DESIGN AND MODELLING OF NANO AERIAL VEHICLE HUMMINGBIRD MECHANISM ON HOVER FLIGHT

İbrahim H. GÜZELBEY*, Müslüm ÖZKESİCİLER and Ahmet ŞUMNU

Department of Aeronautical and Astronautics Engineering, Gaziantep University, Şehitkamil, Gaziantep 27310, TURKEY
guzelbeyih@gantep.edu.tr

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ABSTRACT

In nature, there are thousands of flapping insects and flying bird’s species. Each one has spectacular flight stability, dynamic and operates in high diversity of flight speed and mission. Each one has superior effectiveness and high efficiency. This paper relates with design and model of an efficient hummingbird mechanism during hovering flight. The proposed mechanism represents new and different concept for point of Nano aerial vehicle’s (NAV’s) mechanism design. In this study, flapping wing tip path for hummingbird was generated from morphological experiment data’s. Slider crank mechanism was designed to be an effective mechanism and same motion with path of hummingbird and analyzed on Simulink with driving crank flapping frequency as 25 Hz. During hovering, forces occurring on designed mechanism were calculated. The system modeled on MATLAB using of Sim-mechanics Toolboxes.

Keywords: Path Generation, Hummingbird Mechanism, Kinematic Synthesis.

1. INTRODUCTION

Nowadays, Micro and Nano air vehicles are focused on by scientists since they are used for crucial task such as homeland security, gathering information from surrounding, monitoring some critical area (tunnel and caves).

In history of aviation, scientists think flight with flapping concepts inspiring from nature, but aviation starts with aircraft that has fixed wing due to applicability. Flapping flight completely differs from gliding flight. Nowadays, there are a lot of resource and project about flapping wings and they are known each one is small comparison with aircrafts. To
achieve micro scale vehicle, design of efficient flapping mechanisms of flapping motion should be solved challenging problem.

In biological flight, the wings not only move forward relative to the air, they also flap up and down, plunge and sweep [1]. When Micro and Nano level flight are examined, insect is observed to make swinging path. Hummingbirds flight about 1200 - 3000 Re [2]. Even though hummingbird is a bird, it has swinging path properties like insect [3]. There is a relation with Reynold’s number with swinging. Swinging is observed when Reynold’s number is low. Swinging path can also save power in terms of aerodynamics in low Reynolds number [4]. This is the reason why birds and insects flap their wings and why aircrafts do not flap its wings. Therefore, swinging paths have curial points in Nano and Micro scales.

In order to perform swinging, a special mechanism is needed. There are some mechanism design studies in literature. One of them is flapping mechanism design of bird that was implemented by Grand et al. Wings are motioned by four position controlled brushless motors and these four motors connected rod-crank two by two parallel mechanisms [5]. Dragonfly design was implemented two parallel slider crank mechanisms by Dileo and Deng [6]. Fearing and Wood designed Nano scale 100 mg insects. Using two piezoelectric bimorph bending actuators, two wings are driven. Slider-crank converts actuator linear displacement into input to planar four bars these are coupled each other and create rotational effect to wings. [7].

There are a lot of experimental results for morphological behavior of hummingbirds. In our study, Kruyt et al. presented one of experimental datas. [8]. Using these datas, points of wing tip path were generated. The generated path represented a swinging path as usual. This path is constituted with 41 points. Slider crank mechanism was then synthesized for this path.

Taking reference for Karasek and Preumont study, wing structure was formed with CFRP (Carbon Fiber Reinforced Stiffener) and Mylar [9]. Wings were covered with Mylar as assuming with inspired these similar studies. Due to structural stiffness, very small deflection can occur in the tips so; it is assumed that structure is rigid body. Then, mechanism is driven with frequency of 25 Hz. by inspiring from nature [10]. Reaction forces and required torque are calculated for designed mechanism on Simulink. Consideration of these forces, dimension of the mechanism is evaluated with using similar materials in current applications. All of our mechanism takes 1.14 grams weights without wings. Similar studies have mechanisms weight between 2.5-2.8 grams. Therefore, designed mechanism gives us idea about new approaches for the NAV’s flapping paths.

2. METHODOLOGY

Hummingbird path was created with 41 points from experimental data of Kruyt et al. with discrimination [8]. Slider crank mechanism was synthesized according to this path after MATLAB program was written in our application for synthesis. This program based on multiple points path generation. Program creates database and compares results with target path. After comparison, minimum error value was selected as output path. The linkages lengths were obtained according to results of the MATLAB program.

According to Karasek and Preumont study, wing structure and dimensions were formed in Fig.1. Structure compose of CFRP and Mylar that has been used in similar applications. Alloys aluminum are commonly used hummingbird mechanism applications [11]. Hence, our mechanism was assumed by AL-6069 material and weight of the mechanism is evaluated according to this assumption. Mechanism and wings are shown in Fig.1a. Wings structures size are presented in Fig.1b.

