A novel piezo-actuated flapping mechanism based on inertia drive

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Abstract
In this article, a novel piezo-actuated flapping mechanism based on inertia drive is proposed and developed. In comparison with the existing flapping mechanisms, the proposed one has a more direct driving form simply via a frictional contact without using any transmission mechanism like crank-rocker or crank-slider, making it easier for miniaturization. In addition, it could principally allow for an arbitrary form of flapping motion with unlimited stroke. The flapping principle and the rationale for an arbitrary form of flapping motion with unlimited stroke are presented. A prototype of the proposed flapping mechanism was constructed and tested. The ability in various modulations of flapping motion, including flapping amplitude, position, asymmetry between downstroke and upstroke flapping speeds, and frequency, is demonstrated.

Keywords
Flapping actuation mechanism, unlimited stroke, arbitrary form of flapping motion, piezo-actuator, inertia drive

1. Introduction
Flapping-wing micro air vehicles (FWMAVs) are bio-inspired flying robots taking design cues from flight features of living fliers with flapping wings, such as birds, bats, and insects. To perform tasks in various confined spaces for a wide range of applications, such as exploration of unknown caves, search and rescue in a building on fire or under collapsed structures, and detection of chemical or radiation leakages in related plants, tailless FWMAVs are becoming a popular trend for research (Anderson and Cobb, 2012, 2014; Deng et al., 2006a; Deng et al., 2006b; Doman and Oppenheimer, 2009; Doman et al., 2009; Finio et al., 2009; Hoang et al., 2017; Keennon et al., 2012; Mukherjee and Ganguli, 2010; Nguyen and Chan, 2019; Oppenheimer et al., 2011; Roshanbin et al., 2017; Wood, 2007, 2008), since they have great potential for miniaturization. To achieve lifting, propulsion, and steering simply via wing flapping with the concept illustrated in Figure 1, it has high requirements on flapping mechanisms, since various modulations of flapping motions, including flapping amplitude, flapping position, flapping asymmetry between downstroke and upstroke flapping speeds, and flapping frequency, are required.

Various flapping actuation mechanisms composed of different forms of actuators and flapping transmission mechanisms have been investigated and developed over the last decades. Actuators used for flapping actuation mechanisms include DC motors (Baek et al., 2009; Bejgerowski et al., 2009; De Croon et al., 2009; Hines et al., 2013; Hsu et al., 2010; Lau et al., 2014; Madangopal et al., 2005; Tsai and Fu, 2009), piezoelectric actuators (Arabagi et al., 2012; Cox et al., 2002; Mateti et al., 2013; Mukherjee and Ganguli, 2010; Peng et al., 2017; Syaifuddin et al., 2006; Wood, 2007), electromagnetic actuators (Bontemps et al., 2012; Meng et al., 2012; Zhou et al., 2016), dielectric elastomer actuators (Lau et al., 2014; Zdunich et al., 2007), electrostatic actuators (Suzuki et al., 1994; Yan et al., 2015), and electroactive membranes (Hays et al., 2013). On the basis of the output movements of actuators (i.e. rotational or linear movements), various topologies of the flapping transmission mechanisms (Bejgerowski et al., 2009; Gerdes et al., 2012; Madangopal et al., 2005; Sreetharan and Wood, 2010; Szabo and D’Eleuterio, 2018; Wood et al., 2008; Zbikowski et al., 2005; Zhang...
and Rossi, 2017), generally inspired by the principle of crank-rocker or crank-slider mechanisms shown in Figure 2, were designed to convert the rotational or linear movements of actuators into the required flapping motion. The design topologies of the flapping transmission mechanisms can be realized by conventional rigid-body mechanisms based on rigid links and joints or compliant mechanisms based on flexure-hinges. Despite the reliability and ease of control, rigid-body flapping transmission mechanisms, composed of conventional rigid links and joints, are hard to scale down for a miniaturized FWMAV. Flexure-hinge based compliant flapping transmission mechanisms, which can be fabricated in a monolithic way, are easy for miniaturization, but they involve a complex manufacturing process. Hence, it is more preferable to develop a flapping actuation mechanism in a more direct form without using any flapping transmission mechanism.

