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Enhancing Energy Efficiency in Ornithopters through Spring-Driven Harmonic Oscillations

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Introduction

Ornithopters

Uses

- UAVs emulating birds flight
- Applications in search, rescue, surveillance, monitoring

Challenges

- Energy inefficiency resulting in limited flight time (low flight endurance)

Improvement

- Inspired by the use of tendons in the flapping motion of birds
- Integrating spring mechanism

Aim: Investigation of wing motion trajectory, energy efficiency, and flight performance to enhance energy efficiency.

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Background Information

Prior Research

- Prior research focuses on trajectory optimisation, not mechanical design.
- Tendon mechanism in birds enhances efficiency (60% of work during upstroke).
- Existing studies examine wing motion and shapes but lack focus on spring integration.
  → No actual flight performance

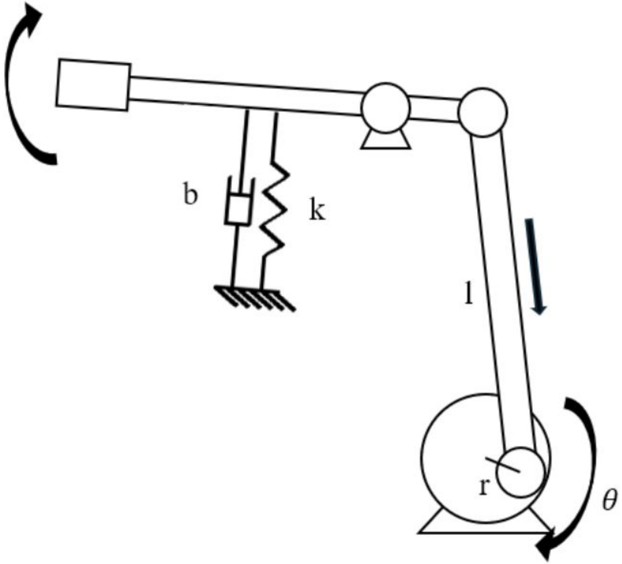
Structure

Wings

- Lightweight materials, flexible frame, membrane-like surface

Springs

- Replicates the tendon-like elastic energ storage of birds



Joints

- Rotating motor connected to a crank road
  → Used to replicate the flapping motion

Mathematical Modeling

Forced Harmonic Oscillators

$$I\ddot{\theta} + b\dot{\theta} + k\theta = T_0\cos(\omega' t)$$

$$\ddot{\theta} + 2\beta\dot{\theta} + \omega^2\theta = \frac{T_0}{I}\cos(\omega' t)$$

$$A = \frac{\frac{T_0}{I}}{\sqrt{(\omega^2 - \omega'^2)^2 + (2\beta\omega')^2}}$$

$$\frac{1}{(\omega^2 - \omega'^2)^2 + (2\beta\omega')^2} > \frac{1}{(\omega')^4 + (2\beta\omega')^2}$$

$$0 < k < 2I(\omega')^2$$

- When k falls within this range, the amplitude of the torsional pendulum with the spring will exceed the amplitude without the spring.

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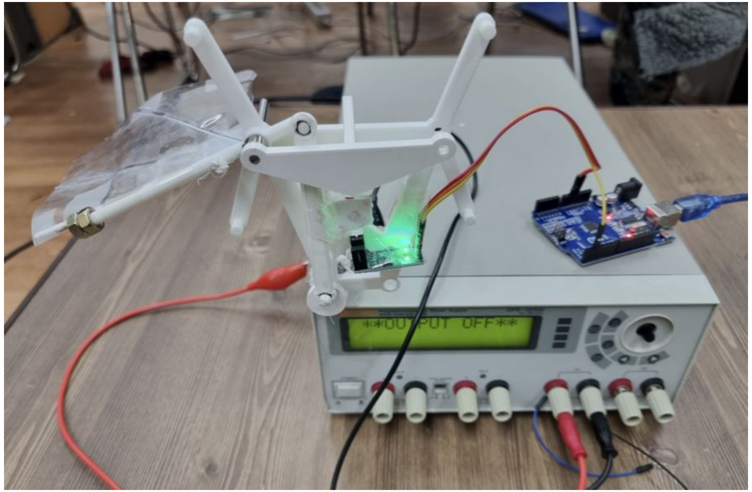
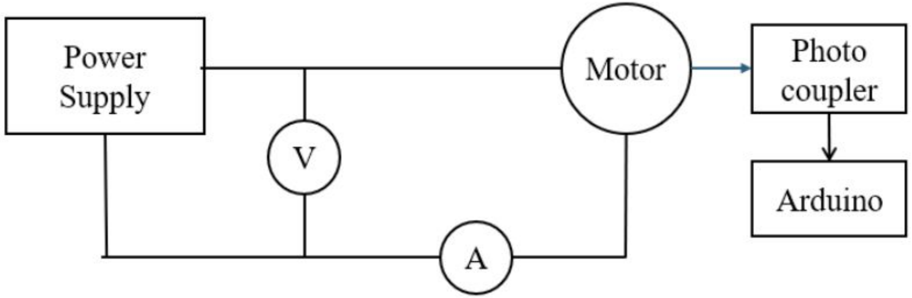
Materials & Methods

