. It can be seen that the curves are smooth and don’t have sharp variation, so it confirm the mechanism is feasible and meets the requirements.

3.2. The planar five-bar mechanism for outputting oval, figure of eight and double eight flapping trajectories

To output figure of both oval and eight trajectory, of “eight”, a planar five-bar mechanism is used by the drive mechanism. Figure 7 gives the schematic illustration of the drive mechanism. In this fixed Cartesian reference coordinate frame, the bar AB, BC, CD, DE and AE are respectively described by l1, l2, l3, l4 and l5. α is the angle between l1 and l5. β is the angle between l4 and the positive half of the x-axis. The degree of freedom of plane five bars mechanism is two. In order to reduce the number of motor, gear mesh is used, and $\omega_1$ and $\omega_2$ are the angular velocity of gears.

Figure 7. Schematic illustration of plane five bars mechanism

The coordinates of the points B, C, D and E are $(x_b, y_b)$, $(x_c, y_c)$, $(x_d, y_d)$ and $(l_5, 0)$. The solve equation can be built as follows.

$$\begin{align}
(x_c - x_b)^2 + (y_c - y_b)^2 &= l_2^2 \\
(x_c - x_d)^2 + (y_c - y_d)^2 &= l_3^2 
\end{align}$$  \hspace{1cm} (15)

Another, among, $x_b=l_1\cos\alpha$, $y_b=l_1\sin\alpha$; $x_d=l_5+l_4\cos\beta$, $y_d=l_4\sin\beta$. Then,
So the coordinates of point C is given by
\[
x_c = x_b + l_2 \cos \left( \arccos \left( \frac{l_2^2 + (x_b - x_d)^2 + (y_b - y_d)^2 - l_2^2}{2l_2 \sqrt{(x_b - x_d)^2 + (y_b - y_d)^2}} \right) \right) + \arctan \left( \frac{y_d - y_b}{x_d - x_b} \right)
\]
\[
y_c = y_b + l_2 \cos \left( \arccos \left( \frac{l_2^2 + (x_b - x_d)^2 + (y_b - y_d)^2 - l_2^2}{2l_2 \sqrt{(x_b - x_d)^2 + (y_b - y_d)^2}} \right) \right) + \arctan \left( \frac{y_d - y_b}{x_d - x_b} \right)
\]

This section investigates the flapping trajectory from two situation which are \( \omega_1=\omega_2 \) and \( \omega_1=2\omega_2 \). When the modulus is same, the pitch diameter decides the angular velocity of gear. Hence, when \( \omega_1=\omega_2 \), there are two inequality constraints.
\[
g_1(x) = l_1 - \frac{1}{2}l_3 < 0, \quad g_2(x) = l_4 - \frac{1}{2}l_5 < 0
\]

Similarly, there are two inequality constraints when \( \omega_1=2\omega_2 \).
\[
g_3(x) = l_1 - \frac{1}{2}l_3 < 0, \quad g_4(x) = l_4 - \frac{2}{3}l_5 < 0
\]

In addition, the gears should have a complete circle. There are two extreme situations in the following figure 8 and 9. According to the existence theorem of triangle, there are two inequality constraints:
\[
g_5(x) = l_1 + l_3 - l_2 - l_4 < 0
\]
\[
g_6(x) = |l_2 - l_1| - (l_3 + l_4 - l_5) < 0
\]

**Figure 8.** Straight BD has the Maximum

**Figure 9.** Straight BD has the minimum
Then, it is also found that the aforementioned constraint conditions are not enough because the width of trajectory is large, as shown in figure 10.

So, the additional constraint conditions are needed and defined as follows.

\[
\begin{align*}
    g_1(x) &= l_2 + l_4 - l_5 < 0 \\
    g_2(x) &= l_3 + l_4 - l_5 < 0 \\
    g_3(x) &= l_1 + l_2 - l_5 < 0 \\
    g_4(x) &= l_1 + l_3 - l_5 < 0
\end{align*}
\]  

(23)

The MAV (micro air vehicle) has strict requirements of size, so it’s better to reduce the mechanism’s size. Hence, the objective function is defined by

\[
f(x) = \min(l_1 + l_2 + l_3 + l_4 + l_5)
\]  

(24)

After numerical optimization, the parameters of each component are: l1=7.5, l2=27.5, l3=37.5, l4=15, l5=52.5. The sum of all components is 150. Although, its sum is bigger than spatial double cranks-rockers mechanism’s, it also can achieve miniaturization of flapping-wing air vehicles. The 3d model which \(\omega_1=\omega_2\) is shown in figure 11.