In this article, a novel piezo-actuated flapping mechanism based on inertia drive is proposed and developed. In comparison with the existing flapping actuation mechanisms, the proposed one has the following two advantages:

1. It has a more direct driving form simply via a friction contact without using any transmission mechanism, such as crank-rocker or crank-slider, thereby making it easier for miniaturization.
2. It could principally allow for an arbitrary form of flapping motion with unlimited stroke.

The rest of the article is structured as follows. Section “Configuration and flapping principle” introduces the configuration and flapping principle of the proposed flapping actuation mechanism. Section “Rationale for an arbitrary form of flapping motion” presents the rationale for arbitrary forms of flapping motion. In section “Experimental study,” a prototype is constructed and tested, and the ability of the proposed flapping mechanism in various modulations of flapping motion is demonstrated. Section “Conclusion” provides summary and future work.

2. Configuration and flapping principle

With reference to Figure 3, the proposed flapping mechanism is composed of a base, a piezo-actuator, a magnet, and a bearing attached with a flapper where a wing can be installed. One end of the piezo-actuator is fixed to the base with the other end glued to the magnet. The bearing with its axis fixed to the base is preloaded to the magnet by magnetic force, thereby allowing for a relative movement with a frictional contact.

It is well known that the piezo-actuator has a limited stroke (microscopic movement) which is too small to be used in flapping motion, so stroke amplification techniques are required. An amplification technique based on the principle of inertia drive is proposed here.
for flapping. This technique has been successfully used in many applications, such as optical alignment (Gao et al., 2010; Li et al., 2019; Peng et al., 2015; Shimizu et al., 2013; Yang et al., 2010), microscopy (Bergander et al., 2002; Fatikow et al., 2008), micro/nano-handling (Lu et al., 2018; Rakotondrabe et al., 2009; Zhang et al., 2018), and biomedical manipulation (Kudoh et al., 1998). With reference to Figure 4, macroscopic flapping motion of the flapper can be accumulated by microscopic step movement, which is realized by inputting a series of asymmetric sawtooth waveform voltage shown in Figure 5. The flapping principle is explained as follows.

In terms of downstroke flapping motion, as shown in Figure 4, a sawtooth waveform voltage of a slow increase and a rapid decrease (namely, a sawtooth wave with a duty ratio larger than 50%), as shown in Figure 5, is used to drive the piezo-actuator. When the piezo-actuator is driven with the slowly increased voltage, the bearing will be rotated by friction force with the slow expansion of the piezo-actuator. Then, when the applied voltage is rapidly decreased, the piezo-actuator will rapidly contract, but the bearing cannot follow the fast contraction and will remain nearly on site due to its inertia. Therefore, a microscopic downstroke step movement can be achieved for one cycle of such an asymmetric vibration. By repeating the cycle of asymmetric vibration via inputting a series of sawtooth voltage waves shown in Figure 5, microscopic step movement can be accumulated to achieve unlimited macroscopic downstroke flapping motion. Likewise, unlimited macroscopic upstroke flapping motion of the wing can be achieved by inputting a series of sawtooth voltage waves composed of a rapid increase and a slow decrease (namely, a sawtooth wave with a duty ratio smaller than 50%), as shown in Figure 5.

3. Rationale for an arbitrary form of flapping motion

In this section, the rationale that the proposed flapping mechanism could principally allow for an arbitrary form of flapping motion with unlimited stroke is presented as follows.
The microscopic downstroke/upstroke step angle $\Delta \theta$ shown in Figure 4 induced by one cycle of input sawtooth waveform voltage shown in Figure 5 can be expressed as follows:

\[
\begin{align*}
\Delta \theta_{d,k} & \approx d_{d,k}/r \quad (1a) \\
\Delta \theta_{u,k} & \approx u_{u,k}/r \quad (1b)
\end{align*}
\]

where $d$ is the vibration amplitude of the piezo-actuator, $r$ is the rotational radius, subscripts “$d$” and “$u$” denote downstroke and upstroke, respectively, and subscript “$k$” denotes a certain cycle of input sawtooth wave voltage.