Materials

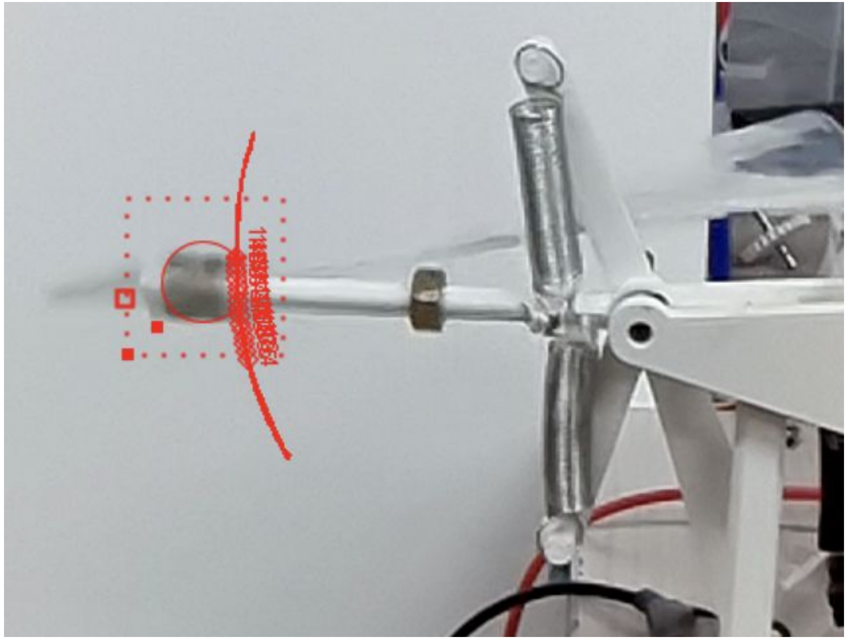
- Test rigs created with 3D modeling and printing
- DC motor
- Rods to attach springs
- 3g nut to control wing weight
- Wings of thin, plastic membranes to provide drag



- Power consumption (voltage, current) displayed on the power supply
- Photocoupler installed to detect movement of the rod
  → Flapping frequency



Trajectory Analysis



- Used to observe trajectories of wing motion to examine flapping behaviours.
- Motion was recorded using a high-speed camera at 960 fps and was processed in the ‘Tracker.’

Energy Efficiency Analysis

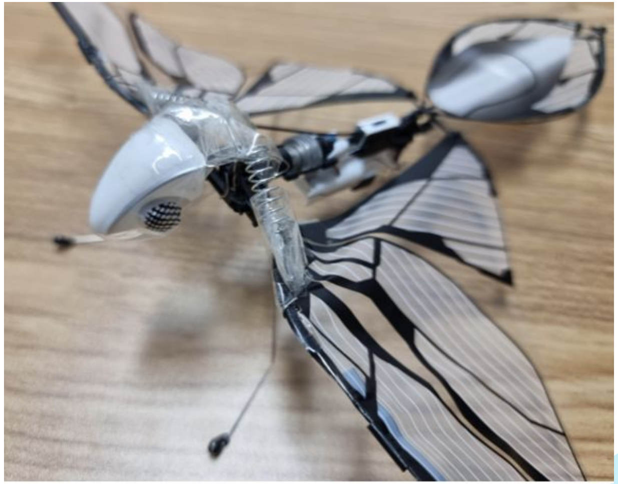
- Experiment conducted with/without springs, varying spring constants (160 N/m, 120 N/m), and wing mass (3 g).
- Measurements of power and flapping frequency
- Voltage adjusted in increments of 0.1V, with each test repeated 3 times for accuracy.
- Graphs:
    - Power vs. Flapping Frequency
    - Power vs. Efficiency
    - Power vs. Percentage Increase in Efficiency Compared to the No-Spring Baseline

Actual Flight Test

Metafly

- Commercially available flapping-wing UAV made by Bionic Bird.
- To integrate the spring mechanism, a spring was then installed between the thin wire support structure and the wing mechanism.

- The test was carried out in an indoor gymnasium under controlled conditions.



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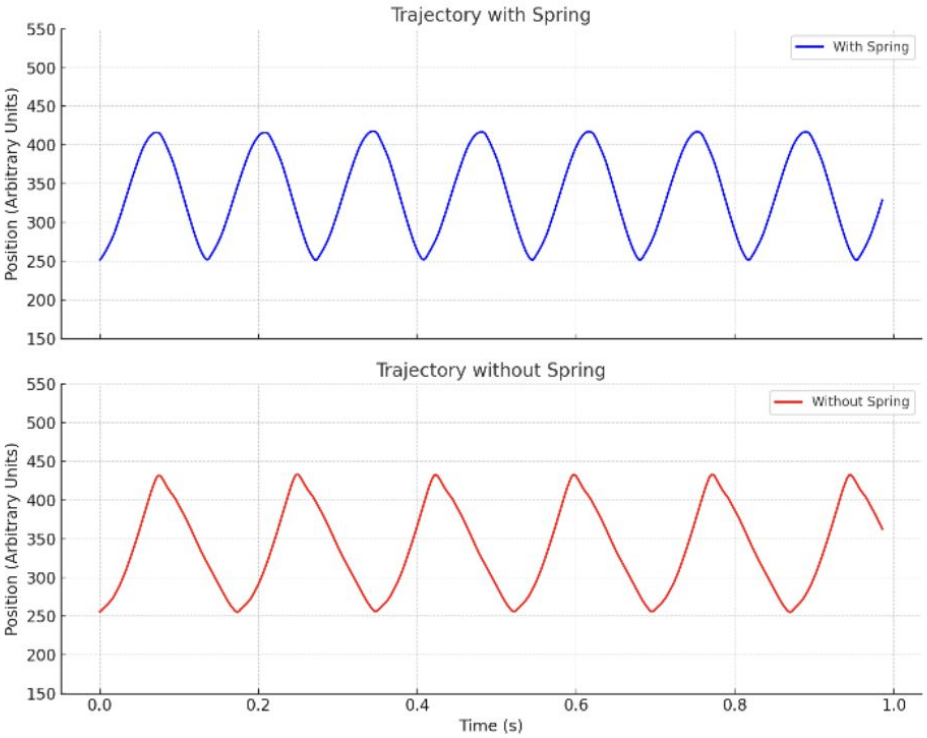
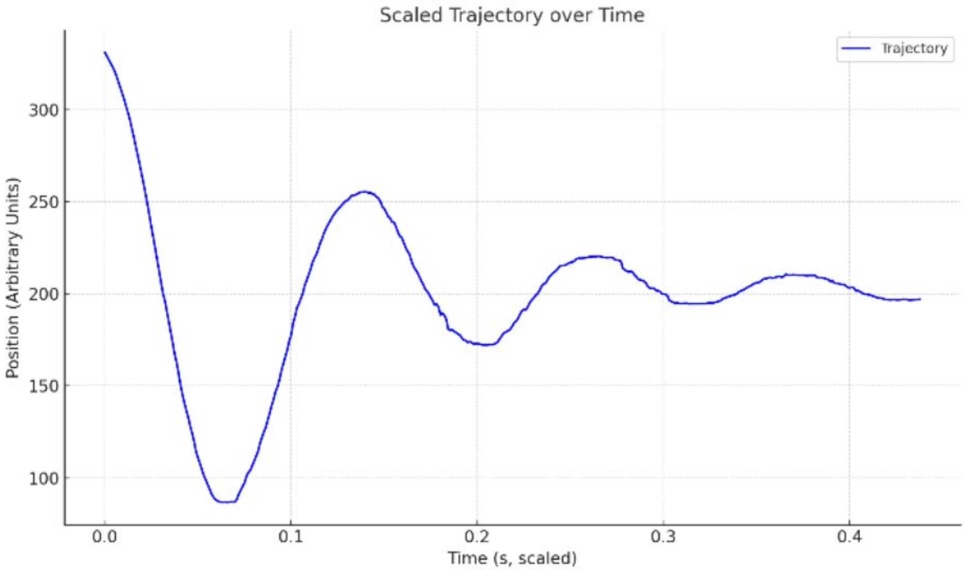
Experimental Result

