The new concept of power transmission to the entomopter wings

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Abstract

The aim of this study is to discuss the design of the mechanism used for power transmission to the entomopter wings in order to perform a flapping motion and control the angle of attack of the wings. The study presents a kinematic diagram and a simulation model obtained in SolidWorks for the proposed mechanism, which includes a slotted link mechanism and a slider mechanism (with bilateral slider) that actuates the rocking lever of the wing. The simulation model allowed for observation of the system work and verification of the adopted kinematic assumptions. The comparative analysis showed that trajectories obtained from the both models are very similar. The correct operation of the proposed solution has been demonstrated by building a prototype of the mechanism and conducting experimental research. In the case of the application of the solution presented for the real object it is sufficient to choose the system parameters in order to properly reflect the living organism. The proposed mechanism is characterized by simplicity and offers opportunity for miniaturization while ensuring reliable work at reduced demand for power to drive the mechanism. A technological advantage of the presented solution is the use of only one component in order to perform flapping wing motion and change the angle of attack of the entomopter.

Keywords Entomopter · Flapping · Angle of attack · Power transmission mechanism · Wing

1 Introduction

Potential applications of entomopters (flying miniature robots) include observation, control and supervision of e.g. building investments, internal monitoring of pipelines (especially those with small diameters), identification of damages caused by natural disasters, battlefield surveillance and inspection of inaccessible regions (forestry, environmental protection), geodetics etc.

The mechanism of power transmission to the entomopter wings has been used worldwide for many years. Various scientific and research centres from various countries have presented plethora of solutions concerning forced movement of

micro air vehicles. The solutions described in the literature concerned the flapping wing movement and changing the angle of attack of wings.

Description of a number of solutions of various types of mechanisms of power transmission to the wings of a flying minirobot included in the article [1]. The proposed mechanisms are primarily designed to reproduce the complicated movement of the wings of a real insect without considering folding their up [2]. Among the studies that have analysed the kinematics of movement and the mechanism of mechanical power transmission into entomopter wings are publications [3–32]. A differential mechanism [3], a crank-and-slider mechanism and a slider-rocker mechanism [4–7], a cam mechanism [8], a four-bar linkage [9–16] or a Scotch yoke [17–19] were used to power transmission. The power transmission system cooperating with the Weis-Fogh mechanism is presented in [20]. The power transmission systems can also be supported by piezoelectric elements. In this case, the basic movement of the wings is realized in the classic way, but with the help of mechanical transmission with periodic modification of the trajectory using the piezoelectric elements [21–23]. In turn, the use of the most advanced projects of the resonant drive is shown in the works [24–26]. A physical model for a micro air vehicle with Flapping Rotary Wings (FRW) is investigated in paper [27]. The comprehensive MAV concepts

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Fig. 3 Model of the mechanism

geometric simulation model was prepared in the SolidWorks program. The simulation model allowed for observation of the system work and verification of the adopted kinematic assumptions.

2.1 Kinematic model

Kinematic model (for one wing) of the proposed mechanism was shown in Fig. 1. It is composed of: 1 - entomopter wing, 2 - rocking lever guide with limiters of the angle of attack 5, 3 - wing rocking lever, 4 - bilateral slide, 6 - slotted-link mechanism, 7 - slotted-link mechanism guide, 8 - bushing and guide of the bilateral slide, 9 - wing rocking level guide bushing, 10 - slotted-link mechanism bushing.

The following symbols were used in the kinematic diagram to describe mechanism motion sequence (Fig. 2): O - origin of the coordinate system, P_1 , P_2 , P_3 - selected points on the wing used to describe wing motion (P_1 - point on the xy -plane), a - distance of the point P_1 from the origin of the coordinate system, b - distance from the centre of the bilateral slider guide to the origin of the coordinate system, c_1 - bilateral slider height, c_2 - wing rocking lever height, d and e - distances of points P_2 and P_3 from the point P_1 , α - angle of flapping motion, β - angle of wing rotation, γ - angle of attack, φ - angle of the position of the driving wheel of the slotted-link mechanism, ω - angular velocity, r -

radius of the driving wheel of the slotted-link mechanism.