The speed of the microscopic downstroke/upstroke step angle can be expressed as follows:

\[
\begin{align*}
\omega_{d,k} &= \Delta \theta_{d,k}/T_{d,k} = \Delta \theta_{d,k}/T_{d,k} \cdot f_{d,k} \quad (2a) \\
\omega_{u,k} &= \Delta \theta_{u,k}/T_{u,k} = \Delta \theta_{u,k} \cdot f_{u,k} \quad (2b)
\end{align*}
\]

where $T$ and $f$ ($f = 1/T$) are the period and frequency of the input sawtooth waveform voltage, respectively.

The macroscopic downstroke/upstroke flapping angle $\theta$ accumulated by each microscopic step angle $\Delta \theta$ can be expressed as follows:

\[
\begin{align*}
\theta_d &= \sum_{k=1}^{m} \Delta \theta_{d,k} \quad (3a) \\
\theta_u &= \sum_{k=1}^{n} \Delta \theta_{u,k} \quad (3b)
\end{align*}
\]

where $a$ and $b$ are the numbers of input sawtooth voltage waves illustrated in Figure 5.

It can be deduced from equation (3) that downstroke $\theta_d$ and upstroke $\theta_u$ are principally unlimited by controlling the number of voltage cycles $m$ and $n$, respectively. The vibration amplitude $d$ of the piezo-actuator is determined by the input sawtooth waveform voltage amplitude $A$, it can be deduced from equations (1) to (3) that each microscopic downstroke/upstroke step movement ($\Delta \theta_{d,k}$, $\Delta \theta_{u,k}$, $\omega_{d,k}$, and $\omega_{u,k}$) can be independently controlled by their corresponding input sawtooth waveform voltage amplitude ($A_{d,k}$ and $A_{u,k}$) and frequency ($f_{d,k}$ and $f_{u,k}$), which could principally allow for arbitrary forms of flapping motion. In practice, it is subject to the physical limitations of the control signal generator and the piezo-actuator.

4. Experimental study

In this section, experiments are carried out to demonstrate the ability of the proposed flapping mechanism in various modulations of flapping motion required in the case illustrated in Figure 1. A prototype and experimental setup are first presented, followed by experimental characterizations of the proposed flapping mechanism and then demonstrations of flapping motion.

### 4.1. Prototype and experimental setup

A prototype of the proposed flapping mechanism with its experimental setup was constructed and shown in Figure 6. The prototype was constructed as introduced in section “Configuration and flapping principle” and is shown in Figure 6(b) with a centimeter ruler used as a contrast to illustrate its dimension. The multilayer piezoelectric actuator (AL1.65 × 1.65 × 5D-4F from NEC TOKIN) with a size of 1.65 × 1.65 × 5 mm$^3$, magnet (N42 from MAGPANDA) with the size of 2 × 2 × 1 mm$^3$, and bearing (NMB 681) with the size of R1.5 × 1 mm$^2$ were used. The flapper where a wing can be installed was three-dimensionally (3D) printed with the size of 8 × 3 × 1 mm$^3$ and attached to the bearing. With regard to the experimental setup, a function generator (KEYSIGHT, 332200A) was used to generate the required voltage signals, which were amplified by a voltage amplifier (ECHO ELECTRONICS, ENP-151U) to drive the piezo-actuator. The flapping motion of the flapper was measured by a laser sensor (KEYENCE, LK-H052) via a reflecting wafer which was attached to the flapper. The measured data were recorded by an oscilloscope (YOKOGAWA, DLM2024). The sampling frequency was set as 25 kHz.

At the current stage, the wing is not attached, and the flapping motion of the flapper was tested at still air. According to Figure 6(a), the rotational angle of the flapper can be expressed in terms of the measured displacement in the following relationship.