![Figure 1. Mechanism and wings (a) Visual representation of mechanism and wings. (b) Dimensions of wing structure.](image)
In section three, using experimental data, flapping angles of hummingbird was created for time incremental way for each time ($\Delta t$). After this processes, all angles were obtained and the points of path were obtained. When points were combined with lines, wing tip path profile of hummingbird was generated. Taking reference for this path, $3^{rd}$ inversion slider crank mechanism was designed for all of variables. Eqns.(4)-(9) show constraint equations of our mechanism according to point that connects the wing.

In section four, mechanism is driven in SimMechanics by 25 Hz (is equal 157 [rad/s]). Results of this simulation represent forces on linkages and required torque.

3. FLAPPING PATH SYNTHESIS

Experimental results show that, hummingbird’s wing tip path has been specified for each different flight characteristic. Due to hovering, velocity of crank is constant and optimum condition occurs. Stroke angle has sinusoidal motion and between $-87.5 \leq \phi \leq 62.5$ degrees in Fig.2. Taking reference of Kruyt et al. [8] research data, path was generated with 41 points by discretization of all data. It can be converted from time domain to x-y Cartesian plane with parameter transformation with Eqns.(1)-(3). It was swinging path as expected like sign curve. Created hummingbird path is shown in Fig. 3.

The curve can be generated with a lot of types of mechanism. Four bar mechanism is an example for this type, but when it is generated mechanism for this path, it has dead point in dynamic motion and heavy compared with slider crank mechanism. For this reason, slider crank mechanism is unique choice.

There are a lot of methods which are sum of absolute difference, sum of squared difference, and correlation Fourier transforms in literature for path generation [12]. Most of methods base on making databases. In this article, desired path was synthesized using sum of absolute difference method on MATLAB program. Constrained equation of the slider-crank offset mechanism’s which is represented in Fig 4. were written in Eqns.(4)-(9).

\[
\begin{align*}
\alpha &= \text{Angle of Attack} \\
\theta &= \text{Flap amplitude angle} \\
\phi &= \text{Stroke angle} [8].
\end{align*}
\]

\[
\begin{align*}
\vec{p}_1 &= b \sin(\phi_1)\hat{x} + b \sin(\theta_1)\hat{y} \\
\vec{p}_2 &= b \sin(\phi_2)\hat{x} + b \sin(\theta_2)\hat{y} \\
\vec{p}_{n+1} &= b \sin(\phi_{n+1})\hat{x} + b \sin(\theta_{n+1})\hat{y}
\end{align*}
\]
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\[ x_2 = x_1 + A \cos \beta , \quad y_2 = y_1 - A \sin \beta \]

(7)

\[ x_c = x_1 + p \cos \beta , \quad y_c = y_1 - p \sin \beta \]

(8)

\[ x_d = x_c - d \sin \beta , \quad y_d = y_c - d \cos \beta \]

(9)

\[ R_1 e^{\theta_1} + R_2 e^{\theta_2} + R_3 e^{\theta_3} + R_4 e^{\theta_4} + R_5 e^{\theta_5} = 0 \]

(10)

\[ x - R_1 \cos(\theta_1) + R_2 \cos(\theta_2) + R_3 \cos(\theta_3) + R_4 \cos(\theta_4) + R_5 \cos(\theta_5) = 0 \]

(11)

\[ y - R_1 \sin(\theta_1) + R_2 \sin(\theta_2) + R_3 \sin(\theta_3) + R_4 \sin(\theta_4) + R_5 \sin(\theta_5) = 0 \]

(12)

Figure 5. Flow-chart of our mechanism synthesis program.

Lengths of linkages were used calculation for each loop with incremental method. Calculation ranges were defined for each linkage. At each increment state, five loops were calculated as shown in Fig. 5. In inner loops path were generated for each values within 41 equal increments of angles between from 0 to 360 degrees. Paths were then classified inside cell array properly. After that, database and target path were normalized in x direction. Each paths and target path were sliced in x axis. First, in down-stroke direction (-x → +x), linear interpolation was done between each 2 points. Then, same process is done for up-stroke direction (-x ← +x). From these equations, vertical deviation of paths with target path was measured. For each paths error function were found and each cells identified with error term. Optimum path was generated with minimum error value. Fig.5 represents flow-chart of our mechanism synthesis. According to length parameters represented in Fig.4, mechanical linkages lengths were computed.

Figure 6. Vector and points of mechanism.
4. MECHANISM CONTROLLING

In this section, force equilibriums represented in Fig. 7 are written for designed mechanism. Reaction forces and required driver torque were then computed. Matrix form of these equations is represented Eqn. (26).

In this study, Simulink/SimMechanics toolbox was used. PID controller was used to control the mechanism for constant angular velocity that was reached 25 Hz flapping frequency of hummingbird. In SimMechanics, force, torque and velocity measurement devices were placed for specified points in Fig. 6. According to simulations results, reaction forces on these points are calculated.