Position of the characteristic points P_1 , P_2 and P_3 , during the mechanism work can be described by means of the following formulae:

$$P_{1x} = a \sin(-\alpha/2), \quad (1a)$$

$$P_{1y} = a \cos(\alpha/2), \quad (1b)$$

$$P_{1z} = 0, \quad (1c)$$

$$P_{2x} = P_{1x} + d \sin(\beta/2) \cos(\alpha/2), \quad (2a)$$

$$P_{2y} = P_{1y} + d \sin(\beta/2) \sin(\alpha/2), \quad (2b)$$

$$P_{2z} = P_{1z} - d \cos(\beta/2), \quad (2c)$$

$$P_{3x} = P_{1x} - e \sin(\beta/2) \cos(\alpha/2), \quad (3a)$$

$$P_{3y} = P_{1y} - e \sin(\beta/2) \sin(\alpha/2), \quad (3b)$$

$$P_{3z} = P_{1z} + e \cos(\beta/2). \quad (3c)$$

The value of the parameters a , d and e (dependent of the wing type) are constants and do not change during mechanism operation. The system motion is defined by value of angles α and β , which depend on the value of angle φ . The limiting value of angle α , which depends on the radius (r) and distance (b) between the bushing of the bilateral slider guide and the bushing of the rocking lever guide can be described by:

$$\alpha = 2 \arctan(r/b). \quad (4)$$

Fig. 4 Limiters of the rotational (rocking) motion for the rocking lever of the wing

Fig. 5 A full sequence of entomopter wing motion (changes in the angle of wing rotation and flapping angle)

The limiting value of the angle β depends on the design of the wing lever guide. Time to reach maximal values depends on the parameter c_2 (the higher value of the parameter, the longer time).

2.2 Structural model and the working principle

A structural model for the proposed mechanism was developed based on the adopted kinematic that concerned the implementation of such a movement of the mechanism, which as a consequence will force the movement of the wings of the model corresponding to the movement of the wings of the real insect.

A solid parametric model was construed using the SolidWorks software [41]. The model (similar to the kinematic design) is composed of the following components: wing 1, rocking lever guide 2, rocking lever 3, bilateral slider 4, limiters of the angle of wing rotation 5 (adequately shaped guide 2), slotted-link mechanism 6, slotted-link mechanism 7, bushing and guide of the bilateral slider 8, and guide bushing 9.

Operation of the mechanism used in the model occurs as follows: the battery-powered electric motor (not shown in Fig. 3) drives the driving wheel of the slotted-link mechanism 6, with the slotted-link moves along the guide 7. The slotted link is connected with bushings and bilateral slider guides 8, on which bilateral slides 4 are fixed. Lower parts of sliders moving in bushings and guides can perform both rotational

Fig. 7 Location of the characteristic points P_1 , P_2 and P_3 in the isometric view during flapping (downstroke (a) and upstroke (b)) and changes in the angle of wing rotation

and sliding movements. Upper parts of bilateral sliders work together with wings' rocking lever guides 3. During the work of the mechanism, the slider performs four movements. Basic movement (reciprocating), resulting from the movement of the slotted-link mechanism and two relative movements, i.e. extension and rotation in the bushing and guide 8. These movements also lead to moving the slider on the rocking lever guide. The rocking lever of the wing moves in the guide 2, which is nested in the bushing 9 and performs partially rotational motion in the range of changes of flapping motion α . The rocking lever performs limited rotational movement with

respect to the guide in the range of the angle of wing rotation β . The range of motion of the rocking lever defined by the angle β is limited by the lever motion limiters. The limiters were obtained by the matching shape of the rocking lever guide (see Fig. 4). Entomopter wings are attached to the rocking levers of the wings located on the other side of the guide.

The described connections of the mechanism components and their movements force the specific movement of the wings. In the beginning of the motion, started from the turning points A and B (see Fig. 5) of the slotted-link mechanism, the

Fig. 8 Location of the characteristic points P_1 , P_2 and P_3 and ranges of angles α and β : projections onto the xy plane (a) and xz plane (b)

Fig. 6 Changes in angles α and β during the mechanism work (changes in the angle φ)

wing first perform the change of the angle of wing rotation β and next the flapping motion (change in the angle α). A full sequence of motion mechanism was illustrated in Fig. 5a-d.

These figures present a simplified form of the slotted-link mechanism and its motion as x and $-x$ displacement of the bushing and guide of the bilateral slider 8. As the mechanism works, bilateral slider 4 moves in the guide 8 in the range of value y_1 . The rocking lever of the wing 3 rests on the limiter 5.

Further movement of the slotted-link x leads to the flapping wing motion (change in the angle α by the value of $\alpha/2$). This motion is continued until the slotted link reaches the extreme location (moving the slotted link to the point A, see Fig. 5a). In the point A, the slotted link switches the direction of motion from x to $-x$ and the returning motion of the slotted link begins. In the first phase of the movement (slotted link movement by the value x_1), it causes the change in the angle of wing rotation by the value β . The rocking lever rests on the opposite limiter and the flapping motion is started (change in the angle α) with the motion of the slotted link moving by x_2 until the second turning point B is reached (Fig. 5c).