![Figure 6. Prototype and experimental setup: (a) schematic and (b) physical implementation.](image)
\[ \theta = \arctan \left( \frac{d - d_0}{a} \right) \]  

(4)

4.2. Experimental characterization

Prior to the tests of flapping motion, the proposed flapping actuation mechanism was experimentally characterized. As justified in section “Rationale for an arbitrary form of flapping motion,” each microscopic downstroke/upstroke step movement \((\Delta \theta_{d,k}, \Delta \theta_{u,k}, \omega_{d,k}, \text{ and } \omega_{u,k})\) can be independently controlled by their corresponding input sawtooth waveform voltage amplitude \((A_{d,k} \text{ and } A_{u,k})\) and frequency \((f_{d,k} \text{ and } f_{u,k})\), subject to the physical limitations of the piezo-actuator and the control signal generator. Therefore, prior to the tests of flapping motion, the effects of the input sawtooth waveform voltage driving frequency \(f\) and amplitude \(A\) on the flapping speed \(\omega\) were characterized, respectively.

To characterize the effect of the driving frequency \(f\) of the input sawtooth waveform voltage, the driving voltage amplitude \(A\) was set as 60 V, and the duty ratios of the input sawtooth waves for downstroke and upstroke were set as 80% and 20%, respectively. The flapping speeds for downstroke and upstroke were tested under various driving frequencies. The experimental data are plotted in Figure 7. The flapping speed \(\omega\) first increased with the driving frequency \(f\) until 20 kHz. This could be easily understood, since the flapping speed can be expressed as \(\omega = \Delta \theta \cdot f\), as shown in equation (2), where \(\Delta \theta\) is the step angular for one voltage cycle. However, when the operation frequency is beyond the bandwidth, the displacement output magnitude \(d\) of the driving mechanism will dramatically decrease with the increase in the frequency, thus resulting in a decreasing output step angle of the rotor \(\Delta \theta\) \((\Delta \theta=d/r\) as shown in equation (1)). Therefore, when the frequency is above 20 kHz, although the frequency \(f\) increases, as the step displacement \(\Delta \theta\) decreases in a faster rate, the flapping speed \(\omega\) showed a decreasing trend.

Furthermore, to characterize the effect of input sawtooth waveform voltage amplitude \(A\), the driving frequency \(f\) was set as 20 kHz, and the duty ratios of the input sawtooth waves for downstroke and upstroke were set as 80% and 20%, respectively. The flapping speeds for downstroke and upstroke were tested under various input voltage amplitudes (peak to peak voltage). The experimental data are plotted in Figure 8. The result showed that the flapper did not move until the voltage was increased to 12 V. This is because the inertia force at low voltage was insufficient to overcome the static friction between the driving mechanism and the flapper and failed to generate a step rotation. When the voltage is above 12 V, the flapping speed almost linearly increased with the voltage for either downstroke or upstroke. This was expected, since the flapping speed can be expressed as \(\omega = f \cdot \Delta \theta = f \cdot d/r\) \((f, \Delta \theta, d, \text{ and } r\) are the driving frequency, step angle, vibration amplitude of the piezo-actuator, and rotational radius, respectively) and the vibration amplitude \(d\) of the actuator almost linearly increased with input voltage amplitude \(A\).

From the aforementioned experiments and analysis, it can be seen that the flapping speed \(\omega\) can be controlled by either input voltage amplitude \(A\) or driving frequency \(f\), and the former is easier. Therefore, the input voltage amplitude \(A\) will be used for controlling the flapping speed \(\omega\) in this study. The downstroke flapping speed \(\omega_d\) and the upstroke flapping speed \(\omega_u\) are further characterized with the input voltage amplitude from the experimental data shown in Figure 8 in the following relations for flapping speed control.

\[ F \frac{\pi}{4} \]
4.3. Experimental demonstrations of various modulations of flapping motion