Trajectory Analysis



- With spring, the trajectory smoothly follows the shape of a sine wave
- Without spring, sharp peaks occur during the reversal of the wing's motion, indicating abrupt impacts.

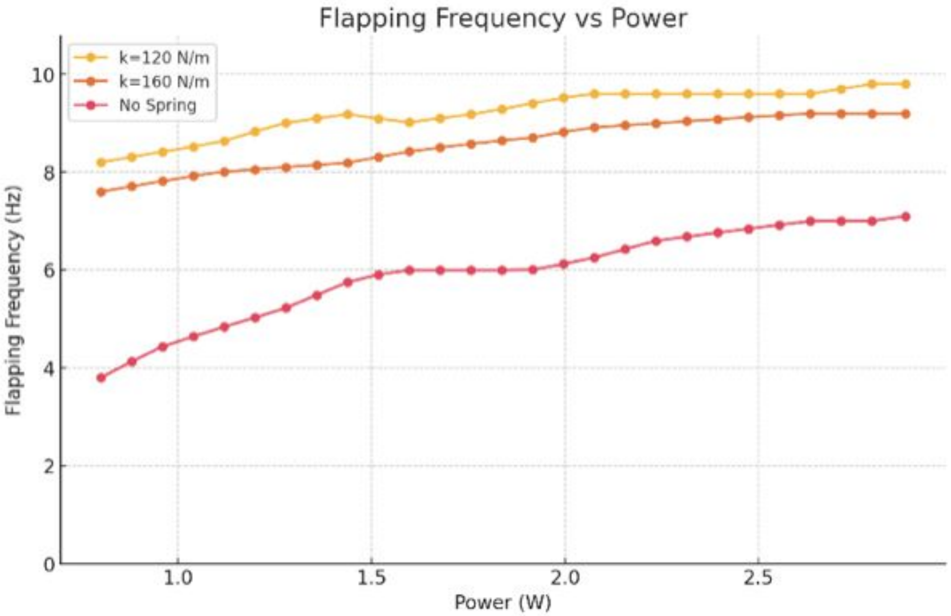


- 120 N/m spring: Resonant period is approximately 0.14 seconds, corresponding to a flapping frequency of about 7.1 Hz.
- 160 N/m spring: Measured period is approximately 0.12 seconds, corresponding to a flapping frequency of 8.1 Hz.

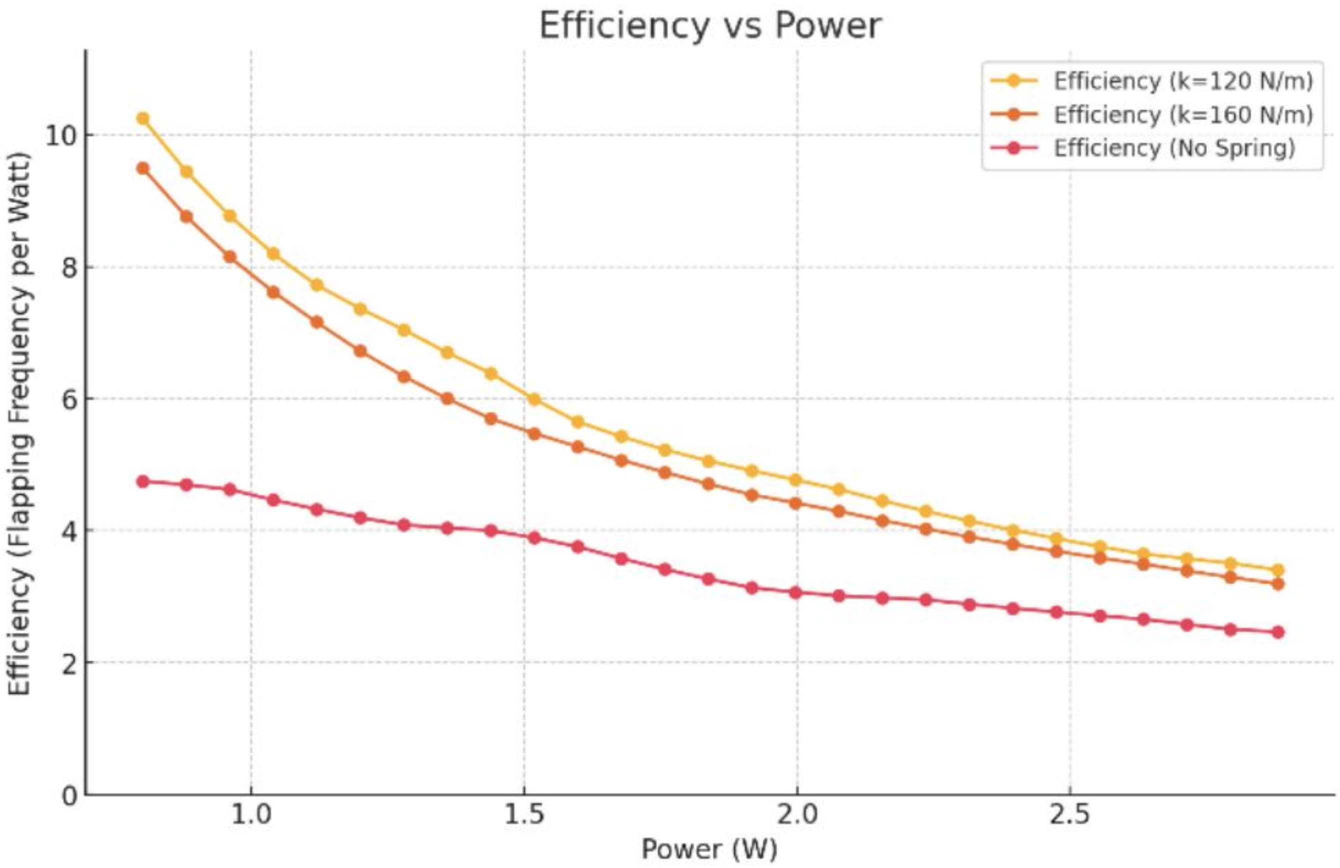
$$f = \frac{1}{2\pi}\sqrt{\frac{k l_s^2}{m L^2}}$$