The change in the direction of the motion of the slotted link mechanism from $-x$ to x occurs in point B. During the mechanism movement by x_3 the angle of wing rotation changes by the value of β (see Fig. 5d).

This represents the starting point of the flapping motion until the mechanism reaches the point A. In this point, the motion sequence of the mechanism is completed, and, consequently the wing motion sequence also ends (change in the angle of wing rotation β and flapping angle α) both in x and $-x$ directions. Next, the sequence of motion and changes in angles is repeated again.

A technological advantage of the presented solution is the use of only one component between the slotted-link mechanism and the rocking lever of the wing in the form of a bilateral slider in order to perform flapping wing motion and change the angle of wing rotation of the entomopter. The simplicity of the solution allows for the independent work of the mechanism, reduction in power consumed to drive the mechanism and opportunities for substantial miniaturization of the design.

3 Example results

During a flight, insects perform a flapping motion over various ranges of the angle α . Example values of the wing flapping angle were presented in the study [18]. As results from the data presented in this study, the angles range from 56° to 91° . Furthermore, the typical

Fig. 9 Geometrical wing model with characteristic points

Fig. 10 Trajectory of the characteristic points during the mechanism operation

angle of attack at 70% wingspan ranges from $\gamma = 25^\circ$ to $\gamma = 45^\circ$ in hovering insects.

The following values of the parameters were adopted in the model (see Fig. 2): $a = 28.57$ mm, $b = 7.4$ mm, $c_1 = 4.9$ mm, $c_2 = 1.6$ mm, $d = 7.21$ mm, $e = 3.56$ mm, $r = 4.74$ mm and $\beta = 77.11^\circ$, and, consequently, using the adopted relationship (4), $\alpha = 67^\circ$.

3.1 Analytical solution

Based on the parameters obtained from the developed geometrical model (see Fig. 3) and the relationships (1–3), we determined locations of the characteristic points of the wing (P_1 , P_2 and P_3) during the mechanism work (Figs. 7 and 8). The driving wheel drives (by changing the angle φ) the slotted-link mechanism, which leads to changes in the angle of wing rotation (β) and wing flapping (α) according to the diagram 6. Figure 6 contains additional points (on the x axis) that show the specific sequence of entomopter wing motion from Fig. 5. Angle φ_1 and φ_5 correspond to the position in Fig. 5a, angle φ_2 to the position in Fig. 5b, angle φ_3 to position in Fig. 5c, and angle φ_4 to position in Fig. 5d.

Fig. 11 Comparison of analytical results (trajectories of the characteristic points) with simulations in SolidWorks software

The values of angles α and β can be described depending on the angle φ with the following equations:

$$\alpha(\varphi) = (\alpha_{\max} - \alpha_{\min}) \left\{ \frac{\frac{\varphi}{\phi_3 - \phi_2} H(\phi_3 - \phi_2 - \varphi) + [H(\phi - \phi_3 + \phi_2) - H(\phi + \phi_2 - \phi_4)] + \frac{\phi_5 - \phi_2 - \phi}{\phi_5 - \phi_4} H(\phi + \phi_2 - \phi_4)}{H(\varphi) H(\phi_5 - \phi_2 - \varphi) - \alpha_{\max}} \right\} \quad (5)$$

where: $H(\cdot)$ is the Heaviside function, $\phi = \phi_b - (\phi_2 - \phi_1)$, φ_b is the current angle position φ in range $<0, 360^\circ>$,

$$\beta(\varphi) = (\beta_{\max} - \beta_{\min}) \left\{ \frac{\frac{\varphi}{\phi_2 - \phi_1} H(\phi_2 - \phi_1 - \varphi) + [H(\phi - \phi_2 + \phi_1) - H(\phi + \phi_1 - \phi_3)] + \frac{\phi_4 - \phi_1 - \phi}{\phi_4 - \phi_3} H(\phi + \phi_1 - \phi_3)}{H(\varphi) H(\phi_4 - \phi_1 - \varphi) - \beta_{\max}} \right\} \quad (6)$$

where: $\phi = \phi_b - \phi_1$.

3.2 Simulation in SolidWorks

Simulation tests were performed in Motion module of the SolidWorks software using a geometrical model (Fig. 3).