**Figure 10.** Sample of large width trajectory

**Figure 11.** The 3D model of planar five-bar mechanism
Through many debugging, there is an ideal “eight” trajectory can be found when the initial conditions are \( \omega_1=\omega_2, \alpha=180^\circ\) and \( \beta=180^\circ\), just like the Figure 11 shows. Its turnings are smooth that help the mechanism work stably and efficiently. Also, the width of flapping trajectory is narrow which is similar with the insect. Figure 12 and 13 show the dynamical parameters of this drive mechanism. It can be seen that the curves are smooth and don’t have sharp variation, so it confirms the mechanism is feasible and meets the requirements.

Furthermore, this mechanism also can achieve other flapping trajectories when change the initial condition. When \( \omega_1=\omega_2, \alpha=180^\circ\) and \( \beta=15^\circ\), the flapping trajectory of class oval can be got as the following figure 14.
In addition, when the $\omega_1=2\omega_2$, $\alpha=120^\circ$ and $\beta=100^\circ$, the flapping trajectory of double “eight” can also be got as shown in figure 15. However, after dynamic analysis by Adams, this drive mechanism’s performance is not good when it output the flapping trajectory of double eight.

3.3. The gear-double slider mechanism for outputting oval, figure of eight and double eight flapping trajectories

This paper uses the gear-double slider mechanism to output double ‘eight’ flapping trajectory. Figure 16 gives a schematic illustration of drive mechanism. A shown in figure 16, the bar O1C, AC, BD, O2D and O1O2 are respectively described by l1, l2, l3, l4, l5. $\alpha$ is the angle between l4 and the positive half of the x-axis. $\beta$ is angle between l1 and l5. Point O1 and O2 are fixed. The mechanism also uses gear mesh to reduce the number of motor. The $\omega_1$ and $\omega_2$ are the angular velocity of gears. The coordinates of the points O1, O2, A, B, C and D are (0, 0), (l5, 0), (xa, ya), (xb, yb), (xc, yc), and (xd, yd). Further,

$$
\begin{align*}
    x_c &= l_1 \cos \beta, \\
    y_c &= l_1 \sin \beta; \\
    x_d &= l_3 + l_4 \cos \alpha, \\
    y_d &= l_4 \sin \alpha, \\
    x_a &= x_b = l_3 + l_4 \cos \alpha - \sqrt{l_3^2 - (l_4 \sin \alpha)^2}.
\end{align*}
$$

Figure 16. Schematic illustration of gear-double sliders mechanism

The length between point C and straight AB is calculated by

$$
|CB| = x_b = x_c = l_3 + l_4 \cos \alpha - \sqrt{l_3^2 - (l_4 \sin \alpha)^2} - l_1 \cos \beta
$$

(25)

The ordinate of a point is given by

$$
y_a = y_c + \sqrt{l_2^2 - |CB|^2}
$$

(26)

For this mechanism, the output trajectories can be controlled by changing the rotating speed ratio. This section investigates three conditions. When $\omega_1=\omega_2$, the output trajectory is oval. When $\omega_1=2\omega_2$, 

the trajectory is figure of eight. When \( \omega_1=3\omega_2 \), the trajectory is double eight. From figure 16, there are a constraint condition that point B should be on the right of point \( O_1 \), so:

\[
g_1(x) = 0 - l_4 + l_4 \cos \alpha - \sqrt{l_4^2 - (l_4 \sin \alpha)^2} < 0
\]  

(27)

Similar with last section, there are two inequality constraints in each rotating speed ratio. For \( \omega_1=\omega_2 \)

\[
g_2(x) = l_1 - \frac{1}{2} l_2 < 0, \quad g_3(x) = l_4 - \frac{1}{2} l_5 < 0
\]

(28)

For \( \omega_1=2\omega_2 \)

\[
g_4(x) = l_1 - \frac{2}{3} l_5 < 0, \quad g_5(x) = l_4 - \frac{1}{3} l_5 < 0
\]

(29)

For \( \omega_1=3\omega_2 \)

\[
g_6(x) = l_1 - \frac{3}{4} l_5 < 0, \quad g_7(x) = l_4 - \frac{1}{4} l_5 < 0
\]

(30)

The optimized object of this mechanism is that make the maximum pressure angle as small as possible. In this mechanism, the pressure angle is between the straight AC and straight AB. From figure 16, the mechanism has the biggest pressure angle when \( \alpha=0 \) and \( \beta=\pi \). Due to the sine function is monotonic in the interval of 0 to 0.5\( \pi \), so it can be replaced the pressure angle as the optimization target. The sine function of the pressure angle is defined by

\[
\sin \theta = \frac{|CB|_{l_1}}{l_2}
\]

(31)