- Theoretical calculation derived from this equation validates the approach and calculations of this research.

Flapping Frequency vs. Power

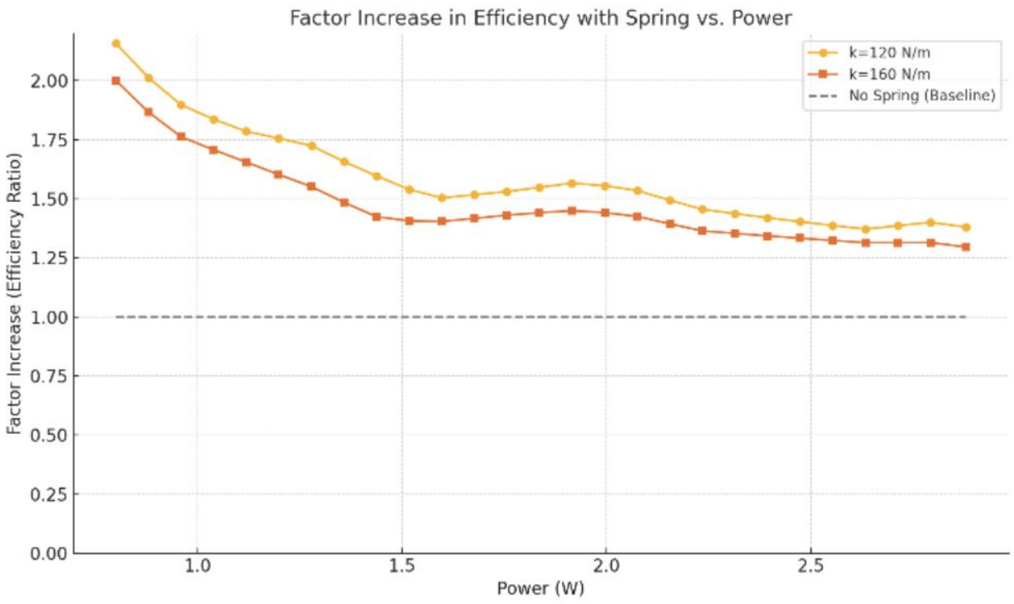


- Systems equipped with springs consistently achieve higher flapping frequencies for the same power input compared to the no-spring condition.
- Spring with a constant of 120 N/m slightly outperforms the one with 160 N/m.



Efficiency vs Power
Efficiency (k=120 N/m)
Efficiency (k=160 N/m)
Efficiency (No Spring)
Efficiency (Flapping Frequency per Watt)
0
2
4
6
8
10
1.0
1.5
2.0
2.5
Power (W)

Factor Increase in Efficiency vs. Power



- The efficiency is observed to improve by approximately 1.3 times at minimum and up to around 2 times at maximum.

Actual Flight Test Analysis

Metric	1	2	3	4	5	6	Average
Without Spring(s)	310	314	302	321	323	317	314.5
With Spring(s)	361	340	379	351	346	351	354.7

- Flight time with the spring is approximately 11% longer compared to without the spring.

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Conclusion

- Experimental results validated these theoretical predictions
  ⟶ spring-equipped system achieved up to twice the energy efficiency compared to the no-spring condition
- Flight tests further confirmed the practicality of the approach
  ⟶ 11% improvement in average flight time with the integration of spring mechanism

⟶ Spring-driven designs mitigate energy losses during wing motion, outperforming traditional systems.

- Further implications of establishing a foundation for bio-inspired UAVs with enhanced energy efficiency and flight endurance.

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Discussion

Limitations	Further Improvements
Weight	• Increased weight inhibited flight time improvements → lighter materials needed
Gravity	• Vertical experiment configuration likely have influenced the dynamics of the wing's upstroke and downstroke differently → adjust spring constants to balance forces
Efficiency	• Experiment in controlled conditions showed up to 100% efficiency improvement, but actual flight tests showed only 11% improvement → explore lighter spring materials or mechanisms to minimize weight

Further development	• Real-time adjustable springs • Outdoor flight tests with wind disturbances

Thank you!

Enhancing Energy Efficiency in Ornithopters through Spring-Driven Harmonic Oscillations

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Abstract – This study investigates the integration of spring mechanisms into the wing systems of ornithopters to enhance energy efficiency and flight performance. Inspired by the elastic energy storage in bird tendons, the research models the wings as harmonic oscillators, aiming to achieve resonance and reduce energy losses during directional changes in wing motion. Theoretical analysis revealed that tuning the spring constants to align the system's natural frequency with its operational frequency significantly enhances efficiency.

Experiments using a flapping test rig demonstrated up to twice the efficiency for spring-equipped systems compared to those without springs, with a maximum efficiency of 9.6 wingbeats per watt. Flight tests using a MetaFly UAV confirmed an average flight time improvement of 11% with spring integration. These findings suggest that spring-driven harmonic oscillations can provide a practical and effective method for optimizing energy use in flapping-wing UAVs. The findings demonstrate the feasibility of bio-inspired mechanical designs for improving UAV performance in applications such as environmental monitoring, infrastructure inspection, and search and rescue operations.