Fig. 12 Mechanism prototype

The system motion was forced by a virtual angular drive, which actuated the motion of the driving wheel. It was assumed that the mechanism would work at the constant speed of 25 rpm. The effect of other forces (e.g. gravitation) was neglected in the system.

Three additional points were added (see Fig. 9) to obtain the trajectories of the characteristic points P_1 , P_2 and P_3 in the geometrical wing model. They allowed for the analysis of their spatial location during the mechanism work.

The system work (animation of the motion of the whole system) was documented for several seconds and the trace path of the added points was recorded (see Fig. 10).

In order to verify the work of the mechanism shown in Fig. 11, we compared the results obtained from the simulation performed in the SolidWorks software and those obtained from the relationship (1–3).

The comparative analysis presented in Fig. 11 shows that trajectories of the characteristic points (mimicking the insect's wing motion) obtained from the model prepared in SolidWorks software and those obtained from the kinematic model are very similar.

Fig. 13 Stepper motor (1), controller (2) and Arduino platform (3)

3.3 Experimental verification of the mechanism's operation

In order to verify the operation of the proposed model, a real object (Fig. 12) was made. Most of the elements were made of PLA material using the FDM (Fused Deposition Modeling) technique [42]. 3D printing was also used to make the wing frame, with which the foil imitating the wing was then welded. Normalized fasteners were used at the joints.

The system was driven using a stepper motor 28BYJ-48 (Fig. 13:1) with a 64:1 integrated gear reduction and a dedicated controller based on the ULN2003 system (Fig. 13:2). For motor control, an Arduino platform equipped with an ATmega2560 microcontroller was used (Fig. 13:3).

Sequences of subsequent wing positions during the mechanism's operation are shown in Fig. 14 (top view) and Fig. 15 (side view), while the work of the mechanism can be seen in the video under the link (http://www.imipkm.pcz.pl/wp-content/uploads/2016/08/New_mechanism.wmv).

The experimental verification of the operation of the entomopter wing drive mechanism confirmed its correct operation and the possibility of using it in the design of entomopters or other flying objects.

In the case of the application of the presented solution for the real object it is sufficient to choose the system parameters in order to properly reflect the living organism. If it is assumed as in the study [18] that wing flapping angle α during a flight is 77° (see Fig. 16), it suffices to modify the radius of the driving wheel of the slotted-link mechanism (r) of the distance between the bilateral slider guide bushing and rocking lever guide bushing (b). According to (4), if the parameter b (7.4 mm) is unchanged, the radius r is 5.89 mm, or if the radius r is unchanged (4.74 mm), the distance b (5.96 mm) is modified.

Furthermore, if the angle of wing rotation (β) was 90° (Fig. 17), the design of wing lever guide would have to be modified.

A full comparative analysis of the model proposed in the work and the real object in terms of similarities and differences as well as the possibilities of controlling the object will be the subject of further work of the Authors.

Fig. 14 Sequence of wing positions during mechanism operation (top view)

Fig. 15 Sequence of wing positions during mechanism operation (side view)

4 Conclusions

The design of the mechanism used for power transmission to the entomopter wings in order to perform a flapping motion and control the angle of attack of the wings was discussed in the paper. The kinematic scheme and the simulation model prepared in SolidWorks program for the proposed mechanism were shown. The results obtained

on the basis of comparative analysis for both models proved that trajectories of the observed characteristic points are very similar. To verify the mechanism's operation, a prototype was built. Most of the elements were performed on a 3D printer, and the drive and control was implemented using a stepper motor with a suitable driver and an ATmega microcontroller. Experimental validation confirmed the correctness of the proposed solution in the scope of transmission of the drive from the motor to the wings of the entomopter by the mechanism of forcing the

Fig. 16 Range of changes in wing flapping angle α [18]

Fig. 17 Range of changes in the angle of wing rotation (β) of the wings [18]

movement of the wings corresponding to the movement of the wings of the real insect (*Melolontha melolontha*).

The presented mechanism for power transmission to entomopter wings using the slotted-link and slider mechanism is characterized by simplicity and offers opportunity for miniaturization while ensuring reliable work at reduced demand for power to drive the mechanism. A technological advantage of the presented solution is the use of only one component between the slotted-link mechanism and the rocking lever of the wing in the form of a bilateral slider in order to perform flapping wing motion and change the angle of attack of the entomopter. Numerical simulations demonstrated that it is possible to design an entomopter model with the mechanism proposed in the study to perform basic insect wing movements in the range of actual flapping angles and angles of attack.

The considered model of the mechanism is under patent protection [43].

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