Figure 7. Free Body Diagram of Mechanism.

\[
F_{01x} + F_{21x} = m_1a_{G1x}
\]

(13)

\[
F_{01y} + F_{21y} = m_1a_{G1y}
\]

(14)

\[
T + F_{01a} + F_{01b} - F_{21a} - F_{21b} = I_{G1}a_1
\]

(15)

\[
T_{24} = m a_{G2x}
\]

(16)

\[
F_{12y} + F_{32y} + F_{42y} = m_2a_{G2y}
\]

(17)

\[
-F_{12x} - F_{12y} - F_{32x} - F_{32y} = F_{42x} + F_{42y} +
\]

\[
F_{42y}d + T_{42} = I_{G2}a_2
\]

(18)

\[
F_{24x} = F = m_3a_{G4x}
\]

(19)

\[
F_{24y} = m_3a_{G4y}
\]

(20)

\[
-F_{24k} + F_{24l} + T_4 = I_{G4}a_4
\]

(21)

\[
F_{03x} + F_{23x} = 0
\]

(22)

\[
F_{03y} + F_{23y} = 0
\]

(23)

\[
F_{10x} + F_{30x} = 0
\]

(24)

\[
F_{10y} + F_{30y} = 0
\]

(25)
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Figure 8. PID control time response. (a) Angular velocity according to time. (b) Driver torque according to time.

Figure 9. The result of linkages forces in SimMechanics during one second for each specified point. (a) Ground-Crank joint pin forces. (b) Crank-Coupler pin forces. (c) Slider-Coupler planer joint contact surface forces. (d) Coupler on stepped corner forces. (e) Wing assembly section contact surface forces.

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As noticed in section 3, synthesis of our mechanism was performed to achieve similar motion of hummingbirds with slider crank mechanism by iteration concept. Wing structure was connected on point 5 that is represented in Fig.6 and this point crucial point in this study. When point 5 of our wing was examined, position of this point gave us similar hummingbird’s path which is shown Fig. 10.

The dimensions of linkages are presented in Table 1. Resultant reaction forces and torque of specified points of mechanism at steady state represented in Fig. 6 are presented in Table 2. The motor drives our crank linkages with output response 25 Hz. Maximum transition angular velocity of dynamic system has 203 rad/s in the first overshoot as seen Fig. 8a. The maximum torque occurs at initial time (T=0.017 Nm) in Fig. 8b. Joint pin forces computed using SimMechanics are presented in Fig. 9 for 5 specified points in designed mechanism during one second in x, y and z directions. It is observed that maximum force occurs on point 1 at initial. Most of reaction forces have largest value at time peak (t_p). Mechanism performed periodic motion due to the fact that the links of the system was assumed rigid and not considering any disturbance effects.

Our mechanism was designed effectively. Roll-yaw and pitch motions can be added practically. Although our mechanism doesn’t have roll-yaw-pitch effects, these motions can be done with using light piezoelectric materials. Birds and insects make roll-yaw and pitch with changing their center of mass. When piezoelectric materials had been used for changing center of mass in our study, it would give same results with nature.

### Table 1. Linkages dimensions results.

<table>
<thead>
<tr>
<th>Distances</th>
<th>Lengths in [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>4</td>
</tr>
<tr>
<td>L</td>
<td>14.7</td>
</tr>
<tr>
<td>z</td>
<td>0.1</td>
</tr>
<tr>
<td>p</td>
<td>12.6</td>
</tr>
<tr>
<td>d</td>
<td>17</td>
</tr>
</tbody>
</table>

### Table 2. Result of Torque, Velocity and Forces.

<table>
<thead>
<tr>
<th></th>
<th>Velocity of Wing</th>
<th>Required Torque</th>
<th>Reaction force of point 1</th>
<th>Reaction force of point 2</th>
<th>Reaction force of point 3</th>
<th>Reaction force of point 4</th>
<th>Reaction force of point 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>157 [rad/s]</td>
<td>0.009 [Nm]</td>
<td>2.3 [N]</td>
<td>2.3 [N]</td>
<td>2.3 [N]</td>
<td>0.25 [N]</td>
<td>1.1 [N]</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

In this study, hummingbird’s mechanism design was focused on. Hence, the inertial forces and torque were only taken into account for mechanism. Slider crank mechanism was proposed with specific linkage lengths for mechanisms. Different from previous studies, proposed mechanism gives us an opportunity creating same motion with hummingbirds using one mechanism input and without any complexity. At the same time, designed mechanism has low weight compared with other studies and has high effectiveness.

REFERENCES


**VITAE**

İbrahim H. Güzelbey received B.Sc degree in 1981 and M.Sc degree in 1985 at Mechanical Engineering from Middle East of Technical University. He obtained Ph.D in 1992 at Mechanical Engineering from Cranfield Institute Technology. Currently, he is a professor at Gaziantep University, Aircraft and Aerospace Engineering Department.

Müslüm Özkesiciler graduated Pertevniyal High School (Istanbul, Turkey) in the year 2014. Then, he started to study Aeronautics and Aerospace Engineering Department of Gaziantep University. He currently studies as junior student in this department.

Ahmet Şumnu works at Aircraft and Aerospace Engineering at Gaziantep University as a Research Assistant. He received B.Sc. degree in 2013 and M.Sc. degree in 2015 at Mechanical Engineering. He is currently Ph.D. student at Mechanical Engineering in Gaziantep University.