Keywords: Energy efficiency, Flapping-wing UAV, Ornithopter, Resonance, Spring mechanism

1. Introduction

Ornithopters are UAVs (Unmanned Aerial Vehicles) designed to emulate the flapping motion of a bird. These aerial vehicles have garnered significant interest due to their potential applications in search and rescue, surveillance, and environmental monitoring [1]. However, current models of ornithopters face limitations in energy efficiency, typically achieving flight times of only 20 to 40 minutes. This is due to its excessive use of energy in the continuous flapping motion of wings, requiring constant power input. The low flight endurance of ornithopters restricts their effectiveness in long-term missions and practical applications like long-range inspection of infrastructures such as power lines. Thus, this research aims to investigate energy efficiency improvement in ornithopters by integrating spring mechanisms that replicate the use of tendons during their flight.

Birds store elastic energy in their tendons and release it during their flapping motion. This elastic mechanism of tendons is found to contribute up to 60% of the net mechanical work for wing upstroke in pigeons, enhancing their flight efficiency [2]. Inspired by these properties of tendons in bird wings, this research takes a similar approach of integrating springs to achieve resonance in the flapping wings of the ornithopter. The resonance is achieved when a system is driven at its natural frequency, resulting in maximized energy efficiency and an aerodynamic lift [3].

In this research, the ornithopter's wings are equipped with spring mechanisms, modeling the system as a form of harmonic oscillator. The study investigates the trajectory of wing motion, energy efficiency, and actual flight performance through controlled experiments. By integrating spring mechanisms into the ornithopter design, this research aims to provide deeper insights into how such a mechanism impacts the energy efficiency and practicality of ornithopter flight.

2. Background

2.1 Previous Research

Existing research on the energy efficiency of ornithopters introduces a computational method for energy-efficient trajectory planning. The research observes gliding and flapping maneuvers, nonlinear dynamics and motion planning. Despite its analysis of efficient trajectory, it does not delve into enhancing the mechanical design of ornithopters. Therefore, by prioritizing mechanical optimization through spring integration, this research intends to develop a highly efficient ornithopter [4].

The energy storage mechanism in tendons is demonstrated by examining the supracoracoideus (SUPRA) muscle and the pectoralis (PECT) muscles. This elastic energy storage during the contraction of SUPRA and PECT muscles helps a bird to power the upstroke efficiently, contributing up to 60% of its net mechanical work.

Other existing research focuses on general comparisons of flight mechanics, examining flapping phases, motion, and wing shape. Though it has analyzed the effect of springs on flight, the research hasn't thoroughly focused on the direct impact of springs to energy efficiency [5]. Hence, this research seeks to further delve into how spring effects the optimization of energy by investigating various spring constants and testing multiple cases with different wing weights. Furthermore, by conducting experiments with realistic consideration of ornithopters, this research aims to provide practical insights into performance and efficiency.

2.2 Structure and Operating of Ornithopter Wings

The wings of an ornithopter are typically designed to emulate the flapping motion observed in bird flight. Each wing consists of lightweight materials to minimize inertia, with a flexible frame and surface covering that resembles bird feathers or membranes. This structure allows for efficient aerodynamic lift and thrust generation during flapping.

In an ornithopter, the joint mechanism consists of a rotating motor connected to a crank rod of radius r. This crank rod is attached to a connecting rod of length l, which moves up and down as the crank rotates. This motion drives the wings to move up and down, mimicking the flapping motion observed in birds.

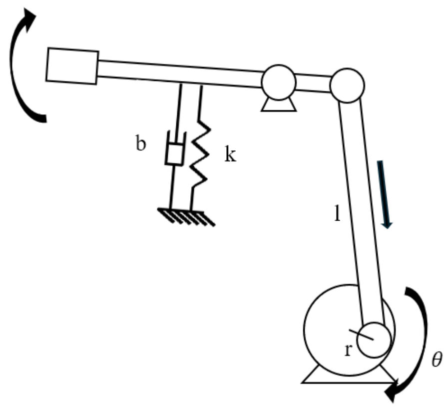

Figure 1. The joint mechanism in ornithopter

In this research, spring mechanisms are integrated into the wing system to replicate the tendon-like elastic energy storage observed in birds. Without a spring, the motor must overcome the load required to reverse the direction of the wing's motion during each stroke, resulting in additional energy consumption. By incorporating a spring, elastic energy is stored during the downstroke and released during the upstroke, reducing the load on the motor during direction changes. This integration minimizes wasted energy and enhances the overall energy efficiency of the system.

The resonance achieved through this mechanism ensures that the system operates near its natural frequency, thereby minimizing energy loss and maximizing aerodynamic performance.

2.3 Mathematical Modeling of Forced Harmonic Oscillations

To improve energy efficiency in ornithopters, it is essential to understand the dynamics of oscillatory systems operating near resonance. Such systems can be modeled as forced harmonic oscillators, described by the following governing equation:

$$I\ddot{\theta} + b\dot{\theta} + k\theta = T_0\cos(\omega' t) \qquad (1)$$

where I is the moment of inertia of the torsional pendulum, b is the damping coefficient, k is the torsional spring constant, T_0 is the amplitude of the driving torque, and ω′ is the angular frequency of the driving torque. Rewriting the equation with normalized parameters:

$$\ddot{\theta} + 2\beta\dot{\theta} + \omega^2\theta = \frac{T_0}{I}\cos(\omega' t) \qquad (2)$$

When $\omega = \sqrt{\frac{k}{I}}$ is the natural angular frequency of the system, and $\beta = \frac{b}{2I}$ is the damping ratio.

By solving the equation, the steady state amplitude A of the system under the sinusoidal driving force is given by:

$$A = \frac{\frac{T_0}{I}}{\sqrt{(\omega^2 - \omega'^2)^2 + (2\beta\omega')^2}} \qquad (3)$$

Resonance occurs when the driving frequency ω′ approaches the natural frequency ω, maximizing the amplitude. Under resonant conditions, the energy efficiency of the system is significantly improved as less input power is required to sustain oscillations.

To analyze the effect of adding a torsional spring, we assume the absence of the spring corresponds to k=0. Under this condition, the system operates purely as a damped harmonic oscillator driven by an external torque. By comparing the amplitudes of the system with k=0 and k>0, we can determine the conditions under which the inclusion of the spring enhances the amplitude.