Five cases listed in Table 1 were studied to demonstrate the ability in various modulations of flapping motion as required in the case illustrated in Figure 1, including flapping amplitude, position, asymmetry between the downstroke and the upstroke flapping speeds, and frequency. Case 1 was targeted at a flapping motion with a flapping stroke from $-25^\circ$ to $25^\circ$ and a flapping frequency of 20 Hz with an equal downstroke/upstroke speed, as shown in Figure 9. This case was used as a benchmark to demonstrate various modulations of flapping motion in Cases 2, 3, 4, and 5. Case 2 was targeted at a flapping motion with a flapping stroke from $-40^\circ$ to $40^\circ$ and a flapping frequency of 20 Hz with an equal downstroke/upstroke speed, as shown in Figure 10. This case was used to demonstrate the ability in modulation of flapping amplitude. Case 3 was targeted at a flapping motion with a flapping stroke from $-10^\circ$ to $40^\circ$ and a flapping frequency of 20 Hz with equal downstroke/upstroke speed, as shown in Figure 11. This case was used to demonstrate the ability in modulation of flapping position. Case 4 was targeted at a flapping motion with a flapping stroke from $-25^\circ$ to $25^\circ$ and a flapping frequency of 20 Hz with a downstroke/upstroke speed ratio of 1:3, as shown in Figure 12, which is used to demonstrate the ability in modulation of flapping asymmetry between downstroke and upstroke flapping speeds. Case 5 was targeted at a flapping motion with a flapping stroke from $-25^\circ$ to $25^\circ$ and a flapping frequency of 20 Hz with equal downstroke/upstroke speed, as shown in Figure 13. This case was used to demonstrate the ability in modulation of flapping frequency.

The input voltage of Case 1 was obtained in the following process. The following conditions during one period of flapping motion ($T_1 = 0.05s$, where $T$ is the period of flapping motion, and “1” is Case 1) can be formulated on the basis of the target flapping motion trajectory shown in Figure 9.

Table 1. Cases for demonstrations of various modulations of flapping motion.

<table>
<thead>
<tr>
<th>Case</th>
<th>Flapping amplitude (degrees)</th>
<th>Mean stroke angle position (degrees)</th>
<th>Flapping frequency (Hz)</th>
<th>Downstroke/upstroke speed ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>0</td>
<td>20</td>
<td>1:1</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>0</td>
<td>20</td>
<td>1:1</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>15</td>
<td>20</td>
<td>1:1</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>0</td>
<td>20</td>
<td>1:3</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>0</td>
<td>30</td>
<td>1:1</td>
</tr>
</tbody>
</table>

\[
\omega_d = 37.368 \cdot A_d - 454.31, R^2 > 0.99 \tag{5a}
\]
\[
\omega_u = -44.167 \cdot A_u + 529.12, R^2 > 0.99 \tag{5b}
\]
\[
\theta_{d_1} = \sum_{k=1}^{m_1} \Delta \theta_{d_1,k} = 25^\circ \quad (6a)
\]

\[
\theta_{u} = \sum_{k=1}^{n} \Delta \theta_{u,k} = -50^\circ \quad (6b)
\]

\[
\theta_{d_2} = \sum_{k=1}^{m_2} \Delta \theta_{d_2,k} = 25^\circ \quad (6c)
\]

\[
\omega_{d_1,k} = \Delta \theta_{d_1,k} \cdot f_{d_1,k} = 2000^\circ/s, \text{ where } k = 1, 2, \ldots, m_2
\]

\[
(6e)
\]

\[
\omega_{u,k} = \Delta \theta_{u,k} \cdot f_{u,k} = -2000^\circ/s, \text{ where } k = 1, 2, \ldots, n
\]

\[
(6f)
\]

In equation (6), subscripts “1” and “2” represent the downstrokes from the periods 0 to 0.25 \( T_1 \) and 0.75 \( T_1 \) to \( T_1 \), respectively.

As justified in section “Experimental characterization” the flapping speed can be easily controlled by changing the input sawtooth waveform voltage amplitude with the driving frequency of the input sawtooth waveform voltage unchanged.