Hence, the objective function is defined by

\[
f(x) = \min \left( \frac{|CB|_{l_1}}{l_2} \right)_{\alpha=0, \beta=\pi} = \min \left( \frac{\left( l_1 + l_4 \cos \alpha - \sqrt{l_4^2 - (l_4 \sin \alpha)^2} - l_3 \cos \beta \right) l_2}{l_2} \right)_{\alpha=0, \beta=\pi}
\]

(32)

After numerical optimization, the parameters of each component are: \( l_1=12.0007, \ l_2=29.9997, \ l_3=23.3582, \ l_4=3.0001, \ l_5=26.3587 \). The sum of all components is 94.7. Its value is small and good to the miniaturization of flapping-wing air vehicles. In addition, the mechanism has the biggest pressure angle which is \( 29^\circ<50^\circ \), so the performance of the gear-double sliders mechanism is good.
Figure 17. The flapping trajectory of double “eight” in Adams

Figure 18. The displacement graph of the output terminal

Figure 19. The velocity graph of the output terminal
Figure 20. The acceleration graph of the output terminal

Through many debugging, there is an ideal double “eight” trajectory can be found when the initial conditions are $\omega_1=3\omega_2$, $\alpha=70^\circ$ and $\beta=90^\circ$, just like the figure 17 shows. Compared with the double “eight” trajectory of plane five bars mechanism, its trajectory is more regular and smooth. Hence, it has the better performance. Figure 18 to 20 show the dynamical parameters of this drive mechanism. It can be seen that the curves are smooth and don’t have sharp variation, so it confirm the mechanism is feasible and meets the requirements.

Furthermore, this mechanism also can achieve other flapping trajectories when the rotating speed ratio is changed. When $\omega_1=\omega_2$, the flapping trajectory of class oval can be got as the following figure 21. When $\omega_1=2\omega_2$, the flapping trajectory of “eight” can be got as the following figure 22. After dynamic analysis by Adams, this drive mechanism’s performance meets the requirements when the flapping trajectory is class oval or “eight”.

4. Conclusion

In this paper, the optimization and analysis about three flapping-wing air vehicles’ drive mechanisms which are based on the flapping trajectory has been carried out. Different drive mechanisms with their unique characteristics can be used to output different flapping trajectories. The spatial double crank-rocker mechanism can output the flapping trajectory of arc. It has the advantages of small volume, high flexibility and efficient space utilization. Hence, it is suitable for the flapping-wing air vehicles which need the high flapping frequency. The plane five-bar mechanism can output the flapping trajectory of “eight”, double “eight” and class oval. It has the advantages of small friction. However, the complicated parameter setting and unsmooth flapping trajectory of double “eight” are its limits. As for the gear-double slider mechanism, it can output the flapping trajectory of “eight”, double “eight”
and class oval, too. Compared with the plane five-bar mechanism, its flapping trajectory of double “eight” is smoother and parameter setting is more convenient. Hence, this helpful drive mechanism can be used to provide the varied flapping trajectories for the MAV.

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References
[1] R. J. Fand and F. J. Wu, The development of the MVA, J. Mechanical & Electrical Technology. 5 (2013) 158-160.
[2] R. C. Michelson, Entomopter and Method for Using Same, U. S. Patent 6,082,671. (2000)
[3] A. S. Kinkade, Ornithopter, U. S. Patent 5,899,408. (2002)
[4] R. Madangopal, Z. A. Khan and S. K. Agrawal, Energerics Based Design of Small Flapping Wing Air Vehicles. Proceeding of the 2004 IEEE, International Conference on Robotics and Automation, New Orleans, 2004, pp. 2367-2372.
[5] S. X. Wang and G. P. Chen, Study on insect-based flapping-wing system driven by piezoelectric bimorph, J. Optics and Precision Engineering, 14 (2006) 617-622.
[6] B. L. Zhu, H. S. Ang and L. Guo, Design and Analysis of New 3D Insect-Like Flapping-Wing Mechanism, J. Nanjing University of Aeronautics & Astronautics, 39 (2007) 457-460.
[7] S. Dalton, The miracle of flight, McGraw –Hill Book Company, New York, 2004
[8] S. Sudo, K. Tsuyuki, and K. Kanno, Wing characteristics and flapping behavior of flying insects. J, Experimental Mechanics. 45 (2005) 550-555.
[9] S. M. Yan and G. G. Jin, A study of average transmission angle of planar linkage and its application, J. Machinery. 35 (2008) 19-22.
[10] Q. H. Sun, E. G. Dong, L. Zhang and S. R. Gao, Parameters analysis and optimal design of four-bar steering mechanism, J. Liaoning Technical University, 26 (2007) 278-280.