If k=0, the natural frequency ω becomes zero, and the system's amplitude simplifies to:

$$A_0 = \frac{\frac{T_0}{I}}{\sqrt{(\omega')^4 + (2\beta\omega')^2}} \qquad (4)$$

To ensure the spring enhances the amplitude, the following inequality must hold:

$$\frac{1}{(\omega^2 - \omega'^2)^2 + (2\beta\omega')^2} > \frac{1}{(\omega')^4 + (2\beta\omega')^2} \qquad (5)$$

Simplifying the inequality leads to:

$$(\omega^2 - \omega'^2)^2 < (\omega')^4 \qquad (6)$$

$$\left(\frac{k}{I} - (\omega')^2\right)^2 < (\omega')^4 \qquad (7)$$

Taking the square root of both sides yields:

$$\left|\frac{k}{I} - (\omega')^2\right| < (\omega')^2 \qquad (8)$$

This inequality can be split into two conditions, combining these, the range for k is:

$$0 < k < 2I(\omega')^2 \qquad (9)$$

This result provides the necessary conditions for the spring constant k. When k falls within this range, the amplitude of the torsional pendulum with the spring will exceed the amplitude without the spring.

By incorporating spring mechanisms to achieve resonance, the energy required for flapping motions in ornithopters can be minimized. Tuning the spring constant k allows the system's natural frequency ω to align with the operational frequency of the wings, thereby enhancing both energy efficiency and flight endurance.

3. Materials and Methods

3.1 Materials

3.1.1 Flapping Test Rig

To conduct experiments and analyze the flapping motion, a flapping test rig was designed and constructed. The test rig was created using 3D modeling and printing techniques, allowing for precise customization of the components. A DC motor, powered by a regulated voltage from a power supply, drives a crank mechanism that moves the connected wings up and down.

Rods were above and below the wings to allow for the attachment of springs, connecting the wings to the main body. This setup enables the springs to compress and extend in response to the wing's motion, simulating harmonic oscillation. There are two springs used in this study, one with a spring constant of 120 N/m and the other with a spring constant of 160 N/m.

At the tips of the wings, a nut weighing 3g, can be attached as the mass of the wings. This allows for precise control over the wing's weight, enabling experiments with varying mass configurations

The wings were constructed using thin plastic membranes to provide drag and weighed less than 1 g. The total length of the wings is 7.5 cm, with the weights mounted 7 cm from the axis and the spring positioned 1.6 cm from the axis.

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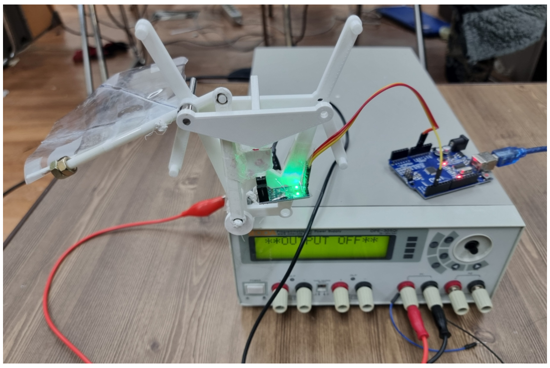

Figure 2. Overall view of the flapping test rig

Power consumption during operation can be monitored by reading the voltage and current values displayed on the power supply, providing measurements of energy usage. Additionally, a photocoupler was installed to detect the movement of the connecting rod between the crank and the wings. This sensor allows for the measurement of the flapping frequency (number of flaps per second). The photocoupler is connected to a computer via an Arduino microcontroller, facilitating data acquisition and analysis.

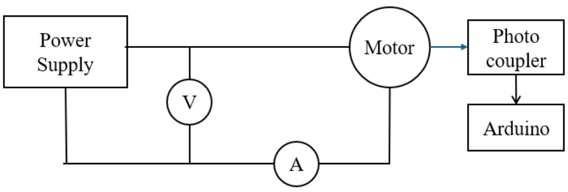

Figure 3. Circuit diagram of flapping test rig

3.1.2 MetaFly

MetaFly is a commercially available flapping-wing UAV developed by Bionic Bird. In this study, it was used for real-flight testing. The specifications are as follows:

- Length: 19 cm
- Wingspan: 29 cm
- Weight: Less than 10 g
- Battery: Rechargeable Li-Po, 58 mAh
- Flight Time: 8 minutes max
- Maximum Speed: 18 km/h

Figure 4. MetaFly

To integrate the spring mechanism, a thin wire support was added to the body, extending to the wings. A spring was then installed between the support structure and the wing mechanism. This modification allows the spring to compress and extend in synchronization with the wing's motion.

Figure 5. Integrated spring on MetaFly

3.2 Methods

3.2.1 Trajectory Analysis of Wing Motion Using Tracker

The trajectory of wing motion was analyzed to examine the differences in flapping behavior with and without the spring mechanism. Theoretically, in the absence of a spring, the system cannot be classified as a harmonic oscillator, and abrupt directional changes during wing motion are expected to occur, leading to energy losses each time the wing changes direction.

For this analysis, the flapping test rig was equipped with springs and adjustable weights. A white screen was placed behind the apparatus, and the motion was recorded using a high-speed camera at 960 fps while the rig was powered. The recorded footage was then processed using the open-source video analysis software, Tracker [6], to track the trajectory of the wings and quantify the motion patterns.

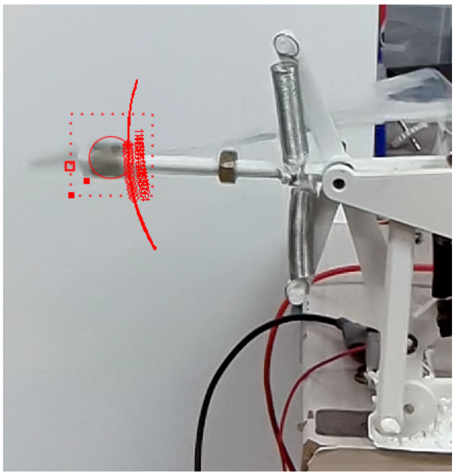

Figure 6. Image Analysis with Tracker

To compare the effects of the spring mechanism, an additional experiment was conducted under the same conditions but with the spring removed. The results of the two experiments were analyzed to identify changes in the trajectory and energy efficiency of the flapping motion.