Equation (5) in section “Experimental characterization” is characterized on the basis of the input sawtooth waveform with a constant driving frequency of 20 kHz.
...and duty ratios of 80% and 20% for downstroke and upstroke, respectively. Hence, the same driving frequency and duty ratios of the input sawtooth waves will be used here to facilitate the design of sawtooth waveform voltage amplitude, which gives

\[ f_{d_1, k} = 20 \text{ kHz} \tag{7a} \]
\[ f_{u_1, k} = 20 \text{ kHz} \tag{7b} \]
\[ f_{d_2, k} = 20 \text{ kHz} \tag{7c} \]
Duty ratio_{d_1, k} = 80\% \tag{7d}
Duty ratio_{u_1, k} = 20\% \tag{7e}

Substituting equation (7) into equation (6) yields

\[ m_1 = 250 \tag{8a} \]
\[ n = 500 \tag{8b} \]
\[ m_2 = 250 \tag{8b} \]

Then, by substituting equations (6d) to (6f) back into equation (5) and fine tuning the calculated results in the experiments, the corresponding voltage amplitudes to achieve the specified flapping speeds can be obtained...
Based on equations (7) to (9), the input voltage of Case 1 was obtained. The input voltages for Cases 2, 3, 4, and 5 were obtained in a similar way. The relevant parameters of the input voltages were listed in Table 2. In Table 2, T is the period of one cycle of flapping, and subscripts “1,” “2,” “3,” “4,” and “5” represent Cases 1, 2, 3, 4, and 5, respectively. I represents the number of repeated flapping cycles (I = 0, 1, 2, ...).

Then, by inputting the obtained input voltage with relevant parameters listed in Table 2, the flapping motions in the five cases are tested and measured. These motions are plotted with the target flapping motion and quantified errors in Figures 9 to 13. It can be seen that the flapping amplitude, position, asymmetry between downstroke and upstroke flapping speeds, and frequency can be modulated as desired, indicating the potential of the proposed mechanism in wing flapping. The errors in the five cases are all within ±5%, and the maximum errors mainly occur at transitions between downstroke and upstroke. This is mainly due to the inertia of the flapper, and the errors can be suppressed using a relatively larger voltage amplitude of the sawtooth waveform voltage inputs at transitions between downstroke and upstroke.

The case used for demonstration is simple to facilitate the presentation. However, the proposed flapping method is not limited to the case demonstrated herein. As justified in section “Rationale for an arbitrary form of flapping motion,” each microscopic downstroke/upstroke step movement \( (\Delta \theta_{d,k}, \Delta \theta_{u,k}, \omega_{d,k}, \text{and } \omega_{u,k}) \) can be independently controlled by their corresponding input sawtooth waveform voltage amplitude \( (A_{d,k} \text{ and } A_{u,k}) \) and frequency \( (f_{d,k} \text{ and } f_{u,k}) \). Moreover, the number of microscopic step movements \( (\theta_d = \sum_{k=1}^{m} \Delta \theta_{d,k} \text{ and } \theta_u = \sum_{k=1}^{n} \Delta \theta_{u,k}) \) can be controlled by the number of input sawtooth voltage waves. Therefore, the proposed flapping method can principally allow for an arbitrary form of flapping motion with unlimited stroke, subject to the physical limitations of the control signal generator and the piezo-actuator.

### 5. Conclusion

In this work, a novel piezo-actuated flapping mechanism based on inertia drive was proposed and developed. In principle, macroscopic flapping motion of the flapper is obtained via accumulating microscopic step movement, which is realized by inputting a series of asymmetric sawtooth waveform voltage. In comparison with the existing flapping mechanisms, the proposed one has a more direct driving form without using any transmission mechanism, such as crank-rocker or crank-slider, making it easier for miniaturization. In addition, as each microscopic step movement can be controlled by their corresponding input voltage waveform and the number of microscopic step movements can be controlled by the number of input sawtooth voltage waves, the proposed flapping method could principally allow for an arbitrary form of flapping motion with unlimited stroke, subject to the physical limitations of the control signal generator and the piezo-actuator.

A prototype of the proposed flapping mechanism was constructed and tested. The ability in various modifications of flapping motion, including flapping amplitude, position, asymmetry between downstroke and upstroke speeds, and frequency modulation, is demonstrated, which indicates its potential for wing flapping.
In future work, wings will be designed and integrated to test the lifting ability.

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