When the connecting rod was detached from the wings, the spring was installed, and the system was oscillated to measure the resonant frequency.

3.2.2 Efficiency Analysis Based on Spring Usage, Spring Constant, and Wing Mass

This study aimed to compare energy efficiency under different conditions, including the presence or absence of a spring, variations in spring constants, and changes in wing mass. The theoretical impact of the spring mechanism on energy efficiency was also tested using experimental validation. The flapping test rig was used to measure power consumption and flapping frequency under controlled conditions. Voltage was adjusted in increments of 0.1 V, and the corresponding current was recorded to calculate power. The flapping frequency at each power level was determined as the average value over a 10-second measurement. All experiments were repeated three times under identical conditions, and the results were averaged to ensure reliability.

Energy efficiency was calculated as the ratio of flapping frequency per unit power, and the percentage improvement in efficiency was analyzed by comparing the spring-equipped cases with the no-spring baseline. Experiments were conducted using two spring constants (160 N/m and 120 N/m) with wing mass (3 g). For each case, three types of graphs were generated:

1. Power vs. Flapping Frequency
2. Power vs. Efficiency
3. Power vs. Percentage Increase in Efficiency Compared to the No-Spring Baseline

3.2.3 Actual Flight Test

The actual flight test was conducted using MetaFly to verify whether the proposed efficiency enhancement method could effectively improve flight performance, even with the added weight of the spring mechanism. This test aimed to confirm the practicality of the proposed approach in increasing flight efficiency under real-world conditions.

To minimize external variables such as wind, the test was carried out in an indoor gymnasium under controlled conditions. Flight time was measured for both configurations—with and without the spring mechanism—from a fully charged battery (4.2 V) until the battery was depleted to the cut-off voltage (3.5 V) triggered by the protection circuit. A total of six measurements were performed for each configuration to ensure reliability and provide robust comparative data.

For clarity of the analysis, the wingspan frequency of MetaFly was also measured using Tracker.

4. Experimental Result

4.1 Trajectory Analysis of Wing Motion Using Tracker

The following graphs show the flapping trajectories for cases with and without a spring, under the conditions of a wingtip mass of 3 g and a spring constant of 120 N/m, and same power consumption.

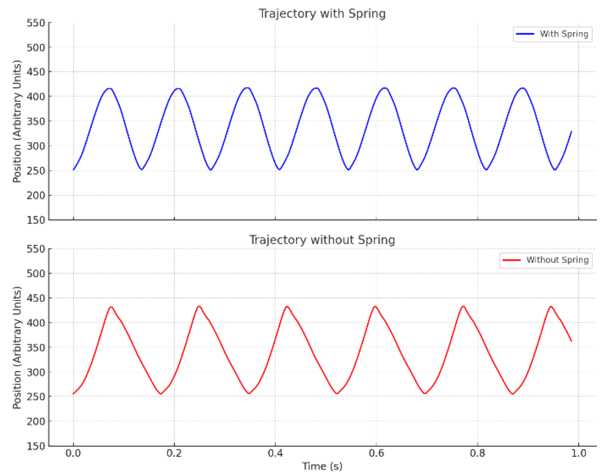

Figure 7. Trajectory of wing tip, with and without spring

These results show that, with a spring, the trajectory smoothly follows the shape of a sine wave, while without a spring, sharp peaks occur during the reversal of the wing's motion, indicating abrupt impacts. Additionally, the flapping frequency is higher with the spring compared to without it. This suggests that, in the absence of a spring, the wing's kinetic energy is being lost during motion.

The following graph represents the trajectory of the wing freely oscillating after being connected to a 120 N/m spring. From this, it can be observed that the resonant period is approximately 0.14 seconds, corresponding to a flapping frequency of about 7.1 Hz.

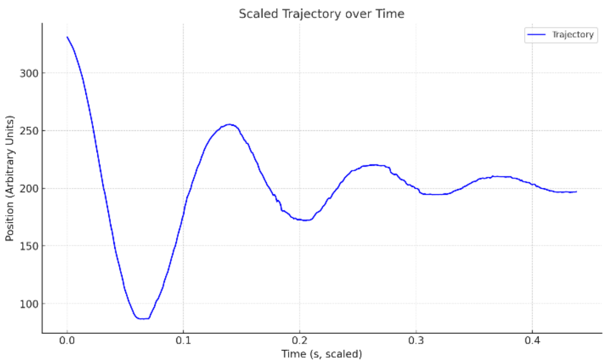

Figure 8. Trajectory of wing tip, free movement

This result is consistent with the theoretical calculation derived from the following equation when the mass m=0.003 kg (3 g), the rod length L=0.07 m (7 cm), the spring constant k=120 N/m, and the distance to the spring attachment point l_s=0.016 m. This agreement validates the approach and calculations of this research.

$$f = \frac{1}{2\pi}\sqrt{\frac{k l_s^2}{m L^2}} \tag{10}$$

With the 160 N/m spring, the measured period is approximately 0.12 seconds, corresponding to a flapping frequency of 8.1 Hz.

4.2 Efficiency Analysis Based on Spring Usage, Spring Constant, and Wing Mass

This graph represents the relationship between power consumption (W) and flapping frequency (flaps per second) for three conditions: with a spring of 120 N/m, with a spring of 160 N/m, and without a spring.

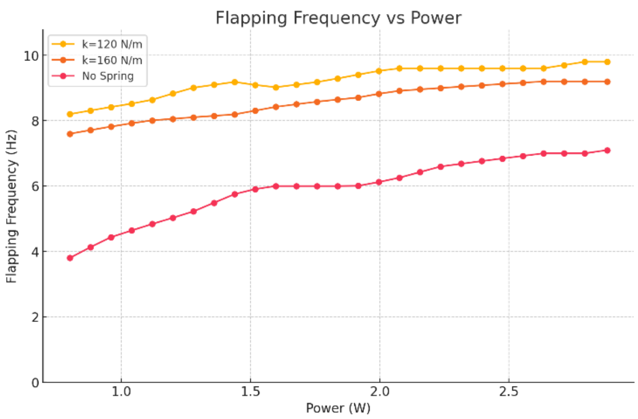

Figure 9. Power vs Flapping frequency

In this experiment, the power was incrementally increased, and the corresponding flapping frequency was measured under each condition. The results show that systems equipped with springs consistently achieve higher flapping frequencies for the same power input compared to the no-spring condition. Additionally, the spring with a constant of 120 N/m slightly outperforms the one with 160 N/m, particularly at lower power levels.

The following graph shows the efficiency (flapping frequency per unit power) as a function of power consumption for three conditions.

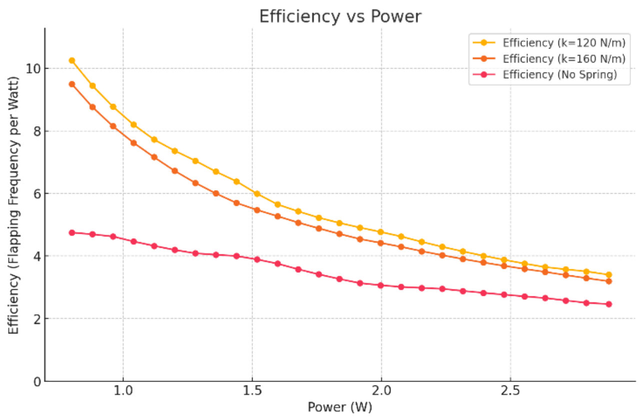

Figure 10. Power vs Energy consumption

The following graph shows how much efficiency improves compared to the no-spring condition. The efficiency is observed to improve by approximately 1.3 times at minimum and up to around 2 times at maximum.

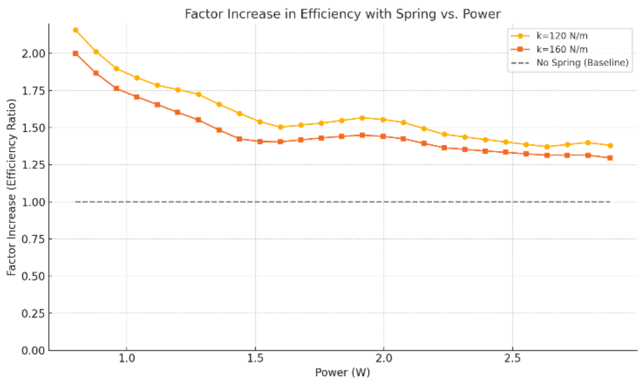

Figure 11. Power vs Efficiency increase

4.3 Actual Flight Test

As a result of the flapping frequency analysis through the tracker, it was found that the flapping per second was 0 to 12 Hz. This frequency range is similar to the analysis in the flapping test rig. The flight test results are as follows.

Table 1. Flight time of Actual flight test

Metric	**1**	**2**	**3**	**4**	**5**	**6**	**Average**
Without Spring(s)	310	314	302	321	323	317	314.5
With Spring(s)	361	340	379	351	346	351	354.7

The average flight time without the spring was 314.5 seconds, while with the spring, it was 354.7 seconds. This indicates that the flight time with the spring is approximately 11% longer compared to without the spring.

5. Conclusion

This study investigated the integration of spring mechanisms into the wing systems of ornithopters to enhance energy efficiency and flight performance. By modeling the wings as harmonic oscillators, the research demonstrated that appropriately tuned spring constants could enable resonance, resulting in smoother wing motion, reduced energy dissipation, and increased mechanical efficiency. Theoretical analysis showed that the inclusion of springs within specific stiffness ranges allowed the natural frequency of the system to align with the operational frequency, maximizing energy efficiency.

Experimental results validated these theoretical predictions, with the spring-equipped system achieving up to twice the energy efficiency compared to the no-spring configuration in controlled test rig experiments. Flight tests further confirmed the practicality of the approach, demonstrating an 11% improvement in average flight time with the spring mechanism. This highlights the potential for spring-driven designs to mitigate energy losses during directional changes in wing motion, a critical limitation of traditional ornithopter designs.

This study establishes the foundation for next-generation UAVs that leverage bio-inspired designs to achieve unmatched energy efficiency and flight endurance, addressing critical challenges in endurance-intensive missions.

6. Discussion

This study demonstrates the effectiveness of spring-driven harmonic oscillations in enhancing the energy efficiency of ornithopters; however, there are some limitations in the current experimental approach that merit discussion. These limitations provide valuable insights for future refinements and investigations.

Although the test rig experiments showed promising efficiency improvements, the real-world application highlighted weight-related limitations, emphasizing the need for further design optimization. The experiments conducted in this study tested flapping motions in a vertical configuration, which closely resembles real-world flight conditions. However, this orientation introduced gravitational forces that were not explicitly considered in the design of the test rig or the analysis. In particular, the force of gravity likely influenced the dynamics of the wing's upstroke and downstroke differently. A potential solution could involve adjusting the spring constants for the upper and lower springs to compensate for the asymmetry introduced by gravity. This would ensure a more balanced force distribution during flapping and potentially improve overall efficiency.

Finally, the experiments were conducted using only two spring constants (120 N/m and 160 N/m) and a single wing configuration. Expanding the range of spring constants and testing diverse wing shapes, including bio-inspired designs, could provide more comprehensive insights into the optimal configurations for energy efficiency. Additionally, the interplay between spring stiffness, wing mass, and damping effects warrants further investigation to refine system performance.

Future work could also integrate real-time control systems to dynamically adjust spring properties during flight, enabling the ornithopter to adapt to different flight scenarios. Incorporating outdoor flight tests with wind disturbances and other environmental factors would also provide a more robust assessment of the system's performance in real-world conditions.

By addressing these limitations, future research can build on the findings of this study to develop more efficient and versatile flapping-wing UAVs. Optimizing the interaction between spring mechanisms and aerodynamic factors will be key to unlocking the full potential of spring-driven harmonic oscillations for practical applications.

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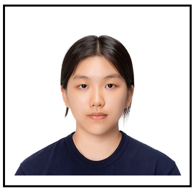

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